Irrigation of Agricultural Crops with Municipal Wastewater - A Review

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Sustainable viticulture is important for socio-economic prosperity in the Western and Northern Cape provinces of South Africa. Limited natural water resources, as well as periodic droughts in these regions necessitate the need to find alternative sources of irrigation water to sustain yield and quality. The large volumes of treated municipal wastewater generated annually holds promise as an alternative water source. Despite various treatment procedures, municipal wastewater may contain high levels of Na^+, B^{3+}, Cl^- and SO_4^{2-}, as well as trace elements and heavy metals. However, it often contains essential plant nutrients, *e.g.* N, P and K^+. If treated properly, municipal wastewater may be beneficial when reused for irrigating agricultural crops. Possible benefits include recycling of nutrients, fertiliser savings, the addition of organic material, a reduced pressure on fresh water sources and reduced environmental contamination. However, high salt loads, in particular Na^+, can have detrimental effects on soil physical and chemical properties, as well as crop sustainability. Therefore, it is essential to implement measures that will limit damage caused by salinity and/or sodicity. The attenuation and accumulation of toxic substances should also be managed to a minimum. Most of the information regarding treated municipal wastewater has been generated through laboratory studies using simulated wastewater, or in some cases actual wastewater. No studies have yet investigated the impact of irrigation with treated municipal wastewater under the conditions that prevail in South African grape growing regions.

INTRODUCTION

To sustain civilisation, a vast selection of materials is sourced from the environment. These materials are processed and/or digested by societies. The useful fraction of the material is consumed for good cause, whereas the unwanted fraction is concentrated into waste. Therefore, the primary objective of sustainable waste management should be to dilute the concentrated waste back into the environment causing as little harm as possible. The greater the area over which the waste is distributed, the more diluted it becomes, thereby reducing the risk of damage to the environment. Irrigation of recreational areas, *e.g.* parks and sports fields in urbanized areas as well as agricultural crops with treated municipal wastewater under controlled conditions is a common means to dilute waste back into the environment. Per definition, treated wastewater has been subjected to one or more physical, chemical or biological processes to reduce its pollution or health hazard (Raschid-Sally & Jayakody, 2008). Treatment can be carried out at central wastewater treatment works (WWTW) or by on-site facilities. Municipal wastewater is usually a combination of (i) domestic effluent consisting of blackwater, *i.e.* excreta, urine and associated sludge, (ii) greywater, *i.e.* kitchen and bathroom wastewater, (iii) water from commercial establishments and institutions, including hospitals and industrial effluent, as well as (iv) storm water and urban runoff (Raschid-Sally & Jayakody, 2008).

The use of wastewater for irrigation of agricultural crops is common practice around the world, particularly in arid and semi-arid regions (Arast *et al.*, 2016 and references therein). This applies to formal and informal agriculture (Table 1). In a Mediterranean climate, wastewater irrigation is also suitable, since it helps to mitigate the effects of dry spells during summer, whereas winter rainfall can leach excess amounts of salts applied *via* wastewater irrigation from the soil. The Western Cape of South Africa has a temperate Mediterranean climate which is characterised by warm, dry summers and mild, wet winters with rainfall mostly occurring

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between May and August. The mean annual rainfall in the province varies from *ca*. 300 mm to over 900 mm in some regions (Botai *et al*., 2017). The climate of the Western Cape is particularly suitable for the production of table and wine grapes, and supports a productive wine industry (Du Plessis & Schloms, 2017). However, fresh water resources are generally limited in grape growing areas. Consequently, sustainable grape production primarily depends on winter rainfall stored in the soil and reservoirs, particularly in the drier regions. Inconsistent rainfall and periodic droughts can therefore have severe negative impacts on the wine industry. During the 2014 to 2017 hydrological years, the province experienced its worst drought since 1904 (Botai *et al*., 2017). The City of Cape Town (CoCT) introduced level 6B water restrictions in February 2018, which limited domestic water consumption to 50 L per person per day. Likewise, the agricultural sector had to reduce its consumption to *ca.* 60% of its normal water allocation. Some regions were more severely affected than others. For example, producers in the Lower Olifants River region only received 13% of their normal water allocation (World Wildlife Foundation, 2018). Furthermore, the South African wine grape harvest amounted to *ca*. 1.2 million tonnes in 2018, which was 15% less than in 2017 and the smallest harvest in more than ten years (Vinpro, 2018). It is evident that water conservation and improved water use efficiency are of cardinal value to the wine industry. In this regard, reusing effluents and wastewater presents a potential solution to relieve pressure on fresh water sources, and provide alternative irrigation water sources during droughts.

The use of wastewater for irrigation in South Africa is limited, and little is known about the use of treated municipal wastewater for irrigation, particularly in the Western Cape. Despite a lack of information on the long- and short-term impacts of its use on vineyards, *ca*. 2 000 ha are being irrigated with treated municipal wastewater in the Swartland and surrounding areas (Myburgh, 2018). This wastewater is sourced from the CoCT Potsdam WWTW in Milnerton, as well as the Malmesbury municipality approximately 55 km north of Cape Town. In an area where grapevines are often grown under dryland conditions due to the lack of irrigation water, the availability of additional water in the form of treated municipal wastewater are extremely valuable to producers in this region (Myburgh, 2018).

Volumes of municipal wastewater generated

Information regarding the volume of municipal wastewater that is generated worldwide tends to be scarce, outdated and/or inconsistent (Sato *et al*., 2013). The United Nations World Water Development Report (2017) estimated that approximately 3.14×10^{11} m^3 of municipal wastewater is generated globally each year. Half of this volume is produced by Brazil, China, India, Indonesia, Japan, Russia and the United States (Mateo-Sagasta *et al*., 2015). According to the FAO AQUASTAT database (2017), 3.54×10^9 m^3 of municipal wastewater was produced in South Africa in 2009. This estimation is 3.42×10^8 m^3 more than was reported for the year 2000 (Sato *et al*., 2013). The Cape Town metropole has 23 wastewater treatment works that can treat approximately 3×10^8 m^3 of wastewater annually (CoCT, 2017). In 2007/2008, 2.18×10^8 m^3 of treated effluent was discharged from 16 of the WWTWs around Cape Town according to the Department of Water Affairs (DWA) (2010). During the 2015/2016 financial year, approximately 2.27×10^8 m^3 of wastewater was collected and discharged by WWTWs around Cape Town (CoCT, 2016). After sufficient treatment, most of the treated municipal wastewater is discharged into rivers, canals, wetlands, aquifers or the ocean. Five percent of the city's used potable water is treated and recycled for non-potable uses, mainly irrigation (CoCT, 2017). This recycled water is redistributed to over 160 consumers in the vicinity of the city, which includes schools, sports centres, golf courses, farms, industries and commercial developments. The water is also used for irrigating municipal parks and flowerbeds in the city. The Potsdam WWTW near Milnerton has the largest capacity to generate recycled effluent, being able to produce 1.67×10^7 m^3 of treated effluent annually. The DWA recorded that 1.28×10^7 m^3 of municipal wastewater was treated and recycled at the Potsdam WWTW in 2007/2008. The CoCT has operated this wastewater reuse system for several decades and is one of the few local authorities that regards the reuse of treated municipal wastewater as a vital component of its integrated water management plan (Adewumi *et al*., 2010).

Quality of municipal wastewater

Knowledge on the quality of irrigation water is critical for understanding its management for long-term use and productivity (Tak *et al*., 2012). For this review, water quality will refer to the characteristics and composition of water that could influence its suitability for irrigating agricultural crops.

TABLE 1
The extent of urban wastewater (WW) used for irrigation by informal and formal farmers in selected regions around the world (after Raschid-Sally & Jayakody, 2008).

Region	No of cities with data	Total WW farmers informal and formal	Total WW area (ha) informal and formal
Africa	9	3 550	5 100
Asia	19	992 880	214 560
Latin America	8	88 300	142 160
Middle East	3	3 320	34 920
Total	39	1 088 050	396 740

The evaluation of irrigation water is normally based on its chemical and physical properties (Ayers & Westcot, 1985; Angelakis *et al*., 1999; Hussain & Al-Saati, 1999; Pedrero *et al*., 2010; Tak *et al*., 2012), as well as its microbiological content (Angelakis, 1999; WHO, 2006; Qadir *et al*., 2007; Pedrero *et al*., 2010). There are numerous indicators to assess the chemical quality of water. The major criteria are as follows:

(i) The pH and alkalinity as it affects the solubility and availability of plant nutrients and toxic metals. Water with an inherently low pH can also be corrosive to pipelines, sprinklers and control equipment (Ayers & Westcot, 1985). In some instances, residual sodium carbonate (RSC) is used to describe the precipitation and dissolution of alkaline earth carbonates (Hussain & Al-Saati, 1999).

(ii) The salinity of irrigation water as quantified in terms of electrical conductivity (EC_w) (Ayers & Westcot, 1985; Hussain & Al-Saati, 1999; Tak *et al*., 2012).

(iii) Chemical oxygen demand (COD) and biochemical oxygen demand (BOD) which are used to describe the organic matter in wastewater (Pescod, 1992; Paranychianakis *et al*., 2010).

(iv) Sodium adsorption ratio (SAR_w), since it can lead to the deterioration of soil physical properties (Ayers & Westcot, 1985; Hussain & Al-Saati, 1999; Laurenson *et al*., 2012; Tak *et al*., 2012; Müller & Cornel, 2017).

(v) Total dissolved solids (TDS) and suspended solids (SS) (Asano *et al*., 2007).

(vi) Specific ion toxicity with special reference to Na^+, chloride (Cl^-) and boron (B^{3+}) (Ayers & Westcot, 1985; Pescod, 1992; Pedrero *et al*., 2010), as well as other ions such as sulfate (SO_4^{2-}) (Hussain & Al-Saati, 1999; Tak *et al*., 2012), and various trace elements and heavy metals (Stevens *et al*., 2004).

(vii) Essential plant nutrients, including nitrogen (N), phosphorus (P) and K^+ (Gupta *et al*., 1998; Yadav *et al*., 2002; Ryan *et al*., 2006; Rusan *et al*., 2007; Singh *et al*., 2012).

Many wastewater quality criteria are based on health risks pertaining to the exposure of farmers, workers and consumers to pathogens (Qadir *et al*., 2010). Therefore, the microbiological quality of municipal wastewater is of utmost importance. The World Health Organisation (WHO) released revised guidelines in 2006 for the safe use of wastewater, excreta and greywater in the agricultural context (WHO, 2006). These guidelines replaced the previous version (WHO, 1989) which stipulated maximum values of faecal coliforms (FC) and helminth eggs allowed in wastewater destined for irrigation use. The new guidelines comprise health-based targets and the standard metric of disease is expressed as Disability-Adjusted Life Years (DALY's). However, FC is still commonly used as health-based criteria for municipal wastewater, along with the presence of *Escherichia coli*, since it is the most representative species to determine the occurrence of faecal contamination (Paranychianakis *et al*., 2010). Wastewater quality variables vary greatly depending on the quality of the water supply, the nature of the wastes that are added during use, as well as the degree to which the wastewater has been treated (Pedrero *et al*., 2010). Due to this variability, quality norms for wastewater irrigation are generally prescribed by legislation. The legislated limits for the most important characteristics of wastewater to be used for irrigation in South Arica are listed in Table 2.

