Wastewater Reuse in Agriculture: Effects on Soil-Plant System Properties

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Abstract The use of non-conventional water resources can help to mitigate water stress and can support the agricultural sector. Treated municipal wastewater is one of the most readily available alternative water resources, and its use in agriculture has been adopted to reduce fresh water usage in several countries, under their respective water quality regulations. This chapter reviews the results of past and current research on the reuse of treated wastewater (municipal and agro-industrial) for irrigation and the corresponding effects on soil and plant systems. Particular attention has been given to research efforts highlighting the effects of chemical-physical

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wastewater characteristics (e.g. nitrogen, phosphorus, potassium, sodium, and heavy metals) and the corresponding microbiological indicators (e.g. *Escherichia coli* and *Salmonella*) on irrigated crops and soils. The selection of irrigation methods is another topic discussed in this chapter. Drip and subsurface irrigation methods are considered the more suitable irrigation techniques to be used with treated wastewater; they minimise toxicity hazards for plants, reduce the contamination of edible crop products, and mitigate human health risks by minimising direct contact between wastewater and plant.

Keywords Agro-industrial wastewater, Crop irrigation, Microbiological risks, Municipal wastewater, Wastewater reuse

1 Introduction

Wastewater reuse has potential benefits for agriculture and water resources management but can also determine substantial risks to public health. Moreover, chemical risks for plant and environment could occur due to soil and groundwater pollution. Indeed, the main problems related to wastewater reuse can be linked to the possible environmental dispersion of macro- and micronutrients, soil and plant accumulation of heavy metals and the contamination due to microbial pathogens.

Once crops are exposed to chemicals, the potential uptake and accumulation in the edible parts (fruits and vegetables) need to be controlled in order to assess their introduction into the food chain.

Water quality criteria and guidelines for effluent reuse in irrigation have been implemented and can act as protecting measures to farmers health as well as to public health; moreover, the quality criteria can prevent problems such as soil salinity and toxicity and other phenomena that can generate issues for soil and crop production.

This chapter does not address the effects of the emerging pollutants (i.e. contaminants of emerging concern, CECs) detected in wastewater sources on the soil-plant system. This research topic is reported in detail in other chapters.

1.1 Legislative Framework

The use of reclaimed wastewater for crop irrigation could play a strategic role in mitigating the problems of decreasing water availability for the agricultural sector and competition with civil and industrial water uses. The use of reclaimed wastewater in agriculture may also increase the environmental sustainability of crop production. However, reuse of wastewater in this sector is constrained by relevant legislative frameworks, which can in turn represent an important driving force in its adoption.

In 2006, the World Health Organization (WHO) released the guidelines for the safe use of wastewater in order to improve its use in agriculture and provide clear guidance for local decision-makers. The purpose of the WHO's guidelines was to support the definition of specific government regulations related to wastewater use and management, in consideration of each country governance [1].

In 2012, based on global data, the United States Environmental Protection Agency (US-EPA) completed the "Guidelines for Wastewater Reuse" that includes an updated overview of water reuse regulations adopted in the USA, current advancements in wastewater treatment technology, international water reuse practices, and other factors supporting the safe and sustainable expansion of wastewater reuse.

The treated wastewater reuse guidelines mentioned above (WHO, FAO, and US-EPA) constitute the basis for the formulation of local regulations in other countries [2].

In the European Union (EU), there currently are no guidelines for wastewater reuse, but according to UE Directives (91/271/EEC, 2000/60/EC) and other international guidelines, several Member States have produced legislative regulations for water reuse applications. Standards differ among and within the Member States, in response to different socio-economic conditions at the regional and local levels.

The Spanish legislation (RD 1620/2007 – *The legal framework for the reuse of treated wastewater*) includes the following different uses of reclaimed water: urban, agricultural, industrial, recreational and environmental. As for the Portuguese guidelines (NP 4434 2005 – *Reuse of reclaimed urban water for irrigation*), they only refer to urban areas irrigation, and the main applications are for agricultural and landscape purpose (e.g. golf courses irrigation).

The French standards on wastewater reuse (JORF no. 0153, 4 July 2014) define water reuse for the irrigation of agricultural lands and green areas and exclude industrial and urban uses and aquifer recharging, while Cypriot regulation (Law 106 (l) 2002 – *Water and Soil pollution control and associated regulations*) does not allow any industrial or urban use of reclaimed water (Water Reuse in Europe, UE 2014).

The Cyprus, Greece and Spain wastewater guidelines include also aquifer recharging with reclaimed water by percolation or direct injection, with the aim to reduce the depletion of groundwater and to mitigate the impacts of saline intrusion in coastal zones.

In Italy, the agricultural reuse of municipal and agro-industrial reclaimed wastewater is regulated by Legislative Decree no. 152/2006 of the Ministry for the Environment, which presents restrictive limits for microbiological parameters (e.g. *Escherichia coli*) [6, 7], but does not define different limits according to the risk associated with different destinations for reuse (e.g. irrigation of food or no-food crops).

To maximise the benefits and minimise the risks related to the use of treated wastewater, uniform legislative frameworks should be adopted [3]. To this regard, a new proposal for European regulation of minimum requirements for water reuse [4, 5] is currently pending approval by the European Parliament and the European Council. This new proposal defines, for the first time, the minimum water quality acceptable for reclaimed water destined for crop irrigation in European Countries.

1.2 Characteristics of the Municipal and Agro-Industrial Wastewaters

Wastewater effluents can originate as by-products from the civil, industrial, and agricultural sectors. Following purification, treated wastewater represents an important and readily available water source to meet the increasing demands of crop irrigation, particularly in water-scarce countries. Indeed, wastewater recycling in agriculture has gained importance as a component of the agricultural water supply in some regions (e.g. Mediterranean area) [8].

Wastewater reuse provides significant amounts of irrigation water and helps reduce the environmental impacts related to the discharge of municipal and/or agro-industrial effluents into water bodies [8, 9]. Municipal and agro-industrial wastewater contains approximately 0.1% solid substances, represented by organic and inorganic solids and microorganisms [10]. The chemical-physical characteristics of the wastewater effluent depend on its origin and vary with climate, social and economic situation and with the habits of the population of origin.

Organic substances can include carbohydrates, lignin, fats, proteins and their decomposition products, as well as various organic chemicals of natural and synthetic origin derived from industrial processes [11].

Inorganic substances include potentially hazardous compounds and heavy metals, which may be present in wastewater at phytotoxic levels and cause health risks [11, 12]. In particular, municipal wastewater can contain wastes from domestic, small-scale craft and livestock activities.

The quality of agro-industrial wastewater is closely related to the type of vegetable products and to the processing systems adopted; such wastewater typically contains organic substances that are suspended and partly dissolved (sugars, proteins, fats, and residues of plant and animal products).

Agro-industrial wastewaters can contain heavy metals, although the concentrations are unlikely to reach levels dangerous for crops and consumers [13]. Health risks associated with the use of wastewater for crop irrigation are primarily due to microbial pathogens (bacteria, viruses, and protozoa) [14, 15]. To mitigate hazards and damage to human and environment health, wastewater should be adequately treated before use in irrigation.

The positive or negative effects of treated wastewater application on the soil and on plants are primarily dependent upon the quality and quantity of the organic and mineral chemical substances (in particular plant nutrients, such as N, P, K, heavy metals, and salts) in the solution.