Characteristics of raw, untreated municipal wastewater

Raw municipal wastewater usually contains a combination of domestic and industrial effluents, as well as storm water or run-off (Qadir *et al.,* 2010). Elevated levels of metals, metalloids and compounds of a volatile or semi-volatile nature often occur in industrial effluents, whereas domestic effluents commonly have a high pathogenic load (Qadir *et al.,* 2010). Pathogenic organisms such as viruses, bacteria, protozoa and helminth eggs, are commonly found in sewage effluents (Iannelli & Giraldi, 2010). These organisms pose a serious threat to farmers and workers, as well as consumers of crops that have been irrigated with untreated wastewater. Frequent exposure to untreated wastewater containing skin irritants and heavy metals such as cadmium (Cd^{2+}), lead (Pb^{2+}) and mercury (Hg^{2+}) is associated with numerous chronic health effects (Dickin *et al.,* 2016).

Several studies have shown that the salinity of untreated wastewater is generally higher than conventional water used for irrigation (Gupta *et al.,* 1998; Rana *et al.*, 2010; Jung *et al.*, 2014; Khan *et al.*, 2015). The EC_w of sewage effluents was 51% higher than that of well waters used for irrigation (Rana *et al.*, 2010). This was due to the exploitation of

TABLE 2.
General Authorisations for legislated limits for pH, electrical conductivity (EC_w), chemical oxygen demand (COD), sodium adsorption ratio (SAR_W) and faecal coliforms (FC) for wastewater used for irrigation in South Africa (Department of Water Affairs, 2013).

Parameter	Maximum irrigation volumes (m^3/day)		
	< 50	< 500	< 2 000
pH	6-9	6-9	5.5-9.5
EC_w (dS/m)	2	2	0.7-1.5
COD (mg/L)	5 000	400	75
SAR_w	< 5	< 5	Other criteria apply
FC (per 100 mL)	1 000 000	100 000	1 000

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water by industries that discharge contaminated water back into sewerage systems (Gupta *et al.,* 1998). Another report showed that untreated wastewater of an industrial nature had EC_w values that were four times higher than that of well waters (Khan *et al.*, 2015). However, it was found that even though EC_w values for untreated wastewater were higher than for groundwater that was used for irrigation (Jung *et al.*, 2014), it was still within the permissible limits to use as irrigation water (Pescod, 1992).

The BOD and COD values of untreated sewage waters are appreciably higher than those of conventional irrigation water (Yadav *et al.,* 2002; Abegunrin *et al.,* 2016; Tripathi *et al.,* 2016). This is because the influent quality of untreated wastewater sent to WWTWs varies on a daily, monthly and seasonal basis (Asano *et al.*, 2007). It is, therefore, nearly impossible to describe a "typical" composition of wastewater.

Characteristics of treated municipal wastewater

The objective of wastewater treatment is to reduce its risk of polluting the environment, and to prevent health hazards through consumption of or contact with contaminated water. Lower levels of heavy metals (De la Varga *et al.,* 2013) and harmful pathogens (Kiziloglu *et al.,* 2008; De Sanctis *et al.,* 2017) have been reported for municipal wastewaters that have been subjected to some form of treatment. The quality of treated wastewater will vary according to its degree of treatment. Wastewater treatment stages are traditionally categorised as preliminary, primary, secondary, tertiary, quaternary or advanced (Iannelli & Giraldi, 2010). Preliminary treatments aim to remove materials such as sand, oil, grease and grit that could interfere in subsequent stages of treatment. Primary treatment is usually a sedimentation process where primary sludge is separated from effluent. Effluents that have been subjected to preliminary and primary treatment processes have reduced BOD, SS and total organic carbon (TOC) levels (Asano *et al.*, 2007). Likewise, the EC_w of preliminarily treated wastewater was lower compared to untreated wastewater and was further reduced after primary treatment.

Secondary treatment processes aim to reach quality standards that would allow municipal wastewater to be safely returned to the natural environment. This is obtained by removal operations such as biological treatments, *e.g.* oxidation ponds and activated sludge, as well as chemico-physical treatments, *e.g.* flocculation and clarification. Wastewater is subjected to tertiary treatment processes to further decrease SS after secondary biological treatments (Asano *al.*, 2007). A disinfection stage is also typically included as part of tertiary treatments (Iannelli & Giraldi, 2010). Considerable reductions in EC_w, turbidity, SS, COD, BOD as well as metal concentrations occurred in wastewater that was subjected to tertiary treatment processes (Rekik *et al.*, 2017). Quaternary treatment is only used in instances where reclaimed water of a very high quality is required, and includes processes such as reverse osmosis and nanofiltration, which removes nearly all compounds possibly present in wastewater, including small ions (Asano *et al.*, 2007). Nanofiltration membranes have been found to reduce ion concentrations in biologically treated municipal wastewater (Bunani *et al.,* 2013). It is clear that wastewater quality increases with higher degrees of treatment. However, capital investment and operational costs are most likely to rise with the level of wastewater treatment.

In the Western Cape, treated municipal wastewater for irrigation of wine grapes near Philadelphia and Malmesbury is sourced from the City of Cape Town and Malmesbury wastewater works, respectively. In 2020, the populations of Cape Town and Malmesbury were estimated at 4 617 560 and 34 991, respectively. Despite the enormous difference in populations, the quality characteristics of the treated wastewaters of Cape Town (10-year average) and Malmesbury (5-year average) are comparable (Figs. 1 & 2). This shows that treated municipal wastewater can be of acceptable quality for irrigation of agricultural crops, irrespective of the scale of wastewater generation.

Effect of irrigation with municipal wastewater on soil properties

Soil chemical properties

pH: Changes in soil pH due to irrigation water occur slowly over time as soils are usually strongly buffered against pH fluctuations (Ayers & Westcot, 1985). Depending on the composition and pH of the specific wastewater used, irrigation with municipal wastewater may have variable effects on soil pH. Irrigation using municipal wastewater has been shown to (i) increase soil pH (Qian & Mecham, 2005; Gwenzi & Munondo, 2008; Hermon, 2011; Lado *et al.,* 2012), (ii) decrease soil pH (Shahalam *et al.,* 1998; Rattan *et al.,* 2005; Keser, 2013; Abunada & Nassar, 2015) or (iii) have no significant effect at all (Stevens *et al.,* 2003; Duan *et al.,* 2010; El-Nahhal *et al.,* 2013). This agrees with inconsistent trends in soil pH where soils were irrigated with treated municipal wastewater for different periods (Rusan *et al.,* 2007). The inconsistent pH responses are most likely due to variations in the buffer capacity of soils.

Salinity: The accumulation of water-soluble salts in the plant root zone can cause salinity problems, which could lead to a reduction in crop yield (Ayers & Westcot, 1985). Electrical conductivity, as measured in a saturated soil extract (EC_e), is the most commonly used parameter for estimating soil salinity. It is easily measured and considered to be a practical index of the total ionised salt concentration in aqueous samples (Rhoades *et al*., 1999). Most studies that have investigated the effect of municipal wastewater irrigation on soils reported significant increases in EC_e as a result of wastewater irrigation (Gupta *et al.,* 1998; Panahi Kordlaghari *et al.,* 2013; Bedbabis *et al.,* 2015; Andrews *et al.,* 2016; Ganjegunte *et al.,* 2017; Nicholás *et al.,* 2016). In most cases, increased soil EC_e values were attributed to higher concentrations of salts and TDS in the irrigation waters. In this regard, no significant difference occurred in soil EC_e where the EC_w of treated wastewater and fresh water used for irrigation was comparably low (El-Nahhal *et al.*, 2013). In contrast, irrigation with treated municipal effluent containing a low level of salinity decreased soil EC_e significantly (Hassanli *et al.*, 2008). It was also shown that irrigation with treated municipal wastewater caused a more pronounced EC_e increase in heavier, clayey soils compared to lighter textured soils (Adrover *et al.*, 2017). This can

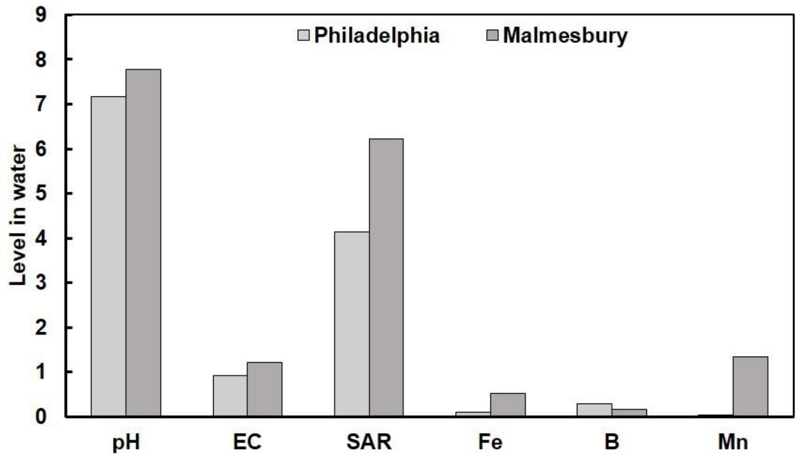

FIGURE 1
The pH, EC (dS/m) and SAR, as well as Fe, B and Mn concentrations (mg/L) in treated municipal wastewater used for irrigation of vineyards near Philadelphia and Malmesbury, respectively (Myburgh, 2018).

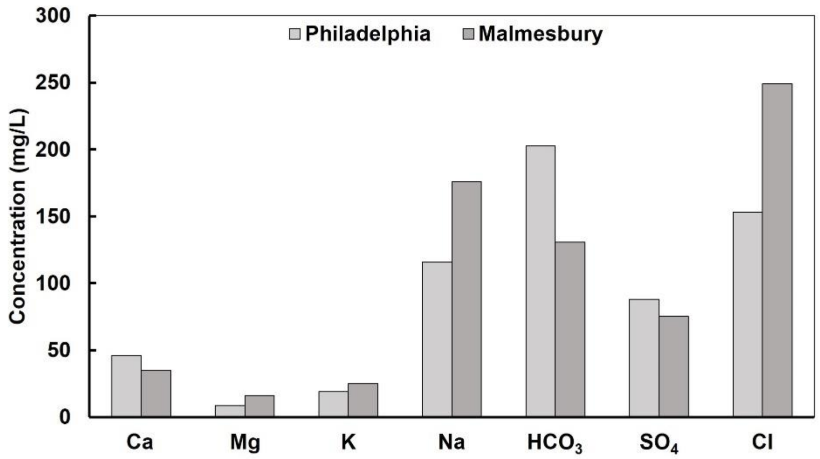

FIGURE 2
Element concentrations in treated municipal wastewater used for irrigation of vineyards near Philadelphia and Malmesbury, respectively (Myburgh, 2018).

possibly be explained by a positive correlation between clay content and EC_e of soils (Sudduth *et al.* 2005). Leaching salts from the root zone in instances where poor quality water is used for irrigation is of particular importance, since it can reduce soil water availability to crops and adversely affect yields (Ayers & Westcot, 1985).