2 Main Advantages and Risks of Treated Wastewater Reuse in Agriculture

2.1 Supply of Mineral Nutrients for Crop Growth

The quantity of crop nutrients supplied to the soil by wastewater (municipal or agro-industrial) in irrigation must be carefully considered. The concentrations of the primary mineral nutrients necessary for plant growth (such as N, P and K) in municipal and agro-industrial wastewater vary significantly according to the quality of the wastewater. Generally, nitrogen concentrations vary from 20 to 35 mg L^{-1}, phosphorus concentrations from 3 to 10 mg L^{-1} [10, 16–19], and potassium concentrations from 10 to 25 mg L^{-1} [18, 20].

Wastewater effluents can also contain high levels of micro-nutrients (e.g., boron, iron, copper, zinc, manganese, and molybdenum), which are essential for the growth and development of crops. The effects of macro- and micronutrients supplied with wastewaters can change in relation to the crop cycle (i.e., vegetable annual crop vs tree crops) and to different intake rate of nutrients.

As for vegetable crops, in a study carried out on a succession of processing tomato (*Lycopersicon esculentum* Mill.) and broccoli (*Brassica oleracea* L. var. *italica*) crops, secondary and tertiary treated agro-industrial wastewaters were compared with groundwater irrigation. The findings indicated that treated agro-industrial effluents supplied greater amounts of mineral nutrients ($N\text{-}NH_4$, $N\text{-}NO_3$, and K^+) to the crops [20]. The authors suggested that the use of treated agro-industrial effluents as irrigation water could reduce the need for supplementary mineral compounds through chemical fertilisation.

Other research has shown that treated wastewater irrigation of vegetable crops (lettuce) could successfully increase the availability of irrigation water and increase the concentration of some soil nutrients (K, Ca, H, Al, and S) [21].

In a study of the effects of secondary and tertiary treated wastewater irrigation on globe artichoke crop performance, Gatta et al. [19] reported that the total inorganic nitrogen (i.e. $N\text{-}NH_4$, $N\text{-}NO_3$) supplied to the crops through treated irrigation water was on average 95 kg ha^{-1} and 66 kg ha^{-1} for the secondary and tertiary wastewaters, respectively, representing approximately 25% to 17% of the nitrogen requirements of the artichoke crop.

As for tree crops, Vivaldi et al. [22] reported the effects of irrigation by treated wastewater and the deficit irrigation strategy on almond trees (*Prunus dulcis* L.). The results of this study showed that the nutritional contribution of treated wastewater to irrigated soil was 35.8 kg ha^{-1} of NO_3^-, 4.41 kg ha^{-1} of PO_4^{3-}, and 149.9 kg ha^{-1} of K^+. Other similar studies on tree crops irrigated by reclaimed water have reported that high concentrations of macro- and meso-nutrients supplied to soil through wastewater could facilitate a significant reduction in fertiliser application [23–25].

The supply of mineral nutrients by wastewater application to cultivated species represents a significant agronomic value of this water resource. However, this benefit must be assessed with particular attention to the possibility of plant nutritional imbalances and phytotoxicity [26]. Each cultivated species is characterised by specific nutrient requirements depending on the phenological phase. Excesses or deficiencies in some mineral elements can significantly affect crop production, both in quantitative and qualitative terms [27].

2.2 Heavy Metal Accumulation in Soil and Crops

Another possible outcome of wastewater reuse for cultivated species is the accumulation of heavy metals in the irrigated soil. The presence of heavy metals in the soil at very low concentrations is necessary for the growth plants, but at high concentrations, they can be toxic and harmful [12, 28]. Although the heavy metal content in wastewater used for irrigation is subject to legal limits, continuous use of wastewater can lead to their buildup in the soil [29]; this can cause stress to plants due to interference with the metabolic activities and physiological functions in the plants [30].

Excessive levels of metals can also degrade soil quality, reduce marketable crop yields, and reduce the quality of marketable agricultural products; these effects can also pose significant hazards to the health of humans and the surrounding ecosystem [12, 31].

The leaves and vegetative tissues of cultivated plants tend to accumulate higher amounts of heavy metals than the fruits [32]. Studies have shown that heavy metals taken up through plant roots can be transported to the shoots through the xylem vessels [33] but have poor mobility in the phloem [34]. Crop storage organs (primarily fruits and seeds) are characterised by low transpiration rates and do not accumulate heavy metals because they are largely phloem-loaded. Harmful effects on human health from soil and vegetables contaminated with heavy metals have, however, been widely reported [12, 35].

Heavy metal activity in the soil is highly influenced by chemical and physical soil characteristics (pH, texture, and organic matter content) and the effect of heavy metals on plants varies by crop. It is therefore challenging to set precise limits and thresholds of tolerance and/or hazard deriving from the presence of heavy metals.

The risk to human health related to the uptake of heavy metals by food crops depends more on the increase in their available fraction than on their total concentration in the soil [36]; moreover, it is dependent on the heavy metal speciation and solubility and on the crops cultivated in contaminated soil [37].

High contents of heavy metals are normally found in industrial wastewater, whereas the concentrations of these metals in domestic wastewater are generally low due to the settling of solids during treatment [29, 38].

Generally speaking, the use of treated municipal wastewater in agriculture may result in heavy metal accumulation in the surface layers of the soil [1, 39, 40] following very long periods (decades) of application, after which concentrations that can cause adverse effects on crop growth are possible [41–43]. However, regardless of the heavy metal content of the wastewater, the metals are only taken up by the crop at certain concentration thresholds, and uptake can only occur if the metals are in the mobile phase. Additionally, the concentration of heavy metals in the soil solution is influenced by soil characteristics.

Heavy metals are less available at soil pH over 6.5, due to precipitation phenomena and the presence of higher amounts of organic substances. On the contrary, at lower pH values, heavy metals become mobile in the soil and can be absorbed by crops [44]. Not all heavy metals are easily absorbed by plants; lead, chromium, and mercury, for example, are bound by soil particles and very slowly absorbed by crops, even when accumulated in the soil. Copper, boron, and zinc are more easily absorbed by plants, sometime reaching levels of accumulation ten times higher in a plant than in its originating soil [45]. In this regard, cadmium and nickel represent the highest risk to human health. The impact of heavy metals on crops is complex, because antagonistic reactions can occur the influence their absorption [46].

Table 1 shows the heavy metal concentrations in wastewater-irrigated soils reported by several authors, considering the irrigation length period (short and long term), type of wastewater, and the effects on soil and plant. The concentration of some heavy metals exceeds the international threshold values, especially in long-term experimental trials, with consequently accumulation in plants.

Table 2 shows a classification of heavy metals added to the soil with wastewater when used for crop irrigation, according to risk characteristics and classes relative to their effect on plant nutrition and human health.

2.3 Microbiological Risks

One of the primary obstacles to the widespread use of reclaimed wastewater for irrigation of agricultural crops is the possible persistence of pathogenic microorganisms through treatments and their potential contamination of vegetable crops, causing outbreaks of foodborne illness. The risk of biological contamination is primarily related to the spread of bacteria, viruses, helminths, and protozoa that are harmful to humans through the soil environment and onto crops which are then ingested.

Bacterial pathogens like *Salmonella* spp., *Shigella* spp. enterohaemorrhagic *E. coli* serotypes, and *Vibrio cholerae* are of major concern for public health systems worldwide. The helminths *Ascaris* and *Tenia* spp. and the protozoans intestinal *Giardia* and *Crysptospridium* are also of public health concern. The waterborne viruses HAV, HEV, rotavirus, and adenovirus are reported to have the greatest risk of transmission through reused wastewater [1]. The direct detection of such a wide array of pathogen microorganisms (whose levels are generally low and fluctuating) by laboratory methods is not an efficient monitoring strategy in terms of monetary cost and time required for the microbial methods of isolation and confirmation. The use of microbial indicators of faecal contamination has therefore been considered for decades by health and environmental authorities worldwide to be the most reliable method of monitoring water quality and the performance of water treatment systems [47, 48].

Table 1 Heavy metal concentrations of wastewater irrigated-soils detected in several field studies, considering the irrigation length period (short and long term), type of wastewater (source), and the effects on soil and plant

	Soil guidelines (mg kg^{-1})					Effect on	
Metal	EUs[a]	IR[b]	Case study (mg kg^{-1})	Source	Period	Soil	Plant
Cd	3.0	3.0[c]	[d]0.2 [41]	PTE effluent	L-T	+	
			3.8 [42]	UE	L-T		+↓
			5–13 [39]	TE	S-T	+	
			[d]0.037 [40]	STE	S-T	–	
Cr	150	100[c]	112.8 [42]	UE	L-T		+↓
			936.5 [43]	UE	L-T	+	–
Cu	140	100[c]	[d]35.0 [41]	PTE	L-T	+	
			75.0 [42]	UE	L-T		+↓
			8–16 [39]	TE	S-T	+	
			[d]1.25 [40]	STE	S-T	–	
			[d]94.4 [43]	UE	L-T	+	+↑
Ni	75	50[c]	[d]5.76 [41]	PTE	L-T	+	
			703.2 [42]	UE	L-T		+↓
			[d]0.80 [40]	STE	S-T	+	
			55.6 [43]	UE	L-T	+	+↑
Pb	300	100[c]	[d]12.8 [41]	PTE	L-T	+	
			135.6 [42]	UE	L-T		+↓
			126 [39]	TE	S-T	–	
			[d]2.0 [40]	STE	S-T	+	
			94 [43]	UE	L-T	+	+↑
Zn	300	300[c]	78.2 [42]	UE	L-T		+↓
			70–80 [39]	TE	S-T	–	
			[d]1.25 [40]	STE	S-T	–	
			285.37 [43]	UE	L-T	+	+↑
Mn		2,000[e]	[d]5.0 [40]	STE	S-T	+	
			77.5 [43]	UE	L-T	+	+↑

PTE primary treated effluent, *UE* untreated effluent, *TE* treated wastewater, *STE* secondary treated effluent, *L-T* long-time trial, *S-T* short-time trial

+, the concentration increases compared to control; +↓, the concentration increase than control, below guideline thresholds [96]; +↑, the concentration increase than control, above guideline thresholds [96]; −, the concentration does not increase compared to control

[a] *EUs* European union standards (EU 2002) [93]

[b] *IR* international references [94, 95]

[c] [95]

[d] Extractable content (DTPA method)

[e] [94]

Rapid and sensitive molecular methods (mostly PCR based) introduced in the 1990s to detect pathogens in water [49] are still facing issues related to sampling DNA preparation, standardising protocols, and assessing only viable. Consequently, the use of indicators is still necessary for the assessment of both water quality and

Table 2 Risk characteristics and classes of heavy metals present in urban wastewater used for crop irrigation [97, 98]

Risk characteristics and classes	Metals
Low risk	Mn, Fe, Zn, Cu, Se, Sb
High risk	Cr, As, Pb, Hg, Ni, Al, Cd
Essential micronutrients for plants	Cu, Fe, Mn, Mo, Zn, Ni
Important elements for some crops	Co, Na, Si
Can accumulate in crops at toxic levels for consumers	Cd, Cu, Mo
No toxicological threshold established for irrigation reuse	Hg
Thresholds high enough for irrigation reuse	Cu, Fe, Mn, Zn
Low absorption by plants	Co, Cu, Mn, Zn

water management [50]. The most important and widely used microbial indicator for faecal contamination of water and wastewater is the species *Escherichia coli*, supported by the previously more frequently considered indicator groups of faecal coliforms and enterococci.

In many countries, the legislation of microbial parameters for wastewater reuse is affected by different interpretations of the concept of microbiological risk; such legislation frequently constitutes a simplification that is inadequate to exploit the full potential of wastewater reuse in agriculture [51].

Table 3 details the dissimilarities of limits for wastewater reuse for various regions, including consideration of different microbial indicators and threshold levels, different methods of detection, inclusion of nematode eggs, and consideration for different types of crops as restricted or unrestricted (herbaceous vs arboreous, food vs feed, etc.).

Ideally, wastewater treatment could effectively and reliably reduce the microbial risk through relatively simple and inexpensive means, justifying the use of reclaimed water as an alternative to higher quality water and securing that supply for conservation or other uses. Wastewater from different sources generally differs to a great extent in its physicochemical and biological characteristics, and any evaluation of possible sustainable reuse must therefore rely on the determination of the specific chemical and biological qualities of the water and their interactions with the field environment and with irrigated crops.

Urban wastewater tends to harbour a higher number of microorganisms of faecal origin and, therefore, to represent a major potential source of human pathogens. Industrial wastewater possesses an intrinsically higher variability due to the different processes for which it is used. In the last 20 years, many studies have focused on the evaluation of microbiological safety in the reuse of treated wastewater for crop irrigation. Assessments of the microbiological quality of agricultural crops irrigated through different methods and by different types of wastewater have frequently reported that possible health risks due to *E. coli* and helminth eggs were not directly correlated with the use of wastewater for irrigation [15].

In some reported cases, crops irrigated with wastewater from various depuration technologies were microbiologically equivalent to the crops irrigated with well

Table 3 Microbial limits for wastewater reuse in different countries

Country or organism		Total coliform (CFU 100 mL)	Faecal coliform (CFU/100 mL)	*E. coli* (CFU/100 mL)	Nematode eggs (no./L)
US – EPA	UR R		Absent 2×10^2		
WHO (2006)	UR R			10^3 –	≤1 ≤1
Italy	ND			10^2	
France	UR R		4^a $2–3^a$	2.5×10^2 $10^4–10^5$	
Spain	UR R			10^2 $10^3–10^4$	0.1 0.1
Portugal	UR R		10^2 $2 \times 10^2–10^4$		
Australia	UR R	10 $10^2–10^4$		$10^2–10^4$	
Israel	ND		10		
Saudi Arabia	UR R	2.2^b 10^{3b}			1 1
China	UR R		2×10^4 4×10^4		
Mexico	UR R		240^b $10^{3\ b}$		

Adapted from Becerra-Castro et al. [51]
UR unrestricted, *U* restricted, *ND* no distinction
[a] Log reduction
[b] MPN/100 mL

water, as assessed by faecal indicators (*E. coli*, faecal coliforms, and enterococci) and pathogens like *Salmonella* spp. *E. coli* O157:H7 and *Listeria* spp. [52, 53].