Organic matter: The addition of organic matter (OM) to soils through the application of municipal wastewater can have significant effects on soil nutrient storage and structure (Jaramillo & Restrepo, 2017). The positive effects of OM on soil physical properties include, amongst others, reduced bulk density, increased water holding capacity and increased aggregate stability (Tisdall & Oades, 1982; Oades, 1984). In addition to effects on cation exchange capacity, buffer capacity, enzymatic activity and availability of contaminants, the OM in wastewater may increase TOC in the soil (Jaramillo & Restrepo, 2017 and references therein). Irrigation with municipal wastewater has been shown to increase soil OM (Mohammad & Mazahreh, 2003; Kiziloglu *et al*., 2007; Al-Omron *et al*., 2012; Bedbabis *et al*., 2014), as well as soil organic carbon (OC) (Rattan *et al*., 2005; Gwenzi & Munondo, 2008; Ghosh *et al*., 2012; Mojid & Weysure, 2013; Andrews *et al*., 2016). Over-irrigation with untreated wastewater in order to supply more nutrients to vegetable crops in alluvial soil also increased soil OM (Angin *et al.*, 2005). In this case, flood irrigation with raw wastewater almost doubled the OM in the top soil layer (Fig. 3). In contrast, soil OM was found to decrease after the application of wastewater irrigation (Herpin *et al*., 2007). This was most probably due to the stimulation of microbial growth resulting from labile C and N supplied *via* the wastewater (Tarchouna *et al*., 2010). However, it was also reported that irrigation with treated municipal wastewater had no significant effect on soil OM (Pedrero & Alarcón, 2009; Chen *et al*., 2015; Pérez *et al*., 2015). Based on the foregoing, the role of OM applied to soils *via* treated municipal wastewater seems to be inconsistent.

Nitrogen: Wastewater contains variable amounts of ammonium (NH_4^+), nitrate (NO_3^-) and organic N depending on the degree of treatment. The sum of this N is referred to as total N (Durán-Álvarez & Jiménez-Cisneros, 2016). Sources of N in municipal wastewater include food scraps, body exudates, N-containing cleaning chemicals and personal hygiene products, as well as faeces and urine (Patterson, 2003). Increases in soil total N were attributed to elevated amounts of N found in treated wastewater used for irrigation (Rusan *et al.*, 2007; Kamboosi, 2017). Irrigation with untreated and treated municipal wastewater in a pot experiment increased levels of soil NO_3^- compared to irrigation with rainwater (Thapliyal *et al*., 2013). It has been suggested that the addition of N through wastewater irrigation may reduce the need for additional N fertilisation (Chen *et al*., 2013a). However, where N levels in wastewater exceed the requirements of cultivated crops, excessive uptake by plants (Tak *et al*., 2012), and/or N leaching to groundwater sources (Kim & Burger, 1997; Candela *et al*., 2007) might pose possible risks. These risks can be reduced by scheduling wastewater irrigation based on crop water use and by cultivating crops that have high N requirements (Stewart *et al*., 1990) such as Pearl millet (Fourie *et al.*, 2015).

Phosphorus: A study carried out in the United Kingdom showed that the main sources of P in domestic sewage were natural diet, food additives, automatic dishwashing detergents, laundry products, P additions to reduce Pb levels in drinking water, food waste and personal care products (Comber *et al.*, 2013). Other sources of P in municipal wastewater include urban run-off, agricultural run-off and industrial discharge. The use of P-rich municipal wastewater for irrigation has been shown to increase soil P levels (Mohammad & Mazahreh, 2003; Adrover *et* al., 2012; Omidbakhsh *et al*., 2012). Likewise, irrigation with 100% wastewater elevated soil-P compared to a non-irrigated control, irrigation with brackish and saline water, as well as a mixture of waste and saline water (Fig. 4). It was also reported that available P increased by 114% in soils that were irrigated with treated sewage water for 40 years (Meena *et al*., 2016). Similar results were obtained where untreated wastewater was used for irrigation (Kiziloglu *et al*., 2008; Rana *et al*., 2010). The elevated levels of P in soils irrigated with wastewater can be attributed to higher P content in the water, as well as added OM to which P can adsorb (Bedbabis *et al*., 2015). In contrast to the foregoing, wastewater irrigation had little or no effect on soil P, although the wastewater contained high levels of P (Midrar *et al*., 2004; Heidarpour *et al*., 2007). In general, it seems that irrigation with treated municipal wastewater could be a potential source of P nutrition for crops. It should be noted that world wide natural P reserves are declining.

Potassium: Although K^+ concentrations in municipal wastewaters are considered to be quite low compared to wastewaters from an agricultural processing origin (Arienzo *et al.*, 2009), numerous studies showed an increase in soil K^+ due to irrigation with K-rich municipal wastewater (Kiziloglu *et al*., 2008; Galavi *et al*., 2010; Bedbabis *et al*., 2015; Alghobar & Suresha, 2016; Kamboosi, 2017). The use of municipal wastewater as an alternative K^+ fertiliser source is particularly suitable since soluble and exchangeable forms of K^+ are more rapidly increased compared to conventional fertilisers (Arienzo *et al.*, 2009). Furthermore, this K^+ is immediately available to plants (Levy & Torrento, 1995). Irrigation with K-rich wastewaters also holds possible benefits in terms of soil fertility where soil K^+ is low (Howell, 2016), but long-term irrigation with K-rich wastewaters may have negative impacts on soil chemical and physical properties (Laurenson *et al*., 2012). The extent to which wastewater irrigation impacts the soil K^+ levels is inherent to the K^+ levels in the particular wastewater used. However, irrigation with wastewater containing relatively low levels of K^+ may have little or no effect on soil K^+ (Pedrero & Alarcón, 2009).

Calcium: Calcium is not only an essential plant nutrient, but it also plays a role in the structural stability of soils (Wuddivira & Camps-Roach, 2007) and the buffering of soil pH (Bache, 1984). Irrigation with wastewater appears to

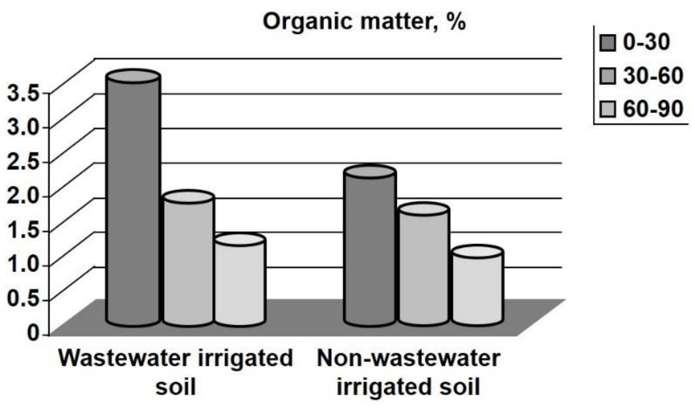

FIGURE 3
Effect of wastewater irrigation on soil organic matter in an alluvial soil (redrawn from Angin *et al*., 2005).

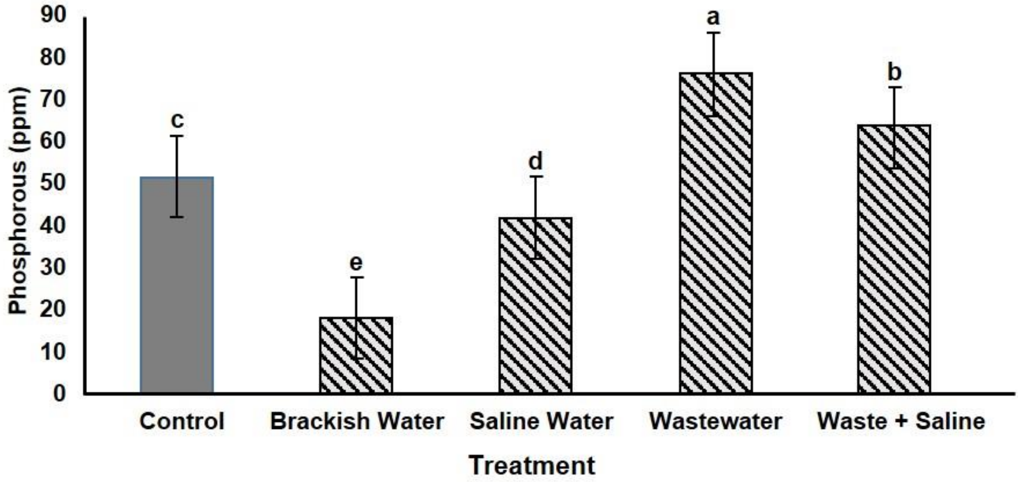

FIGURE 4
Effect of irrigation with different waters on phosphorous content in the 0 to 30 cm layer of a loamy clay soil in Iran compared to a non-irrigated control (Arast *et al*., 2016).

increase soil Ca^{2+} (Kiziloglu *et al.*, 2007; Galavi *et al.*, 2010; Rana *et al.*, 2010; Thapliyal *et al.*, 2011). The addition of Ca^{2+} *via* wastewater irrigation not only increases plant available Ca^{2+}, but wastewaters that contain appreciable amounts of Ca^{2+} and Mg^{2+} can indirectly assist in the amelioration of excessive Na^{+} application by reducing SAR (Howell, 2016). Some studies have found that well waters containing higher amounts of Ca^{2+} than wastewaters had a greater impact on soil Ca^{2+} levels (Neilsen *et al.,* 1991; Heidarpour *et al.,* 2007). In contrast, soil Ca^{2+} levels decreased under treated wastewater irrigation although the water contained high amounts of Ca^{2+} (Laurenson, 2010). This could be explained by Ca^{2+} uptake by plants, excessive losses through leaching or transformations of Ca^{2+} in the soil (Abdelrahman *et al.,* 2011).

Magnesium: It is widely reported that municipal wastewater is a viable source of Mg^{2+} in soils (Gwenzi & Munondo, 2008; Samaras *et al*., 2009; Thapliyal *et al.,* 2013; Bedbabis *et al*., 2015) but some studies have shown no such effect (Pedrero & Alarcón, 2009; Duan *et al*., 2010). In some instances, irrigation with municipal wastewater even resulted in decreased soil Mg^{2+} levels (Abdelrahman *et al.,* 2011). Soil Mg^{2+} also decreased where irrigation with municipal wastewater was compared to irrigation with well water, although the two water types contained similar levels of Mg^{2+} (Neilsen *et al*., 1991). It is most likely that high Na^{+} and K^{+} contents in the wastewater caused a decrease in soil Mg^{2+} through mass exchange.

Sodium: Sodium is considered to be one of the most hazardous elements present in municipal wastewater. Since these ions are not easily removed by conventional WWTW, the salinity of reclaimed water is usually 1.5 to 2 times more compared to municipal drinking water (Chen *et al.,* 2013a). Accumulation of excessive amounts of Na^{+} in the soil may cause sodic soil conditions. These conditions are often characterised by swelling and dispersion of clays, clogging of soil pores, surface crusting, obstruction of water infiltration and increased runoff (Tak *et al.*, 2012). Soil physical degradation restricts the movement of water into and throughout the soil profile, thereby limiting water availability to active growing plant roots. The Na^{+} content of water and soils is most commonly characterised by the relation of Na^{+} relative to Ca^{2+} and Mg^{2+}, or SAR. Therefore, the sodium adsorption ratio (SAR_w) is often used to predict the sodicity hazard of irrigation water (Tak *et al*., 2012). For example, guidelines for the assessment of the sodium hazard of irrigation water are based on SAR_W in relation to EC_W (Table 3).