Orlofsky et al. [54] carried out field experiments to monitor the human pathogenic bacteria, protozoa, and viruses in parallel trials of tomatoes watered with treated wastewater or with fresh water using a combination of microscopic, cultivation-based, and molecular techniques. The results revealed that microbial contamination on the surface of the tomatoes was not associated with the source of the irrigation water. In the specific case of greywater (domestic wastewater that excludes wastewater from toilets), contradicting results regarding increasing levels of faecal coliforms in soils following long-term greywater irrigation have been reported [55].

Efficacy of removal of pathogens and indicators is strictly dependent on the type of treatment conducted prior to irrigation reuse of wastewater: engineered systems that may include membrane filtration and UV disinfection units typically achieve the highest performance but also have higher installation and upkeep costs. Conversely, constructed wetlands and phytodepuration systems are considerably less technologically and energetically demanding, but their performance is consequently more variable [56].

In addition to the efficacy of the water treatment prior to reuse, it must be considered that the survival rate of potential pathogenic microorganisms in the treated water is highly variable, depending on the type of microorganism, water stocking and distribution system, environmental conditions, and other variables. Moreover, irrigation water is only one of the potential sources of contamination for cultivated crops, and the safe reuse of wastewater alone is not sufficient to eliminate risks related to other sources of potential contamination [57]. Therefore, an integrative approach aiming to assess and evaluate risks through microbiological laboratory tests, epidemiological studies, and quantitative microbiological risk assessment (QMRA) is necessary to elaborate novel safety rules for wastewater reuse in agriculture [2]. A balance must be struck between excessive restrictions that hamper the reuse of wastewater reuse and a lack of safety procedures that could lead to foodborne outbreaks; balanced legislation should therefore be a priority on the agenda of national and international regulation agencies. For example, a scientific study aiming at modelling the impact of recent FDA rules on the microbial safety of lettuce production illustrated how less stringent microbial parameters could maintain safety levels suitable for consumption [58].

3 Agronomic Practices Related to Treated Wastewater Reuse: The Role of Irrigation Methods

The use of treated wastewater for crop irrigation requires proper management of these resources at the farm and at the district level. The irrigation strategies for crops should consider the characteristics of the available water sources. Irrigation variables such as irrigation interval, irrigation volume, and seasonal irrigation volume should be established according to the adopted irrigation method and regime (full irrigation or deficit irrigation), temporal availability of the water source, climatic trends, and crop phenological stage.

In the use of treated municipal and agro-industrial wastewater, the definition of irrigation variables is based on the same principles and criteria used for conventional water [59]. For this reason, the irrigation scheduling strategies adopted for conventional water use are also considered valid for wastewater irrigation reuse. Regardless, the selection of adequate irrigation techniques for wastewater use plays an important role in the qualitative and quantitative increase of yields, water resource preservation, and environment protection.

The choice of irrigation system is related to factors including the socio-economic condition and the orographic characteristics of the agricultural area, the adopted crop system, the level of agricultural mechanisation of the farm, and the availability and qualitative properties of the irrigation water resource.

For irrigation with treated wastewater, the most suitable methods are drip and subsurface irrigation systems. These methods offer several advantages. First, the irrigation water efficiency of drip irrigation systems is very high, achieving efficiencies of 90–95% and allowing up to 30–40% water saving as compared to sprinkler and surface irrigation systems. Localised irrigation systems save water through mitigation of water loss through evaporation from the soil.

Drip irrigation systems are characterised by more frequent applications of smaller water volumes, thus ensuring a low and nearly constant soil water tension in the root zone (about −0.1/−0.2 MPa). These aspects mitigate the problems of salt concentration in the root zone due to possible salt addition from wastewater application.

Finally, drip irrigation is considered the more suitable irrigation method to use with treated wastewater because it minimises toxicity hazards for plants, reduces the contamination risk for edible crop products, and mitigates hazards to human health by minimising direct contact with the wastewater. These latter advantages can also be achieved by adopting the sub-irrigation method, with the concurrent benefits of lower water loss to evaporation (15–30%), maximum irrigation efficiency, and lower visual/environmental impact of wastewater distribution.

Experimental trials comparing wastewater application by drip and subsurface irrigation methods did not show significant differences in the irrigated crop yields or for the microbiological contamination levels of the soil and the marketable crop [3, 19, 60].

Drip irrigation methods for crop irrigation with wastewater present a suitable and useful technical solution applicable to all types of soil and crops. However, wastewater containing high total dissolved solids (TDS) can cause nozzle clogging in drip irrigation systems and require the adoption of appropriate filtering systems and treatment of the irrigation water with acid and/or chlorine [61].

Table 4 details the factors influencing the choice of irrigation method, the safety measures that farmers must adopt for treated wastewater, and recommendations for use relative to crop type.

4 Effects of Wastewater on Soil-Plant System

4.1 Effects on Physical and Chemical Characteristics of the Soil

Many studies have been carried out to determine the effects of wastewater use on various soil characteristics. Particular emphasis has been placed by some authors on long-term variations in soil physical and chemical properties [62, 63].

The physical and mechanical properties of the soil (such as porosity, stability of aggregates, water retention, infiltration, and permeability) are very sensitive to organic matter and exchangeable ion types present in the irrigation water [64, 65].

The organic materials added by wastewater irrigation can accumulate in the soil fraction where intense microbial degradation and transformation of these substances occur, leading to the formation of humic compounds and the release of mineral elements. The mineral elements released in the soil following organic substance

Table 4 Suitability of irrigation methods for applying wastewater

Irrigation method	Factors influencing the choice of the irrigation method	Safety measures to adopt for irrigation wastewater reuse	Suitable crops to irrigate with wastewater
Submersion	• Low irrigation water efficiency • Low cost • No soil preparation	• Maximum protection for field workers and consumers	• Use on non-food crops is recommended
Furrow infiltration	• Low cost • Required soil surface levelling	• Maximum protection for field workers and consumers	• Use on non-food crops is recommended
Sprinkler irrigation	• Good irrigation water efficiency • No soil preparation	• Requires protection for workers • Distance of filed from the houses is needed	• Non-food crops • Irrigation of golf courses • Irrigation of parks and gardens
Subsurface irrigation	• High irrigation water efficiency • High plant cost • Difficult control of irrigation lines	• No precaution Wastewater can be used in all cases	• Irrigation of all the food and non-food herbaceous and tree crops
Drip irrigation	• High irrigation water efficiency • High plant cost • No soil preparation	• No precaution Wastewater can used in all cases	• Irrigation of the food and non-food herbaceous and tree crops

degradation enrich the soil with elements useful for plant nutrition, while the humic compounds improve the soil structure and increase its stability, facilitating the movement of water and air along the soil profile.

The integration of the organic substances into soil aggregates guarantees the physical protection of organic substances, limiting their mineralisation by microorganisms and enzymes [66]. This increase in structural stability is due to the cementing action of substances originating from the decomposition of the organic fraction of wastewater and primarily consists of organic polymers (polysaccharides), which form bonds between the soil particles.

In Mediterranean agricultural areas, the soils are frequently characterised by low organic matter contents due to intensive cropping systems and high temperatures that facilitate organic matter mineralisation. In these agricultural contexts, the use of wastewater for crop irrigation could reduce the depletion of soil organic matter.

Once applied to the soil, soluble and insoluble compounds contained in wastewater are involved in numerous physicochemical and microbiological processes that influence their mobility and biodegradability [67].

Field research carried out in the Apulia region of Italy aimed to verify the effect of secondary and tertiary treated municipal wastewater on artichoke crops in comparison with conventional groundwater. No significant differences were found for several chemical parameters (pH, EC, NO_3-N, NH_4-N, and organic matter content) in the upper 30 cm layer of the soil irrigated with the three different water sources [68]. On the contrary, Vergine et al. [20] and Libutti et al. [60] compared the use of groundwater with secondary and tertiary treated municipal wastewater to irrigate a succession of tomato and broccoli crops and found that the soil irrigated with secondary treated wastewater resulted in a significant increase of pH and NH_4-N, as well as of Na^+, SAR, and EC, although these were below the threshold value used to define the soil as saline. According to the authors, the EC increase due to salt accumulation was particularly evident during the cultivation of tomatoes, while this condition changed completely during the cultivation of the broccoli due to the leaching effect of the autumn and winter rains.

However, other researchers have noted that use of low-quality irrigation water requires the addition of a leaching fraction to avoid salt accumulation in the root zone. Basic recommendations to appropriately manage low-quality water and avoid salinity hazards and soil degradation have been provided by Ayers and Westcot [69] and Rhoades and Loveday [70]. Moreover, numerous studies reported the impacts of salinity control measures in irrigated agriculture [60, 71–73].

In terms of the accumulation of heavy metals in soil, Campi et al. [74] carried out a 3-year field study within the In.Te.R.R.A. project in which annual energy crops were irrigated with secondary and tertiary treated municipal wastewater and compared with crops irrigated with conventional water. The results showed that the concentrations of heavy metals in the soil were characterised by negligible mean variations and no significant differences were found among the experimental treatments.

These results confirm those reported by other authors in studies conducted over middle-term time scales. Surdyk et al. [75] in the European FP6 SAFIR project examined heavy metal comportment in soils irrigated by treated wastewater over 3 years in Serbia, Crete, Italy, and China. The authors reported that, when properly treated, wastewater influent with higher heavy metal contents can be used over the middle-term (about 3 years) without visible degradation of the soil, even if long-term cumulative effects cannot be excluded. To this note, some long-term studies have reported significant increases in heavy metal concentrations in soil surface layers, although these were below the critical thresholds established by the international guidelines [62, 76, 77].

Other authors define the effect of wastewater in the long term. Dere et al. [78] and Lucho-Constantino et al. [79] evaluated the effects of heavy metal concentrations in soils irrigated over several decades (up to 100 years) with the low-quality wastewaters (raw sewage) of two cities (Paris and Mexico City). They found significant heavy metal accumulation, especially in wastewater-irrigated soil zone.

Similar research conducted in three different areas of Zimbabwe [34] has demonstrated that the concentrations of the analysed heavy metals (i.e. Cu, Zn, Cd, Cr, Pb, and Ni) in the wastewater-irrigated soils were significantly higher respect to the concentrations found in the non-irrigated soils. These results highlighted that the application of wastewater had enriched the soils with heavy metals, and the authors concluded that soil contamination by wastewater use presents long-term environmental and health risks.

The effect of wastewater on the accumulation of heavy metals in soil profiles and groundwater was examined by monitoring zones irrigated with wastewater for different years (20, 30, and 40 years) in China [80]. The authors reported that long-term wastewaters irrigation does not constitute heavy metals pollution in soil and groundwater; however, they suggested that the monitoring of Hg, Pb, and Cu concentrations should be evaluated in areas that use treated wastewater irrigation to avoid health risks.

4.2 Effects on Soil Microbiological Characteristics

The soil microbiota is an essential component of the soil system, interacting with inorganic components, the atmosphere, soil organic matter, and with other organisms of the soil ecosystem, including plant crops. Microorganisms provide many functions in the soil ecosystems that are essential for the quality and productivity of agricultural products, including plant growth promotion, organic matter turnover, availability of nutrients, and plant pathogen suppression. The application of treated wastewater to agricultural soil can affect the structure and functions of the soil microbiome in two primary ways: first, through the introduction of exogenous microorganisms (with repeated events following each irrigation treatment) leading to changes in microbial diversity and dynamics; and second, through changes in the physicochemical properties of soil due to the composition of the wastewater and the consequent intake of salts, inorganic nitrogen and phosphorous, metals, and micro-pollutants, with unavoidable impacts on the properties of the soil and on cultivated crops.

There is still a lack of information regarding the stability of exogenous microbial communities from wastewater. One study [3] found that short-term applications of treated industrial wastewater could cause a shift in soil microbial communities during a single tomato crop season. More recently, Dang et al. [81] found that irrigation with treated industrial wastewater had a greater impact on microbial community structures than domestic wastewater; irrigation significantly affected the composition of indigenous soil microbial communities at different soil depths and might therefore introduce exogenous microbes into the soil environment.

The composition of wastewater can effect of the degree to which its application modifies the physicochemical properties of the soil; generally, any deviation from the native soil structure and composition (pH, salinity, etc.) tends to reduce microbial diversity, and bacteria are particularly sensitive to soil perturbations. However, an increase in microbial diversity does not necessarily imply an increase in functional diversity, in terms of microbial metabolic activity within the soil. As an example, Cheng et al. [82] found that aquaculture wastewater irrigation of agricultural soil reduced the functional activity of microbial communities (primarily due to increased salinity) but induced a higher richness of microbial taxa.

4.3 *Quantitative and Qualitative Response of Crops to Irrigation with Wastewater*

The quality of water used for crop irrigation can impose a major constraint to agricultural productivity because of its influence on soil fertility and crop yields. Therefore, the knowledge of the effects of the water quality used for irrigation on crop yield response is critical to the understanding of necessary management criteria for long-term productivity as well as to develop the most suitable irrigation schedule to get the optimum plant yield and the desired profit from irrigation. These aspects are of particular importance if considering that the continuous decrease in water resources in the world in general, and in arid and semi-arid regions in particular, is continuously forcing farmers to use wastewaters and modify the conventional irrigation practices.

The plant responses in terms of yield and quality of agricultural products to wastewater are often contrasting; generally, either positive or negative and sometimes even neutral effects have been reported for crops. Positive effects of treated wastewaters reuse on the growth and production of cultivated crop, as well as on the chemical and microbiological characteristics of crop products, were observed within the experimental trials of the already mentioned In.Te.R.R.A project.

Field experiments were carried out in different pedoclimatic conditions of the Apulia region (Southern Italy) with the aim to evaluate the quali-quantitative response of several horticultural and vegetable crops to the irrigation with municipal and agro-industrial-treated wastewaters [3, 17, 18, 60]. At the same time, the hygienic traits of crop products, such as the presence of Coliforms, *Escherichia coli* and *Salmonella*, and the risks for human and environmental health related to the reuse of this irrigation source, were verified. Horticultural crops, such as processing tomato (*Lycopersicon esculentum* Mill.), artichoke (*Cynara cardunculus* L. subsp. *scólymus* Hayek), broccoli (*Brassica oleracea* L. var. *italica*), and vegetable crops for fresh consumption, such as lettuce (*Lactuca sativa* L.), fennel (*Foeniculum vulgare* Mill.), melon (*Cucumis melo* L.) and cucumber (*Cucumis sativus* L.), were examined. The results obtained indicated that the qualitative traits of crop products (e.g. dry matter content, diameter, soluble solid content, titratable acidity, pH) were similar to those obtained when the crops were irrigated with conventional water.