An abundance of Na^{+} in irrigation waters can have detrimental effects on soil structure. Increases in exchangeable soil Na^{+} and/or SAR_S have been reported where soils were irrigated with municipal wastewater (Kiziloglu *et al*., 2007; Galavi *et al*., 2010; Morugán-Coronado *et al*., 2011; Kallel *et al*., 2012). Likewise, irrigation with treated wastewater and well water increased SAR_S in a sandy soil compared to rain-fed conditions (Bedbabis *et al*., 2014) (Fig. 5). A study carried out in a humid region where soils were irrigated with municipal wastewater for over 50 years showed that the SAR_S at sites irrigated with wastewater increased due to elevated amounts of Na^{+} in the irrigation water, and not necessarily greater amounts of Ca^{2+} or Mg^{2+} (Andrews *et al*., 2016). The high Na^{+} content in these wastewaters was most likely caused by the increased use of water softeners in the region.

The addition of NPK-fertilizer to treated municipal wastewater decreased the Na^{+} concentration in a clay soil under a Mediterranean climate (Netzer *et al*., 2014). The cations in the NPK-fertilizer likely competed with Na^{+} for adsorption sites on the soil's exchange complex. Previous studies have suggested that irrigation volumes should exceed actual crop water use to promote the leaching of salts, and maintain soil salinity below threshold values for specific crops where saline water is used for irrigation (Ayers & Westcot, 1985; Dudley *et al*., 2008). However, it was shown

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TABLE 3
Guidelines for the assessment of sodium hazard of irrigation water based on sodium adsorption ratio (SAR_W) and electrical conductivity of irrigation water (EC_W) (after Ayers & Westcot, 1985).

	Potential for water infiltration problem	
	Unlikely	Likely
SAR_W	EC_W (dS/m)	EC_W (dS/m)
0-3	> 0.7	< 0.2
3-6	> 1.2	< 0.4
6-12	> 1.9	< 0.5
12-20	> 2.9	< 1.0
20-40	> 5.0	< 3.0

that this practice accelerated the accumulation of Na^+ and increased SAR_S in clay loam soil (Netzer *et al*., 2014).

Chloride: Since Cl^- is only essential to plants in small quantities, literature on the effect of this anion applied *via* municipal wastewater irrigation on soil Cl^- content is limited (Tak *et al*., 2012). However, Cl^- can be toxic to plants if high concentrations occur in the soil. Tertiary treated municipal wastewater often contains high amounts of Cl^- as it is used in disinfection processes to remove harmful pathogens from wastewater before reuse (Asano & Levine, 1996). Irrigation with treated municipal wastewater may increase soil Cl^- (Hogg *et al*.; 1997; Pedrero & Alarcón, 2009; Bedbabis *et al*., 2015). It was suggested that Cl^- is a good indicator to estimate salt loads since it (i) correlates strongly with EC, (ii) has a low relative absorption rate, *i.e.* ratio between absorbed and supplied amounts, (iii) has a low adsorption rate and high mobility in soils and (iv) often occurs in wastewater (Segal *et al*., 2011). Although both Cl^- and Na^+ are considered to be the principal elements contributing to soil salinity (Chen *et al*., 2013a), it was concluded in another study that Cl^- leaches more easily from the soil compared to Na^+ (Netzer *et al*., 2014). Therefore, excessive soil Cl^- is probably easier to manage than soils containing high levels of Na^+.

Trace elements: Micronutrients or trace elements, *e.g.* Boron (B^{3+}), copper (Cu^{2+}), iron (Fe^{2+}), manganese (Mn^{2+}), molybdenum (Mo^{2+}) and zinc (Zn^{2+}) are essential to plant growth, but are required in much smaller quantities compared to macronutrients such as N, P and K^+. Trace elements are normally present in municipal wastewater at relatively low concentrations as a result of industrial wastewater contamination (Tak *et al*., 2012). Depending on the source and the specific ion content of the water, municipal wastewater irrigation has been shown to increase soil B^{3+} (Neilsen *et al*., 1991; Qian & Mecham, 2005; Pedrero & Alarcón, 2009; Lado *et al*., 2012), Cu^{2+} (Gupta *et al*., 1998; Kiziloglu *et al*., 2007; Meena *et al*., 2016), Fe^{2+} (Galavi *et al*., 2010; Singh *et al*., 2012; Bedbabis *et al*., 2015), Mn^{2+} (Kiziloglu *et al*., 2008; Omidbakhsh *et al*., 2012; Bedbabis *et al*., 2015), Mo^{2+} (Galavi *et al*., 2010) and Zn^{2+} (Samaras *et al*., 2009; Rana *et al*., 2010; Thapliyal *et al*., 2013; Meena *et al*., 2016). However, according to literature there are inconsistencies regarding the effect of wastewater irrigation on soil trace elements. Wastewater irrigation increased Fe^{2+} and Mn^{2+} levels, but had no significant effect on Cu^{2+} and Zn^{2+} (Mohammad & Mazahreh, 2003). Furthermore, it was reported that soil Fe^{2+}, Mn^{2+} and Zn^{2+} were not consistently affected by wastewater irrigation, and that soil Cu^{2+} was completely unaffected (Rusan *et al*., 2007).

Heavy metals: Heavy metals such as arsenic (As^{3+}), Cd^{2+}, chromium (Cr^{3+}), Pb^{2+}, Hg^{2+} and nickel (Ni^{2+}) can be present in municipal wastewater at varying levels depending on the source and degree of treatment. Heavy metal concentrations are usually low, but the application of reclaimed water can lead to heavy metal accumulation in soils over time (Chen *et al*., 2013b). However, heavy metals can be removed effectively from the wastewater stream by conventional treatment processes, and concentrate in the sewage sludge or solid phase waste (Chipasa, 2003; Qdais & Moussa,

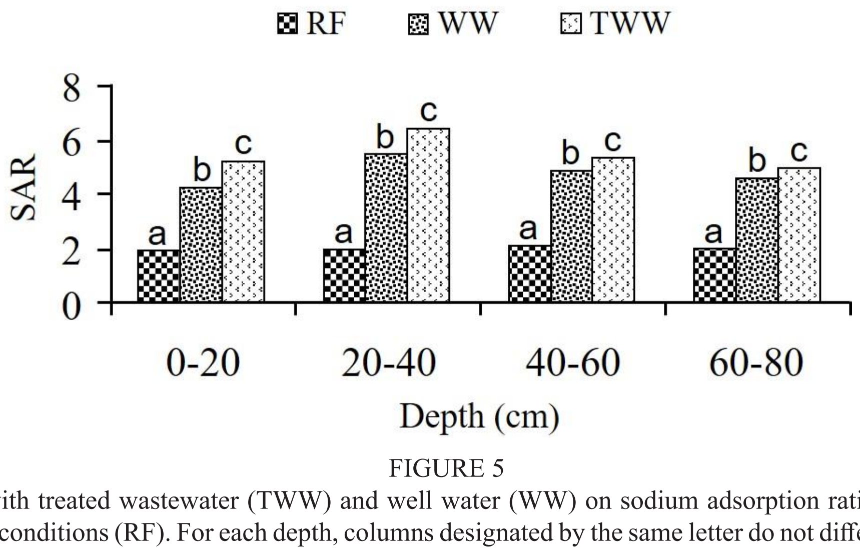

FIGURE 5
Effect of irrigation with treated wastewater (TWW) and well water (WW) on sodium adsorption ratio (SAR) in a sandy soil compared to rain-fed conditions (RF). For each depth, columns designated by the same letter do not differ significantly ($p \leq 0.05$) (redrawn from Bedbabis *et al*., 2014).

2004). In this regard, it was shown that irrigation with tertiary treated wastewater did not cause significant heavy metal accumulation in soils (Christou *et al*., 2014; Bedbabis *et al*., 2015). In contrast, many studies showed that heavy metals are likely to accumulate in soils irrigated with treated municipal wastewater (Rattan *et al*., 2005; Rusan *et al*., 2007; Ghosh *et al*., 2012; Bao *et al*., 2014; Meena *et al*., 2016). It is important to note that quite a number of these studies did not indicate to what extent the wastewater had been treated before application *via* irrigation. The degree of treatment is important, since heavy metals are mostly removed from wastewater only during tertiary treatment stages (Asano *et al*., 2007). However, it is evident that irrigation with untreated municipal wastewater, or minimally treated wastewater, will most likely increase heavy metal content in soils (Shariatpanahi & Anderson, 1986; Liu *et al*., 2005; Rana *et al*., 2010; Singh *et al*., 2012; Abunada & Nassar, 2015; Aydin *et al*., 2015; Meng *et al*., 2016).

Soil physical properties

Clay dispersion and aggregate stability: Clay dispersion during wastewater irrigation can result from the interaction between the dissolved organic molecules in the wastewater and the clay particles of soil (Lado & Ben-Hur, 2009). It was reported that this interaction caused increased dispersion of clay into suspension (Tarchitzky *et al*., 1999). This was attributed to the adsorption of negatively charged dissolved organic molecules to the positively charged edges of clay particles, thereby preventing edge-to-face association between the clay particles. Generally, soil aggregate stability and OM content are closely related (Tisdall & Oades, 1982). The addition of OC through municipal wastewater irrigation has been linked to improved aggregate stability in soils (Vogeler 2009; Tunc & Sahin, 2015). Conversely, aggregate stability became lower in soils that were irrigated with treated municipal wastewater compared to soils irrigated with fresh water (Schact & Marschner, 2015). An improvement in the aggregate stability of soils that were irrigated with wastewater increased the water retention capacity (Gharaibeh *et al*., 2007).

Bulk density: The application of municipal wastewater irrigation can have adverse effects on soil bulk density due to the high concentration of SS that is present in most wastewaters. The accumulation of SS in soils through wastewater irrigation can result in decreased macro-porosity and increased micro-porosity, ultimately affecting bulk density (Tunc & Sahin, 2015). Many authors have observed lower bulk densities in soils due to municipal wastewater irrigation (Mathan, 1994; Vogeler, 2009; Mojiri, 2011; Mojid & Wyesure, 2013). However, the lower bulk density in soils irrigated with wastewater might be practically insignificant compared to soil irrigated with groundwater (Tunc & Sahin, 2015). Other studies have shown increased bulk densities following irrigation with municipal wastewater (Hassanli *et al*., 2008; Azouzi *et al*., 2016). In contrast to the aforementioned, some studies have concluded that municipal wastewater irrigation had little or no effect on soil bulk density (Abedi-Koupai *et al*., 2006; Bardhan *et al*., 2016; Urbano *et al*., 2017).

Porosity: As soil porosity and bulk density are inversely related, opposite trends for porosity have been reported compared to those of bulk density. In some cases, wastewater irrigation improved soil porosity (Mathan, 1994; Shahalam *et al*., 1998; Vogeler, 2009; Mojid & Wyesure, 2013), whereas in other cases porosity decreased upon wastewater irrigation (Coppola *et al*., 2004; Aiello *et al*., 2007). There is a strong correlation between soil water content and pore size distribution (Tunc & Sahin, 2015). Macro-pores are responsible for drainage and aeration, meso-pores facilitate water conduction, while micro-pores effect water retention (Hillel, 2004). An increase in the volume of micro-pores due to wastewater irrigation has been reported to enhance the water retention capacity of soils (Mojid & Wyesure, 2013; Tunc & Sahin, 2015).