In some cases, when the amounts of nutrient elements (N, P, K) supplied to the crops by wastewater were higher than those supplied by conventional water, also the productive response of the crops, in terms of both total and marketable yield, was positive. During the considered crop cycles, a sporadic presence of pathogenic microorganisms was observed in the soil and, only in rare cases, on the aerial part of the plants. However, in no case the presence of pathogenic microorganism was possible related to the wastewaters microbiological quality, because other potential contamination factors, such as vector insects, aerosols, wild animals, birds, processing and harvesting personnel, endogenous environmental factors, can likely have played a role in microbial contamination of soil and plants [83]. As consequence of irrigation with wastewater, a reduction of the crop cycles, ranging from 7 to 10 days, was also observed within these experimental trials, but without compromising crop qualitative and quantitative performances. This was due to the high amount of nutrients, especially nitrogen, not removed by depuration processes in the considered treated wastewaters that were frequently applied to the plants (2–3 days interval), up to a few days before harvesting.

In this regard, it is well known that treated municipal wastes, if not undergone to denitrification treatment, contain high quantities of nitrates, ammonia salts, mineral perphosphates, and macro-elements than conventional water. High nitrogen supply to the plants, especially close to product harvest, affects crop cycle duration, delaying the reproductive phase and reducing the vegetative phase. Therefore, the plants whose crop cycle ends with the reproductive phase (seed production), under the irrigation with wastewater, tend to lengthen the crop cycle; on the contrary, species that are harvested before the production of seeds (horticultural crops whose product is intended for cooked and/or raw consumption), such as fennel, lettuce, chicory, cucumber, and barter, can reduce their crop cycle [84]. All the quali-quantitative crop response observed within the In.Te.R.R.A research activities confirm the results of previous studies aimed at evaluating the agricultural reuse of municipal wastewaters as alternative irrigation water source, carried out in Apulia region (Southern Italy) [85, 86].

A field experiment carried out by Qaryouti et al. [87] showed the increase of some cucumber and tomato crop parameters when wastewater from industry rich in organic matter and nutrients, particularly K, was reused for irrigation. Especially in cucumber plant the height, fruit yield and average fruit weight, as well as the tomato leaf area and plant dry weight were even significantly increased due to the replacement of K-chemical fertilizer by the wastewater. Also Al-Lahham et al. [88] reported an increase in tomato fruit size and weight when irrigated with reclaimed domestic wastewater. Any adverse effect on chemical quality of several vegetable crop fruits, such as okra (*Abelmoschus esculentus L.*), bean (*Phaseolus vulgaris* L.), corn (*Zea Mays* L.) and sunflower (*Helianthus annuus* L.) was observed when grey treated wastewater, characterized by high BOD and COD values, was used for irrigation [89].

In addition to plant nutrients, wastewaters may contain various potentially toxic mineral elements (see Sect. 2.2) with harmful effects on human and animal health [90]. The transfer of heavy metals to plants irrigated with wastewater may cause accumulation in plant tissues, and in some cases, the content of these metals may reach phytotoxicity thresholds. Particularly, high concentration of heavy metals can result in the reduction in marketable crop yield and/or poor quality of marketable agricultural products [12]. To this regard, Gatta et al. [29] observed heavy metal contents (Al, Cd, Co, Cr, Cu, Fe, Ni, Pb, Zn, and Mn) of artichoke heads, harvested after irrigation with secondary and tertiary treated wastewaters, lower than the international threshold values. They also found low bioaccumulation factors for the edible part of the artichoke crop and not significant health risks (hazard index <1.0) to adults and children after the consumption of the artichoke heads.

On the contrary, other authors [13] found concentrations of Ni, Pb, Cd, and Cr in the edible portions of okra vegetable crop grown on a soil irrigated with treated wastewater well above the safe limit and a Health Risk Index (HRI) higher than 1, indicating a potential health risk. Similarly, heavy metal concentrations (Zn, Pb and Cd) several times higher than the WHO prescribed permissible limits were observed by Uddin et al. [91] in edible portions of red amaranth (*Amaranthus cruentus* L.) and tomato irrigated with industrial wastewater.

The results of several research activities on wastewaters (untreated and treated) clearly highlight that these irrigation sources are a rich source of nutrients and most crops give higher than hypothesized yields with the adoption of a wastewater irrigation system, diminishing the requirement for synthetic fertilizers and bringing about reduction of investment cost to farmers. Nevertheless, if the estimated nitrogen provided for harvesting by the wastewater system exceeds the required dosage for the ideal yields, it may reinforce vegetative development, but it may delay growth and cause adverse effect on crop yield [92]. The presence of toxic elements in wastewater must be also considered since they are hazardous and might be poisonous to plants in high amounts and to human health. Therefore, evaluating the impacts of wastewater irrigation sources on characteristics of crop yield in the different agronomic situations is fundamental in a perspective of wastewater irrigation system development, under the best agronomic and water management practices.

5 Final Considerations

In this chapter, the possibility of recovery of wastewater for irrigation purposes was illustrated and discussed, highlighting the advantages, disadvantages, and possible risks of the practice. Interest in wastewater reuse is continuously developing and derives from the growing worldwide demand for water resources, particularly for food crop irrigation, and not restricted to countries characterised by water scarcity.

The primary results of past and recent research on irrigation reuse of treated wastewater, both of municipal and agro-industrial origin, can be summarised as follows:

- The reuse of treated municipal and agro-industrial wastewater in agriculture can mitigate the increasing scarcity of conventional water resources for a particularly water-demanding sector such as agriculture; agricultural wastewater use could improve the chemical fertility of the irrigated soils; treated wastewater could represent a resource of strategic importance in terms of nutrient availability (e.g. N, P, and K) for the irrigated plants. However, this benefit must be assessed with particular attention because can cause plant nutritional imbalance and phytotoxicity.
- The use of treated wastewater in agriculture (with particular reference to industrial or agro-industrial wastewaters) can lead to heavy metal accumulation in the soil following long periods of application. Therefore, the monitoring of heavy

metals in wastewater-irrigated soils and crops is very important for the prevention of potential environmental and human health risks.
- The application of treated wastewater to agricultural soil can affect the structure and functions of the soil microbiome, mainly owing to the introduction of exogenous microorganisms, with effects on some physical-chemical properties of the soil.
- Soil salinization can become a problem in the long term, particularly if wastewater irrigation takes place in soils already affected by salinity problems.

Finally, the assessment of the suitability of treated wastewater in the agricultural sector cannot be separated from specific scientific studies on the effects of emerging micro-pollutants (e.g. contaminants of emerging concern, CECs) both on the soil-plant system and on human health.