Hydraulic conductivity: The hydraulic conductivity (K) of a soil refers to its ability to conduct water within its volume (Lado & Ben-Hur, 2009). It is affected by the pore geometry of the soil, as well as the density and viscosity of the conducted liquid (Hillel, 2004). Kinematic viscosities of secondary treated municipal wastewater were similar to pure water over temperatures ranging between 15°C and 35°C (Lin *et al*., 2003). This indicated that the effects of wastewater density and viscosity on soil K might be insignificant. The pore geometry of soils can be altered through various physical, chemical and biological clogging (Rice, 1974). Many studies have linked a change in K to the physical clogging of soil pores by SS that is supplied through irrigation with municipal wastewater (Metzger *et al*., 1983; Vinten *et al*., 1983; Levy *et al*., 1999; Viviani & Iovino, 2004; Sepaskhah & Sokoot, 2010; Gharaibeh *et al*., 2016). Suspended particles in the wastewater are filtered through the soil pores as the water moves down the soil profile. This causes the accumulation of these particles in the topsoil, and could lead to a reduction in the intrinsic K of the irrigated soil (Lado & Ben-Hur, 2009). More pronounced reductions in K occurred in soils having a finer texture due to the accumulation of coarse SS at the soil surface (Vinten *et al*., 1983). Likewise, the greater entrapment of SS was attributed to the large proportion of small pores in a clay soil (Lado & Ben-Hur, 2010). The subsequent clogging caused a reduction in the saturated hydraulic conductivity (K_S). The fact that greater reductions in K are likely to occur where higher concentrations of SS occur in wastewater used for irrigation emphasises the importance of the organic load in the water (Levy *et al*., 1999).

Chemical clogging of soil pores occurs as a result of changes in soil swelling and clay dispersion (Lado & Ben-Hur, 2009). Chemical interactions between the dissolved salts in the irrigation water and the soil can reduce pore diameters, which could subsequently decrease water permeability (Rice, 1974). The occurrence of chemical clogging depends on the soil's clay mineralogy, exchangeable sodium percentage (ESP) and exchangeable potassium percentage (EPP) in the irrigated soil, as well as the EC_w of the irrigation water. It was previously reported that K decreases with an increase in ESP and a decrease in EC_w of the percolating solution (Quirk & Schofield, 1955). An ESP of 15% and higher is the proposed level at which soil structure will be adversely

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affected (United States Salinity Laboratory, 1954). Yet, according to Sumner (1993 and references therein), many studies have reported soil structure degradation and reduced K_S at ESP values lower than 15% (Fig. 6). A significant reduction in K_S occurred where calcareous loamy soil was irrigated with municipal wastewater that had undergone reverse osmosis (Lado & Ben-Hur, 2010). This reduction was ascribed to soil swelling and clay dispersion caused by the high soil ESP (11%) and the low EC_w of the wastewater (0.2 dS/m). In contrast, K_S did not necessarily decrease, although higher ESP caused a more pronounced tendency towards soil dispersion (Balks *et al*., 1998).

Biological clogging of soil pores occurs when micro-organic biomass, such as algae, bacterial growth and their by-products reduce the pore diameter (Rice, 1974). It was shown that *K* decreased in soils irrigated with wastewater having high C:N ratios (Vandevivere & Baveye, 1992; Magesan *et al*., 2000). This confirmed that the addition of growth substrates, *e.g.* C, increased the activity of micro-organisms and accelerated the pore clogging process. Although there is a strong correlation between K_s and ESP, the relationship may be affected by other factors, *e.g.* TOC in the soil (Assouline & Narkis, 2011). In this regard, it was shown that the K_s *vs* ESP relation was different for fresh water and wastewater irrigation (Fig. 7A). However, when the TOC is considered, the relationship for both waters could be described by a single function (Fig. 7B). It is important to note that the majority of the above-mentioned studies to investigate soil *K* were carried out in laboratories. Consequently, the results of these studies do not necessarily represent field conditions, and might not be directly comparable to *in-situ* measurements. Therefore, a need exists for studies that focus on the effect of municipal wastewater irrigation on *K* under field conditions. It is noteworthy that reduced K_S also occurred at ESP values lower than 15% (Fig. 7A).

Infiltration rate: Infiltration is the process by which water enters the soil *via* downward flow through all, or part of the soil surface (Hillel, 2004). Therefore, infiltration rate (I) is the surface flux at any rate or pressure at which water is supplied to the soil (Hillel, 2004). Clogging of soil pores by high levels of SS in wastewater can reduce water infiltration substantially (Rice, 1974). At low SS concentrations, I decreases rapidly with small increases in SS (Fig. 8). This trend diminishes as the SS loads in wastewater increases. Cohesion between soil particles decreases during wetting and leaching cycles which causes instability of the soil structure (Lado *et al*., 2004). The exposure of the soil's surface to impacts from water droplets, *i.e.* either through rainfall or irrigation, can therefore lead to the development of a seal on the soil surface which could reduce the infiltration rate (Assouline, 2004). Seal or crust formation arises from two possible mechanisms, *i.e.* (i) physical dispersion of soil aggregates caused by the impact of water droplets and (ii) chemical dispersion which depends on the soil's ESP, as well as the EC_w of the applied water (Agassi *et al*., 1981). In general, soils that were irrigated with municipal wastewaters tend to have higher ESP values, and are susceptible to decreases in infiltration rate when low EC_w solutions, such as rainwater, infiltrate the soil. This phenomenon caused greater decreases in infiltration rate in soils irrigated with treated municipal wastewaters compared to rain-fed conditions or fresh water irrigation (Assouline & Narkis, 2011; Bedbabis *et al*., 2014). The infiltration rate of a highly permeable volcanic ash soil in New Zealand decreased by nearly 50% after three years of wastewater irrigation (Cook *et al*., 1994).

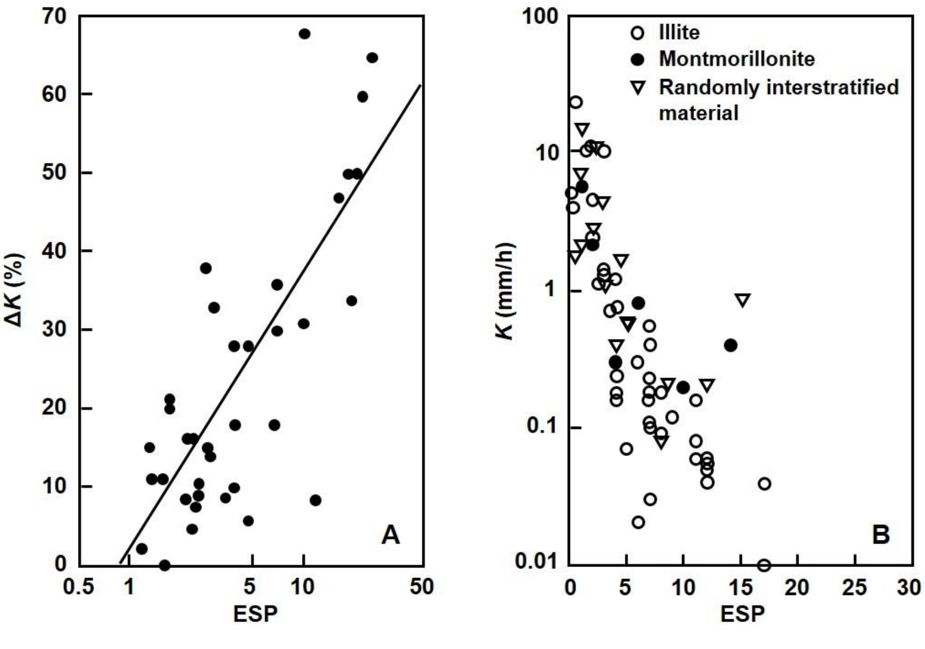

FIGURE 6
Decrease in hydraulic conductivity (ΔK) caused by leaching in selected South African soils of varying exchangeable sodium percentage (ESP) (A) and *K* of Australian soils with a range of ESP values (B). All soils were leached with 0.7 $mmol_c$/L tap water (redrawn from Sumner, 1993).

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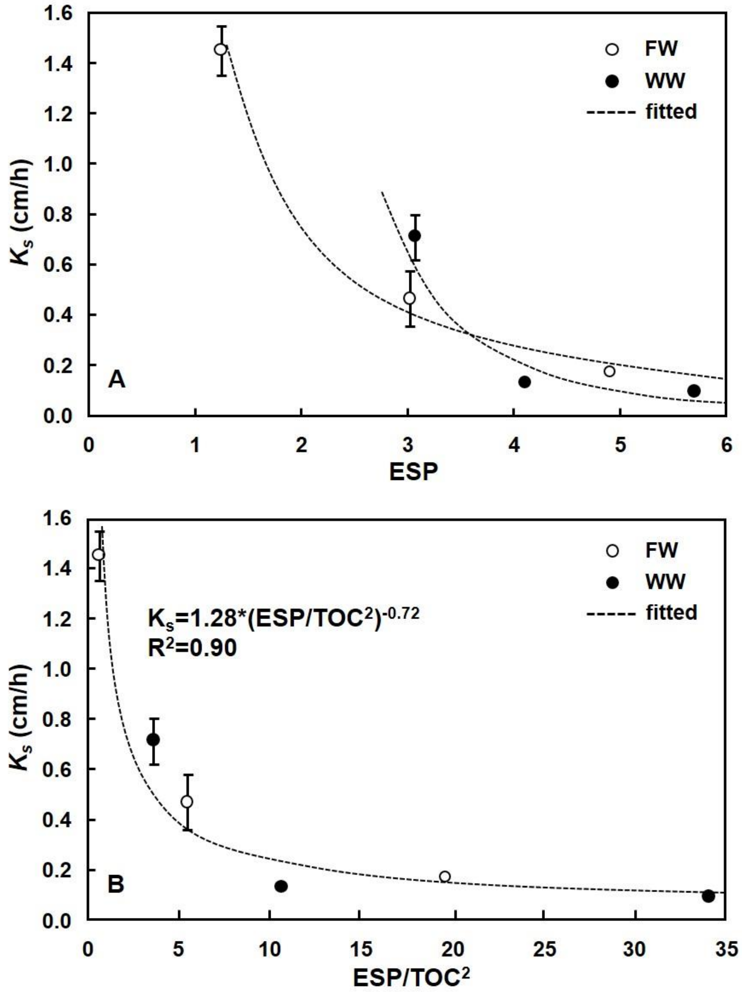

FIGURE 7
Relationship between saturated hydraulic conductivity (*Ks*) and (A) the exchangeable sodium percentage and (B) the ratio between ESP and total organic carbon (TOC^2) for wastewater (WW) and fresh water (FW) irrigated soil (redrawn from Assouline & Narkis, 2011).

Irrigation with treated municipal wastewater reduced the infiltration rate of vertisols irrigated with wastewater for two and five years, respectively, compared to a rain-fed control (Gharaibeh *et al*., 2007). The decrease in infiltration rate was attributed to clay swelling that diminished the cracks typical to vertisols. However, the same study showed that soils irrigated for 15 years had higher infiltration rates compared to the control, although the ESP was 16.6%. Furthermore, these soils were characterised by a higher percentage of large cracks which allowed dispersed material to pass through the soil surface and increase the infiltration rate (Gharaibeh *et al*., 2007). Another potential problem is that the addition of organic material *via* treated wastewater irrigation may induce soil surface water repellence, which could cause water infiltration problems (Nadav *et al.*, 2013).

Effect of irrigation with municipal wastewater on agricultural crops

Plant water relations

High concentrations of salts in municipal wastewater can affect the water relations and gas exchange of irrigated crops (Paranychianakis *et al*., 2004). Salinity negatively affects the water absorption capacity of plants, which could result in water stress (Gómez-Bellot *et al*., 2015). Saline soil conditions can cause systematic accumulation of ions, particularly Na^+ and Cl^-, in the aerial parts of plants (Gómez-Bellot *et al*., 2013). This ion accumulation can affect plant metabolic processes if the ions are not compartmentalised within the cell vacuoles. Plants adapt to these osmotic stresses by exercising osmotic adjustment that maintains a positive turgor that is required for the opening of stomata and cell enlargement (Álvarez *et al*., 2012). Severe water losses are prevented by decreasing the stomatal aperture (Gómez-Bellot *et al*., 2015). These effects were demonstrated in a study on *Euonymus japonica* (Japanese spindle) shrubs irrigated with treated municipal wastewater (Gómez-Bellot *et al*., 2013). The midday stem water potential (Ψ_S) in *E. japonica* irrigated with wastewater (EC_w 4 dS/m) was significantly lower than those irrigated with low salinity, fresh water (EC_w < 0.9 dS/m). Midday Ψ_S in *Viburnum tinus* L. (laurustinus) responded in a similar way to EC_w (Gómez-Bellot *et al*., 2015). In contrast, treated municipal wastewater did not affect Ψ_S of mandarin trees after six years of irrigation, despite consistently lower salinity in the fresh water control

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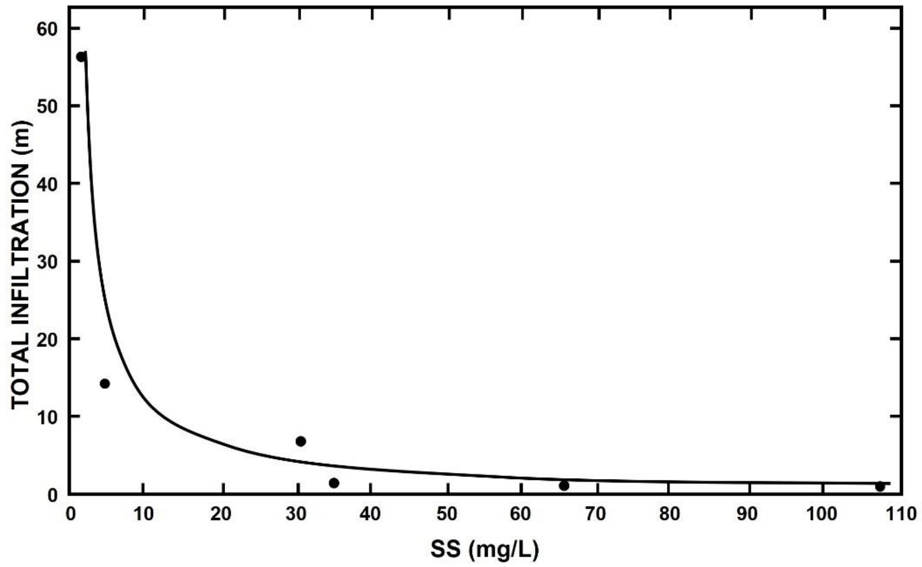

FIGURE 8
Effect of suspended solids (SS) in secondary effluent on total water infiltration in a loamy sand (redrawn from Rice, 1974).

(Nicolás *et al*., 2016). Predawn stem water potential (Ψ_{PD}) and Ψ_S in sugarcane also appeared to be insensitive to irrigation with saline water (Gonçalves *et al*., 2017). A study carried out with one-year-old Sultanina grapevines showed that municipal wastewater irrigation did not affect Ψ_S compared to fresh water (Paranychianakis *et al*., 2004). However, municipal wastewater irrigation reduced Ψ_{PD} in the grapevines compared to fresh water. The lower Ψ_{PD} was caused by the osmotic effect due to the accumulation of salts in the root zone. The insensitivity of midday Ψ_S was considered to be the result of grapevines' isohydric behaviour which controls water use and helps to maintain the minimum Ψ_L at a constant value (Winkel & Rambal, 1993; Paranychianakis *et al*., 2004). Compared to the use of saline groundwater, irrigation with treated municipal wastewater has also been reported to enhance the water use efficiency (WUE) of forage maize (Alkhamisi *et al*., 2011). In contrast, WUE for eggplant and okra was significantly lower when irrigated with treated municipal wastewater (Balkhair *et al*., 2014).

Plant chemical status

Nitrogen: The use of municipal wastewater irrigation as a source of N for plant production is well documented. Based on petiole analyses, levels of N were adequate in Shiraz grapevines that were irrigated with treated municipal effluent at a rate of 45 L of effluent per grapevine per week compared to 135 L potable water per grapevine per week (McCarthy, 1981). Neither of the treatments received additional N fertilisation. Furthermore, grapevines irrigated with treated municipal effluent at a rate of 135 L of effluent per grapevine per week did not exhibit excessive vegetative growth, nor did it reduce fruitfulness. Similar findings were reported for the leaves of apple (Neilsen *et al*., 1989b), olive (Bedbabis *et al*., 2010), sweet cherry (Neilsen *et al*., 1991) and sugarcane (Gonçalves *et al*., 2017). In contrast, municipal wastewater irrigation had no significant effect on the petiole-N of Riesling grapevines compared to ones irrigated with well water (Neilsen *et al*., 1989a). Nitrogen in melon leaves (Martínez *et al*., 2013) and lettuce (Urbano *et al*., 2017) also appeared to be insensitive to wastewater irrigation. Where Sultanina grapevines received deficit irrigation, recycled water had no effect on leaf-N compared to fresh water (Paranychianakis *et al*., 2006). However, in the case of irrigation at 100% ET, recycled water caused lower leaf-N, irrespective of leaf age (Table 4). This agrees with lower concentrations of NO_3^- in tomatoes irrigated with secondary treated agro-industrial wastewater compared to tomatoes irrigated with groundwater (Libutti *et al*., 2018). The same irrigation water sources produced higher concentrations of NO_3^- in broccoli heads upon wastewater irrigation. Likewise, it was shown that treated municipal wastewater can be used as a viable alternative to N fertiliser to enhance the growth rate and production of cultivated fennel (Vergine *et al*., 2017).

Phosphorus: Studies were carried out to assess the effects of sewage water irrigation on P uptake of different cropping sequences, *i.e.* food grain, agroforestry, fodder and vegetable production (Lal *et al*., 2015). Results showed that P uptake improved by 30% due to sewage water irrigation. As a result, sewage water irrigation supplied 20% to 40% of the crops' P requirements (Lal *et al*., 2015). Irrigation with municipal wastewater also increased leaf-P of olive trees compared to fresh water irrigation (Bedbabis *et al*., 2010; Bourazanis *et al*., 2016; Bedbabis & Ferrara, 2018). In contrast, municipal wastewater had no significant effect on leaf-P of olive trees after three years (Petousi *et al*., 2015), or four years (Segal *et al*., 2011) of irrigation. Municipal wastewater irrigation also increased levels of P in barley (Rusan *et al*., 2007) and cabbage (Kiziloglu *et al*., 2008).

Irrigation with 135 L sewage effluent per week reduced petiole-P of Shiraz grapevines compared to the same volume of fresh water (McCarthy, 1981). Application of only 45 L sewage effluent irrigation per week tended to reduce the level of P even further (Fig. 9). The lower P is surprising since the sewage water contained substantially more P than the fresh water. A possible reason could be that the solubility of P depends on the soil pH. It was previously reported that plant available P in a sandy soil decreased substantially as the pH changed upon wastewater irrigation (Mulidzi *et al.*, 2016). This trend was attributed to the possible formation of stable complexes in the wastewater that could not be extracted by the Bray II reagent. Based on the foregoing, wastewater irrigation might not always be a source of P for agricultural crops, although the water could contain high levels of P.

Potassium: Crops that have shown increased K^+ concentrations when irrigated with municipal wastewater include olive (Bedbabis *et al.*, 2010; Bourazanis *et al.*, 2016; Bedbabis & Ferrara, 2018), apple (Neilsen *et al.*, 1989b), sweet cherry (Neilsen *et al.*, 1991), grapevines (Neilsen *et al.*, 1989a), barley (Rusan *et al.*, 2007) and cabbage (Kiziloglu *et al.*, 2007). Conversely, it was shown that irrigation with treated municipal wastewater did not affect K^+ levels in citrus leaves (Koo & Zekri, 1989; Zekri & Koo, 1993; Pedrero & Alarcón, 2009; Pedrero *et al.*, 2012). Petiole-K of Shiraz grapevines irrigated with fresh water was higher compared to those irrigated with sewage effluent, although the two water sources had similar K^+ concentrations (McCarthy, 1981).

Calcium: Irrigation with municipal wastewater enhanced Ca^{2+} levels in Riesling grapevine petioles (Neilsen *et al.*, 1989a), olive fruits (Batareseh *et al.*, 2011; Bourazanis *et al.*, 2016), maize roots (Khaskhoussy *et al.*, 2013), cabbage heads (Kiziloglu *et al.*, 2008) and tomato fruits (Libutti *et al.*, 2018). In contrast, leaf-Ca concentrations of sweet

TABLE 4
Effect of irrigation with recycled and fresh water at different irrigation levels on leaf-N (%) in Sultanina grapevines (after Paranychianakis *et al.*, 2006).

Water quality	Irrigation level	Old leaves	Middle leaves	Young leaves
Recycled water	0.05ET	1.68a*	1.99ab	2.38ab
	0.75ET	1.41c	1.83b	2.40ab
	1.00ET	1.31dc	1.78b	2.22b
Fresh water	0.05ET	1.66a	2.00ab	2.42a
	0.75ET	1.46bcd	2.00ab	2.42a
	1.00ET	1.56ab	2.14a	2.55a

* Numbers with different letters differ significantly at $P < 0.05$ By Tukey's significant difference.

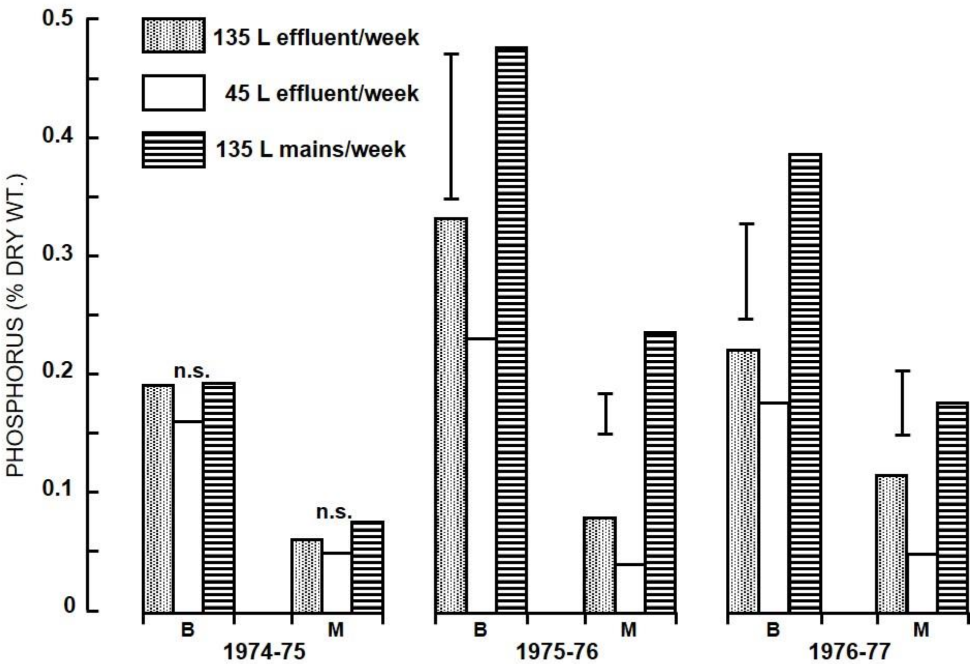

FIGURE 9
Effect of irrigation with two levels of sewage effluent on petiole-P at bloom time (B) and berry maturity (M) of Shiraz grapevines compared to "mains" water, *i.e.* fresh water (redrawn from McCarthy, 1981). Vertical lines indicate he least significant differences ($p \leq 0.05$) and n.s. ⇒ not significantly different.