References

1. WHO (2006) Guidelines for the safe use of wastewater, excreta and greywater. In: Wastewater use in agriculture, vol 2. World Health Organization, Geneva
2. Jaramillo MF, Restrepo I (2017) Wastewater reuse in agriculture: a review about its limitations and benefits. Sustainability 9:1734. https://doi.org/10.3390/su9101734
3. Gatta G, Libutti A, Gagliardi A, Beneduce L, Brusetti L, Borruso L, Disciglio G, Tarantino E (2015) Treated agro-industrial wastewater irrigation of tomato crop: effects on qualitative/ quantitative characteristics of production and microbiological properties of the soil. Agric Water Manag 149:33–43. https://doi.org/10.1016/j.agwat.2014.10.016
4. COM_{2018}/0337. https://eurlex.europa.eu/resource.html?uri=cellar:e8951067-627c-11e8-ab9c-01aa75ed71a1.0001.03/DOC_1&format=PDF. Accessed 13 Apr 2020
5. $2018/0169_{(COD)}$. https://oeil.secure.europarl.europa.eu/oeil/popups/ficheprocedure.do?lang=fr&reference=2018/0169(COD). Accessed 13 Apr 2020
6. Licciardello F, Milani M, Consoli S, Pappalardo N, Barbagallo S, Cirelli G (2018) Wastewater tertiary treatment options to match reuse standards in agriculture. Agric Water Manag 210:232–242. https://doi.org/10.1016/j.agwat.2018.08.001
7. Ventura D, Consoli S, Barbagallo S, Marzo A, Vanella D, Licciardello F, Cirelli GL (2019) How to overcome barriers for wastewater agricultural reuse in Sicily (Italy)? Water 11:335. https://doi.org/10.3390/w11020335
8. Pedrero F, Kalavrouziotis I, Alarcón JJ, Koukoulakis P, Asano T (2010) Use of treated municipal wastewater in irrigated agriculture-review of some practices in Spain and Greece. Agric Water Manag 97:1233–1241. https://doi.org/10.1016/j.agwat.2010.03.003
9. Agrafioti E, Diamadopoulos E (2012) A strategic plan for reuse of treated municipal wastewater for crop irrigation on the island of Crete. Agric Water Manag 105:57–64. https://doi.org/10.1016/j.agwat.2012.01.002
10. von Sperling M (2007) Wastewater characteristics, treatment and disposal, vol 1. IWA Publishing, London, pp 1–292
11. Bundi KL, Njeru CW (2018) Use of vegetative wastewater treatment systems for counties' effluent management in Kenya. RJESTE 1(1). https://doi.org/10.4314/rjeste.v1i1.1S
12. Khan I, Ghani A, Rehman AU, Awan SA, Jawed H, Gul R (2016) The analyses of heavy metal concentration in soil, wastewater and Raphanus sativus (L.) at three different growth stages. Pyrex J Res Environ Stud 3:42–48

13. Balkhair KS, Ashraf MA (2016) Field accumulation risks of heavy metals in a soil and vegetable crop irrigated with sewage water in western region of Saudi Arabia. Saudi J Biol Sci 23(1S):S32–S44. https://doi.org/10.1016/j.sjbs.2015.09.023
14. Petterson SR, Ashbolt NJ, Sharma A (2001) Microbial risks from wastewater irrigation of salad crops: a screening-level risk assessment. Water Environ Res 73(6):667–672. https://doi.org/10.2175/106143001x143402
15. Forslund A, Ensink JHJ, Markussen B, Battilani A, Psarras G, Gola S, Sandei L, Fletcher T, Dalsgaard A (2012) Escherichia coli contamination and health aspects of soil and tomatoes (Solanum lycopersicum L.) subsurface drip irrigated with on-site treated domestic wastewater. Water Res 46:5917–5934. https://doi.org/10.1016/j.watres.2012.08.011
16. Metcalf and Eddy (1991) Wastewater engineering: treatment, disposal and reuse, 3rd edn., p 1334
17. Vergine P, Lonigro A, Salerno C, Rubino P, Berardi G, Pollice A (2016) Nutrient recovery and crop yield enhancement in irrigation with reclaimed wastewater: a case study. Urban Water J 14 (3):325–330. https://doi.org/10.1080/1573062X.2016.1141224
18. Lonigro A, Rubino P, Lacasella V, Montemurro N (2016) Faecal pollution on vegetables and soil drip irrigated with treated municipal wastewaters. Agric Water Manag 174:66–73. https://doi.org/10.1016/j.agwat.2016.02.001
19. Gatta G, Libutti A, Beneduce L, Gagliardi A, Disciglio G, Lonigro A, Tarantino E (2016) Reuse of treated municipal wastewater for globe artichoke irrigation: assessment of effects on morpho-quantitative parameters and microbial safety of yield. Sci Hortic 213:55–65. https://doi.org/10.1016/j.scienta.2016.10.011
20. Vergine P, Salerno C, Libutti A, Beneduce L, Gatta G, Berardi G, Pollice A (2017) Closing the water cycle in the agro-industrial sector by reusing treated wastewater for irrigation. J Clean Prod 164:587–596. https://doi.org/10.1016/j.jclepro.2017.06.239
21. Urbano VR, Mendonca TG, Bastos RG, Souza CF (2017) Effects of treated wastewater irrigation on soil properties and lettuce yield. Agric Water Manag 181:108–115. https://doi.org/10.1016/j.agwat.2016.12.001
22. Vivaldi GA, Camposeno S, Lopriore G, Romeros-Trigueros C, Salcedo FP (2019) Using saline reclaimed water on almond grown in Mediterranean conditions: deficit irrigation strategies and salinity effects. Water Supply 19(5):1413–1421. https://doi.org/10.2166/ws.2019.008
23. Pedrero F, Maestre-Valero JF, Mounzer O, Alarcón JJ, Nicolás E (2014) Physiological and agronomic mandarin trees performance under saline reclaimed water combined with regulated deficit irrigation. Agric Water Manag 146:228–237. https://doi.org/10.1016/j.agwat.2014.08.013
24. Vivaldi GA, Stellacci AM, Vitti C, Rubino P, Pedrero F, Camposeno S (2017) Nutrient uptake and fruit quality in a nectarine orchard irrigated with treated municipal wastewaters. Desalin Water Treat 71:312–320. https://doi.org/10.5004/dwt.2017.20564
25. Montemurro N, Cucci G, Mastro MA, Lacolla G, Lonigro A (2017) The nitrogen role in vegetables irrigated with treated municipal wastewater. Agron Res 15(5):2012–2025. https://doi.org/10.15159/AR.17.044
26. Grattan SR, Díaz FJ, Pedrero F, Vivaldi GA (2015) Assessing the suitability of saline wastewaters for irrigation of Citrus spp.: emphasis on boron and specific-ion interactions. Agric Water Manag 157:48–58. https://doi.org/10.1016/j.agwat.2015.01.002
27. Segal E, Dag A, Ben-Gal A, Zipori I, Erel R, Suryano S, Yermiyahu U (2011) Olive orchard irrigation with reclaimed wastewater: agronomic and environmental considerations. Agric Ecosyst Environ 140:454–461. https://doi.org/10.1016/j.agee.2011.01.009
28. Almuktar SAAN, Scholz M (2016) Mineral and biological contamination of soil and Capsicum annuum irrigated with recycled domestic wastewater. Agric Water Manag 167:95–109. https://doi.org/10.1016/j.agwat.2016.01.008
29. Gatta G, Gagliardi A, Disciglio G, Lonigro A, Francavilla M, Tarantino E, Giuliani MM (2018) Irrigation with treated municipal wastewater on artichoke crop: assessment of soil and yield heavy metal content and human risk. Water 10:255. https://doi.org/10.3390/w10030255