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cherry trees irrigated with municipal wastewater were lower compared to trees irrigated with well water (Neilsen *et al*., 1991). This trend was ascribed to high K^+ levels in the applied wastewater that may have induced an antagonistic effect on Ca^{2+} and Mg^{2+} uptake. Municipal wastewater irrigation had no significant effect on the leaf-Ca in melon (Martínez *et al*., 2013), citrus (Zekri & Koo, 1993; Pedrero & Alarcón, 2009; Pedrero *et al*., 2012), olives (Petousi *et al*., 2015) and lettuce (Urbano *et al*., 2017).

Magnesium: Using municipal wastewater as an alternative irrigation water source increased the Mg^{2+} content in olive leaves (Bourazanis *et al*., 2016; Bedbabis & Ferrara, 2018) and fruits (Batareseh *et al*., 2011), grapevine petioles (McCarthy, 1981), citrus leaves (Zekri & Koo, 1993; Morgan *et al*., 2008; Pedrero & Alarcón, 2009), maize leaves (Khaskhoussy *et al*., 2013), sugarcane leaves (Gonçalves *et al*., 2017) and cabbage heads (Kiziloglu *et al*., 2008). In contrast, it was shown that municipal wastewater irrigation had little or no effect on the Mg^{2+} levels in olive leaves (Petousi *et al*., 2015), citrus leaves (Koo & Zekri, 1989; Pedrero *et al*., 2012) and lettuce (Urbano *et al*., 2017). Compared to irrigation with well water, municipal wastewater irrigation reduced petiole-Mg of Riesling grapevines (Neilsen *et al*., 1989a) and leaf-Mg of sweet cherry (Neilsen *et al*., 1991). This was probably due to a K-Mg antagonism within the plants where the wastewater contained appreciable amounts of K^+.

Sodium: The uptake of Na^+ by plants upon municipal wastewater irrigation is well documented. In Superior seedless grapevines, municipal wastewater irrigation caused an accumulation of Na^+ in the xylem sap, trunk wood, bark and leaves compared to those irrigated with fresh water (Netzer *et al*., 2014). The Na^+ accumulation occurred irrespective of fertilizer application, and decreased with the level of irrigation applied (Table 5). Similar Na^+ accumulation upon wastewater irrigation was reported for Shiraz petioles (McCarthy, 1981), olive leaves (Bedbabis & Ferrara, 2018), citrus leaves (Koo & Zekri, 1989; Zekri & Koo, 1993), root vegetables such as radish and carrots (Zavadil, 2009), maize roots (Khaskoussy *et* al., 2013), tomatoes and broccoli (Libutti *et al*., 2018), as well as cabbage heads (Kiziloglu *et al*., 2008). Irrigation with treated municipal wastewater also increased Na^+ concentrations in pea and celery shoots by 54% and 19%, respectively (Grewal & Maheshwari, 2013). On the other hand, municipal wastewater irrigation had little or no effect on Na^+ levels in various crops (Pedrero & Alarcón, 2009; Bedbabis *et al*., 2010; Segal *et al*., 2011; Pedrero *et al*., 2012; Martínez *et al*., 2013; Petousi *et al*., 2015).

Chloride: Studies addressing the effect of municipal wastewater irrigation on the uptake of Cl^- by plants are limited. Irrigation with treated municipal wastewater in the long-term elevated Cl^- concentrations in the leaves of olive (Bedbabis & Ferrara, 2018) and citrus (Zekri & Koo, 1993; Pedrero & Alarcón, 2009; Pedrero *et al*., 2012). Irrigation with sewage effluent also increased petiole-Cl of Shiraz grapevines compared to fresh water irrigation (McCarthy, 1981). In contrast, irrigation with treated municipal wastewater in the short-term had no effect on the leaf-Cl of olive trees compared to irrigation with well water (Bedbabis *et al*., 2010; Segal *et al*., 2011).

Trace elements: Municipal wastewater irrigation had no effect on the Cu^{2+} and Zn^{2+} levels in wheat grains and maize kernels compared to irrigation with potable water (Asgari & Cornelis, 2015). However, wheat grains contained higher levels of Cu^{2+} compared to maize kernels. This suggested that wheat had a higher ability to take up heavy metals from the soil compared to maize. Irrigation with treated municipal wastewater caused higher Zn^{2+} concentrations in wheat grains compared to well water, but had no effect on Cu^{2+} (Aydin *et al*., 2015). Brown rice irrigated with treated wastewater showed a similar trend (Chung *et al*., 2011). Although higher concentrations of Cu^{2+}, Fe^{2+}, Mn^{2+} and Zn^{2+} occurred in globe artichokes irrigated with treated municipal wastewater, the concentrations were still within permissible limits as prescribed by the WHO (Gatta *et al*., 2018). A number of studies showed an increase in B^{3+} concentrations of citrus leaves following municipal wastewater irrigation (Zekri & Koo, 1993; Morgan *et al*., 2008; Nicholás *et al*., 2016). In contrast, no significant increases occurred in lemon leaves, although municipal wastewater used for irrigation contained high levels of B^{3+} (Pedrero *et al*., 2012). Irrigation with municipal wastewater for two years increased levels of leaf Mn^{2+} and Zn^{2+} in olive trees compared to fresh water irrigation (Bedbabis *et al*., 2010; Bourazanis *et al*., 2016).

TABLE 5

Effect of irrigation with treated municipal wastewater (TWW) on petiole-Na^+ ($mg.kg^{-1}$) of Superior seedless grapevines at harvest compared to TWW plus fertilisers (TWW + F) and fresh water plus fertilisers (FW + F) at three levels of irrigation (after Netzer *et al*., 2014). Data are means of six years.

Level of irrigation	Water quality treatment		
	TWW	TWW + F	FW + F
High	5.610 A a	5.107 A a	2.631 A b
Medium	4.932 AB a	4.811 AB a	2.231 AB b
Low	3.772 B a	3.556 B a	1.980 B b

* Means within a column followed by the same upper case letter and means within each row followed by the same lower case letter do not differ significantly ($p < 0.05$).

Likewise, leaf-Mn and -Zn of olive trees were higher after 10 years of treated municipal wastewater irrigation (Bedbabis & Ferrara, 2018). In addition to Mn^{2+} and Zn^{2+}, higher Cu^{2+} and Fe^{2+} concentrations occurred in the leaves of olive trees irrigated with municipal wastewater (Batareseh *et al*., 2011).

Heavy metals: In India, heavy metal contamination in vegetables was several times higher under wastewater irrigation compared to irrigation with fresh water (Singh *et al*., 2010). The same study showed that lower concentrations of heavy metals occurred in wheat and rice compared to vegetables. However, due to the higher dietary consumption of wheat and rice, these crops pose a greater risk to human health. Irrigation of wheat and maize with municipal wastewater for 30 and 40 years, respectively, increased concentrations of Pb^{2+} in wheat grains and maize kernels compared to well water irrigation (Bao *et al*., 2014). However, municipal wastewater irrigation did not affect levels of Cd^{2+}, Cr^{3+} and Hg^{2+} in these crops. Similar results were reported for wastewater irrigated wheat (Aydin *et al*., 2015). In the latter case, Pb^{2+} levels exceeded the permissible limit of 0.2 mg/kg dry weight as prescribed by the Turkish Food Codex. Furthermore, no translocation of Cd^{2+} from soil to plant was observed, whereas the translocation of Cr^{3+} and Ni^{2+} was insignificant. In contrast, municipal wastewater irrigation did not affect the Pb^{2+} concentrations in alfalfa compared to well water (Abunada & Nassar, 2015). However, following five years of municipal wastewater irrigation, a steady increase in the Pb^{2+} concentration of alfalfa was observed, but it was still below the permissible limit of 9 mg/kg that is enforced by the Chinese State Environmental Protection Administration (SPEA). Municipal wastewater irrigation had no effect on the Cd^{2+} and Pb^{2+} concentrations in alfalfa and radish compared to fresh water (Shahalam *et al*., 1998). On the other hand, higher Cd^{2+} and Pb^{2+} concentrations were reported for vegetables irrigated with municipal wastewater (Shariatpanahi & Anderson, 1986). Another study showed that municipal wastewater irrigation increased the concentrations of Cd^{2+}, Cr^{3+}, Ni^{2+} and Pb^{2+} in lemongrass, although these elements were within permissible limits (Lal *et al*., 2013). However, the accumulation of heavy metals did not reflect in the essential oils extracted from the lemon-grass.

The effect of treated municipal wastewater irrigation on the heavy metal uptake of olive trees was studied in Jordan (Batarseh *et al*., 2011). Although the wastewater used for irrigation contained high amounts of Ni^{2+} and Pb^{2+}, the concentrations of these elements in the leaves and fruits were extremely low. In contrast, significant quantities of Cr^{3+} accumulated in the leaves and, to a lesser extent in the fruits, despite relatively low levels of Cr^{3+} in the wastewater (Batarseh *et al*., 2011). These results do not only suggest that the uptake of heavy metals by olive trees is a selective process, but that it often depends on the concentration of heavy metals in the wastewater used for irrigation.

Yield and biomass production

There are numerous reports that the high nutrient content, particularly N and P, in municipal wastewater used for irrigation can increase the yield and biomass production of crops. Municipal wastewater irrigation increased yield and biomass production of permanent crops such as olive (Charfi *et al*., 1999; Bedbabis *et al*., 2010; Bedbabis *et al*., 2015; Bourazanis *et al*., 2016), apple (Neilsen *et al*., 1989b) and grape (Neilsen *et al*., 1989a; Mendoza-Espinosa *et al*., 2008), as well as willow trees (Nissim *et al*., 2015). Similar trends were reported for vegetables, *e.g.* tomato (Cirelli *et al*., 2012), cucumber (Safi *et al*., 2018), lettuce (Zavadil, 2009; Urbano *et al*., 2017; Vergine *et al*., 2017), artichoke (Gatta *et al*., 2016), cauliflower (Kiziloglu *et al*., 2008; Tripathi *et al*., 2016), as well as fennel (Lonigro *et al*., 2016; Vergine *et al*., 2017) and lemongrass (Lal *et al*., 2013). Grain crops such as rice (Jung *et al*., 2014), sunflower seeds (Papadopoulos & Stylianou, 1991), maize (Alkhamisi *et al*., 2011; El-Nahhal *et al*., 2013) and barley (Rusan *et al*., 2007) showed increased biomass production upon irrigation with municipal wastewater. Likewise, municipal wastewater irrigation increased the biomass of *Panicum maximum* grass (Abdoulkader *et al*., 2015). In contrast, wastewater irrigation reduced yields of alfalfa (Shahalam *et al*., 1998), cabbage (Balkhair *et al*., 2013), okra and aubergine (Balkhair *et al*., 2014), as well as snow peas and celery (Grewal & Maheshwari, 2013). Decreased yields were attributed to the accumulation of toxic elements in the stems and leaves of plants (Balkhair *et al*., 2014), and soil salinization (Shahalam *et al*., 1998).

The use of secondary treated municipal wastewater and a mix of tertiary treated municipal wastewater plus fresh water for irrigation were compared in a lemon tree orchard (Pedrero *et al*., 2012). The secondary treated wastewater irrigation reduced yields, whereas the mixed irrigation water produced higher yields. The reduction in yield was most likely caused by the salinity induced by the lesser treated wastewater. Numerous studies showed that irrigation with municipal wastewater had no significant effect on crop yield compared to fresh water irrigation (McCarthy, 1981; Aiello *et al*., 2007; Segal *et al*., 2011; Martínez *et al*., 2013; Netzer *et al*., 2014; Ganjegunte *et al*., 2017; Libutti *et al*., 2018). This suggested that municipal wastewater may not adversely affect plant growth. Moreover, due to the nutrient supply through wastewater, similar yields could be obtained without the application of additional fertilisers (Table 6). Other studies have indicated greater yields and biomass production of crops irrigated with municipal wastewater compared to crops produced under dryland conditions (Wang *et al*., 2007; Ayoub *et al*., 2016; Gonçalves *et al*., 2017). Therefore, the use of municipal wastewater for irrigation in water-scarce regions may significantly increase crop productivity when no alternative water sources are available. In fact, where no other irrigation water was available, using treated municipal wastewater increased grapevine growth and yield substantially compared to rain-fed conditions in the coastal region of the Western Cape (Myburgh, 2018) (Table 7).

Crop and product quality

The quality of crops and their processed products can be assessed in terms of their general qualitative characteristics that depend on the specific crop in question, *e.g.* phenolic composition of oils, juice characteristics of fruits and physical appearance of cut flowers. The irrigation of olive trees in

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TABLE 6
Effect of irrigation with treated municipal wastewater (TWW) on yield of Superior seedless table grapes compared to TWW plus fertilisers (TWW + F) and fresh water plus fertilisers (FW + F). There were no significant differences in any of the years ($p \leq 0.05$) (Netzer *et al*, 2014).

Yield (t/ha)	2002	2003	2004	2005	2006	2007	Average
TWW	34.9	19.0	40.6	15.2	47.4	20.0	29.5
TWW + F	32.7	22.1	43.4	10.3	44.4	20.1	29.0
FW + F	37.1	20.1	40.4	13.5	51.8	20.7	30.6

TABLE 7
Effect of irrigation with treated municipal wastewater on cane mass and yield of two grapevine cultivars compared to no irrigation, *i.e.* rain-fed (Myburgh, 2018). Cane mass and yield data are means for four and five years, respectively.

Cultivar	Cane mass (t/ha)		Yield (t/ha)	
	Rain-fed	Irrigated	Rain-fed	Irrigated
Sauvignon blanc	0.6±0.3	1.6±0.7	6.9±4.4	11.2±3.8
Cabernet Sauvignon	1.1±0.8	2.1±0.6	6.6±3.6	12.3±2.7

semi-arid regions using treated municipal wastewaters has been the subject of many research studies. Although irrigation with secondary treated municipal wastewater enhanced the number of polyphenols in oil produced from Chemlali olive trees in Tunisia compared to well water irrigation, the olives were appreciably more sensitive to oxidation after harvest (Gharsallaoui *et al*., 2011). It was also shown that Chemlali olive trees irrigated with treated municipal wastewater for 10 years increased total phenols and free acidity (Bedbabis & Ferrara 2018). However, earlier studies on Chemlali as well as Koroneiki olive trees showed no such effects (Bedbabis *et al*., 2009; Bedbabis *et al*., 2015; Bourazanis *et al*., 2016).

Irrigation with treated municipal wastewater increased levels of titratable acidity (TA) and total soluble solids (TSS) in the extracted juice of oranges (Morgan *et al*., 2008). Similar trends occurred in lemon juice upon irrigation with secondary or tertiary treated municipal wastewater over a three-year period (Pedrero *et al*., 2012). This could be explained by the fact that some plants could adapt to salinity. Under saline conditions, increased production of secondary metabolites including organic acids, proteins and sugars, enhances the quality and market value of the fruit (Pedrero *et al*., 2012). Irrigation of Hamlin and Valencia oranges with municipal wastewater reduced TA and TSS compared to fresh water (Koo & Zekri, 1989). The lower TA and TSS were attributed to higher soil water content due to the application of excessive amounts of wastewater irrigation.

Two levels of irrigation with sewage effluent had almost no effect on juice TSS, pH and TA of Shiraz grapevines compared to fresh water irrigation (McCarthy, 1981) (Table 8). In contrast, irrigation with treated municipal wastewater increased juice pH and TSS of Riesling grapes, but did not affect TA (Neilsen *et al*., 1989a). However, the wastewater irrigation did not negate the production of high quality wine. Another study showed that irrigation with secondary treated municipal wastewater did not affect TA, TSS and pH in Cabernet Sauvignon and Merlot grapes compared to groundwater irrigation (Mendoza-Espinosa *et al*., 2008). Concentrations of N, P, K^+, Na^+, Cl^- and Mg^{2+} in wines produced from Shiraz grapevines irrigated with municipal wastewater were elevated compared to those irrigated with fresh water (McCarthy & Downton, 1981). The wines produced from wastewater irrigated grapevines also had higher anthocyanin and phenolic contents. Although the levels of K^+ and pH in the wines were high, they were still acceptable for red wine production according to Australian standards (McCarthy & Downton, 1981).

The effects of irrigation with 100% municipal wastewater on the quality of *Gladiolus communis* flowers were compared to 100% potable water irrigation, as well as irrigation with different ratios of the two water sources in a glasshouse experiment in Jordan (Hasan *et al*., 2014). It was shown that irrigation with a combination of 75% potable water and 25% wastewater produced longer spikes, larger spike diameter and bigger newly formed corms compared to 100% potable water irrigation. Under open field conditions, irrigation with 100% potable water produced flowers of inferior quality compared to the municipal wastewater and combinations thereof (Table 9).

The quality of crops irrigated with municipal wastewater can also be evaluated in terms of their microbial safety, since it is one of the most important factors that determine the suitability of wastewater for crop irrigation (Chen *et al*., 2013a). Irrigation of tomatoes and broccoli with treated municipal wastewater increased FC counts on the plant itself, compared to the edible products (Libutti *et al*., 2018). However, the FC counts for tomatoes and broccoli did not differ from those recorded for fresh water irrigation (Libutti *et al*., 2018). Other studies showed similar results for tomatoes (Shahalam *et al*., 1998; Aiello *et al*., 2007; Forslund *et al*., 2012; Gatta *et al*., 2015; Lonigro *et al*., 2016; Orlofsky *et al*., 2016), as well as lettuce (Urbano *et al*., 2017; Intriago *et al*., 2018), artichokes (Gatta *et al*., 2016), strawberries (Christou *et al*., 2016) and lemons (Pedrero *et al*., 2012). It

TABLE 8
Total soluble solids (TSS), pH and acidity in juice of Shiraz grapevines irrigated with two levels of sewage effluent and “mains” water, *i.e.* fresh water (after McCarthy, 1981).

Season	Treatment	TSS (°Brix)	pH	Acidity (g/L as tartaric)
1974-75	135 L effluent	19.3	3.8	4.4
	45 L effluent	20.1	3.8	4.1
	135 L mains	19.1	3.8	4.1
1975-76	135 L effluent	22.8	3.9	7.9
	45 L effluent	22.6	3.8	8.0
	135 L mains	22.6	3.8	8.0
1976-77	135 L effluent (7/3/77)*	25.4	3.8	5.5
	45 L effluent (24/2/77)*	23.1	3.4	9.8
	135 L mains (28/2/77)*	23.8	3.6	7.5

* Grapes were harvested at different dates to obtain fruit of similar degree of ripeness for small scale wine making.

TABLE 9
Effect of irrigation with treated municipal wastewater (WW) and potable water (PW), as well as combinations of WW plus PW on flower characteristics of *Gladiolus communis* under open field conditions (adapted from Hasan *et al*., 2014).

Treatment	Spike length (cm)	Spike diameter (mm)	Florets/ spike	Newly formed corm size (cm)
100% WW	86.63 a	8.00 a	13 a	2.71 a
100% PW	71.40 b	6.90 b	11 b	1.94 b
75% WW+25% PW	86.60 a	8.10 a	14 a	2.69 a
50% WW+50% PW	84.77 a	7.80 a	13 a	2.56 a
25% WW+50% PW	85.27 a	7.90 a	13 a	2.55 a

is important to note that in most cases, the aforementioned studies assessed the use of tertiary treated municipal wastewater rather than untreated municipal wastewater. The use of untreated or partially treated municipal wastewater for irrigation of vegetables increased microbial contamination (Rosas *et al*., 1984; Minhas *et al*., 2006; Rai & Tripathi, 2007). Irrigation of tomatoes with tertiary treated municipal wastewater caused significant microbial contamination only where fruits were in direct contact with the soil or plastic mulch (Cirelli *et al*., 2012). Recommendations proposed to minimise the microbial contamination of vegetables grown under municipal wastewater irrigation include (i) avoiding direct contact between wastewater and vegetables, (ii) exposing vegetables to adequate sunlight to enhance the die-off of pathogens and (iii) where possible, removing the outer layers of vegetables exposed to wastewater, *e.g.* the outer leaves of cabbage (Minhas *et al*., 2006).

CONCLUSIONS

Considering the existing knowledge, it is evident that variability is an integral part of using municipal wastewater for irrigation of agricultural crops. Numerous factors contribute to the complexity. Due to the variability in the composition of the waste load in the water, as well as the volume of water used for irrigation, the amounts applied per unit of land can vary considerably. In addition to the composition of the waste load, the degree of wastewater treatment also creates variability in the amounts of waste applied *via* wastewater irrigation. Differences in the chemical characteristics of soils causes variation in the accumulation or attenuation of specific elements or compounds in the root zone. Consequently, changes in soil chemical and/or physical status in response to municipal wastewater irrigation may vary considerably. Differences in climate also contribute to variation in the sustainability of irrigation with treated municipal wastewater. Rainfall, in particular, plays an important role, since attenuation or accumulation of elements will be higher in arid climates compared to high rainfall climates where leaching is likely to reduce the risk of salinity or toxicity.

Treated municipal wastewater may contain high levels of Na^+, Cl^- and B^{3+}, as well as other ions such as SO_4^{2-} and heavy metals. Since some of these elements could be detrimental to soil physical and chemical status, it is essential to implement measures such as frequent soil and water analyses to limit damage. The absorption of substances applied *via* wastewater by plants will vary according to the capacity of the soil to release it into the soil solution, as well

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as crop-specific uptake due to physiological adaptations. An advantage of irrigation with treated municipal wastewater is the possibility to supply nutrients such as N, P and K^+, as well as trace elements to crops. Given the variable nutrient load in the wastewater, it is essential to follow an integrated fertiliser program by adjusting fertiliser amounts according to the amount of nutrients applied *via* the wastewater. Variation in the physiological ability of plants to tolerate chemical stress, *e.g.* the tolerance of halophytes to soil salinity, also determines the suitability of agricultural crops for irrigation with municipal wastewater. Based on the foregoing, production criteria such as biomass, yield and product quality of agricultural crops may vary substantially upon irrigation with treated municipal wastewater. To enable sustainable crop production, management of irrigation with municipal wastewater should be adapted for each water quality, climate, soil and crop combination. In other words, a holistic approach should be followed to use treated municipal wastewater in a beneficial way in the long run.

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