30. Singh RP, Agrawal M (2010) Effect of different sewage sludge applications on growth and yield of Vigna radiata L. field crop: metal uptake by plant. Ecol Eng 36(7):969–972. https://doi.org/10.1016/j.ecoleng.2010.03.008
31. Gatta G, Libutti A, Gagliardi A, Disciglio G, Beneduce L, d'Antuono M, Rendina M, Tarantino E (2015) Effects of treated agro-industrial wastewater irrigation on tomato processing quality. Ital J Agron 10:97–100. https://doi.org/10.4081/ija.2015.632
32. Sawidis T, Chettrib MK, Papaioannouc A, Zachariadisc G, Stratisc J (2001) A study of metal distribution from lignite fuels using trees as biological monitors. Ecotox Environ Safe 48 (1):27–35. https://doi.org/10.1006/eesa.2000.2001
33. Thakur S, Singh L, Ab Wahid Z, Siddiqui MF, Atnaw SM, Md Din MF (2016) Plant-driven removal of heavy metals from soil: uptake, translocation, tolerance mechanism, challenges, and future perspectives. Environ Monit Assess 188:206. https://doi.org/10.1007/s10661-016-5211-9
34. Mapanda F, Mangwayana EN, Nyamangara J, Gillera KE (2005) The effect of long-term irrigation using wastewater on heavy metal contents of soils under vegetables in Harare, Zimbabwe. Agric Ecosyst Environ 107:151–165. https://doi.org/10.1016/j.agee.2004.11.005
35. Zhuang P, McBride MB, Xia H, Li N, Li Z (2009) Health risk from heavy metals via consumption of food crops in the vicinity of Dabaoshan mine, South China. Sci Total Environ 407:1551–1561. https://doi.org/10.1016/j.scitotenv.2008.10.061
36. Remon E, Bouchardon JL, Cornier B, Guy B, Leclerc JC, Faure O (2005) Soil characteristics, heavy metal availability and vegetation recovery at a former metallurgical landfill: implications in risk assessment and site restoration. Environ Pollut 137:316–323. https://doi.org/10.1016/j.envpol.2005.01.012
37. Ismael A, Riaz M, Akhtar S, Ismail T, Amir M, Zafar-ul-Hye M (2014) Heavy metals in vegetables and respective soils irrigated by canal, municipal waste and tube well waters. Food Addit Contam 7:213–219. https://doi.org/10.1080/19393210.2014.888783
38. Toze S (2006) Reuse of effluent water: benefits and risks. Agric Water Manag 80:147–159. https://doi.org/10.1016/j.agwat.2005.07.010
39. Khaskhoussy K, Kahlaoui B, Nefzi BM, Jozdan O, Dakheel A, Hachicha M (2015) Effect of treated wastewater irrigation on heavy metals distribution in a Tunisian soil. Eng Technol Appl Sci Res 5(3):805–810
40. Abedi-Koupai J, Mostafazadeh-Fard B, Afyuni M, Bagheri MR (2006) Effect of treated wastewater on soil chemical and physical properties in an arid region. Plant Soil Environ 52 (8):335–344
41. Abd-Elwahed MS (2018) Influence of long-term wastewater irrigation on soil quality and its spatial distribution. Ann Agri Sci 63:191–199. https://doi.org/10.1016/j.aoas.2018.11.004
42. Dotaniya ML, Rajendiran S, Meena VD, Coumar MV, Saha JK, Kundu S, Patra AK (2018) Impact of long-term application of sewage on soil and crop quality in vertisols of Central India. Bull Environ Contam Toxicol 101:779–786. https://doi.org/10.1007/s00128-018-2458-6
43. Masona C, Mapfaire L, Mapurazi S, Makanda R (2011) Assessment of heavy metal accumulation in wastewater irrigated soil and uptake by maize plants (Zea Mays L) at Firle Farm in Harare. J Sustain Dev 4(6). https://doi.org/10.5539/jsd.v4n6p132
44. Gola D, Malik A, Ahammad Shaikh Z, Sreekrishnan TR (2016) Impact of heavy metal containing wastewater on agricultural soil and produce: relevance of biological treatment. Environ Process 3:1063–1080
45. Wuana RA, Okieimen FE (2011) Heavy metals in contaminated soils: a review of sources, chemistry, risks and best available strategies for remediation. Isrn Ecol 2011:20. https://doi.org/10.5402/2011/402647
46. Chibuike GU, Obiora SC (2014) Heavy metal polluted soils: effect on plants and bioremediation methods. Appl Environ Soil Sci:12. https://doi.org/10.1155/2014/752708
47. WHO (2001) Indicators of microbial water quality. In: Fewtrell L, Bartram J (eds) Water quality: guidelines, standards and health: assessment of risk and risk management for water-related infectious diseases. IWA Publishing, London

48. Fujioka RS (2002) Microbial indicators of water quality. In: Hurst CJ, Crawfod RL, Knudsen GR, McInerney MJ, Stetzenbach LD (eds) Manual of environmental microbiology. American Society for Microbiology Press, Washington, pp 234–243
49. Toze S (1999) PCR and the detection of microbial pathogens in water and wastewater. Water Res 33(17):3545–3556. https://doi.org/10.1016/S0043-1354(99)00071-8
50. García Aljaro C, Blanch A, Campos C, Jofre J, Lucena F (2019) Pathogens, faecal indicators and human specific microbial source tracking markers in sewage. J Appl Microbiol 126:701–717. https://doi.org/10.1111/jam.14112
51. Becerra-Castro C, Lopesa AR, Vaz-Moreiraa I, Silva EF, Manaia CM, Nunes OC (2015) Wastewater reuse in irrigation: a microbiological perspective on implications in soil fertility and human and environmental health. Environ Int 75:117–135. https://doi.org/10.1016/j.envint.2014.11.001
52. Christou A, Maratheftis G, Eliadou E, Michael C, Hapeshi E, Fatta-Kassinos D (2014) Impact assessment of the reuse of two discrete treated wastewaters for the irrigation of tomato crop on the soil geochemical properties, fruit safety and crop productivity. Agric Ecosyst Environ 192:105–114. https://doi.org/10.1016/j.agee.2014.04.007
53. Beneduce L, Gatta G, Bevilacqua A, Libutti A, Tarantino E, Bellubbi M, Troiano E, Spano G (2017) Impact of the reusing of food manufacturing wastewater for irrigation in a closed system on the microbiological quality of the food crops. Int J Food Microbiol 260:51–58. https://doi.org/10.1016/j.ijfoodmicro.2017.08.009
54. Orlofskya E, Bernsteinb N, Sacksc M, Vonshaka A, Benamia M, Kundud A, Makid M, Smithe W, Wuertzd S, Shapirof K, Gillor O (2016) Comparable levels of microbial contamination in soil and on tomato crops after drip irrigation with treated wastewater or potable water. Agric Ecosyst Environ 215:140–150. https://doi.org/10.1016/j.agee.2015.08.008
55. Benami M, Gillor O, Gross A (2016) Potential microbial hazards from graywater reuse and associated matrices: a review. Water Res 106:183–195. https://doi.org/10.1016/j.watres.2016.09.058
56. Shingare RP, Thawale PR, Raghunathan K, Mishra A, Kumar S (2019) Constructed wetland for wastewater reuse: role and efficiency in removing enteric pathogens. J Environ Manag 246:444–461. https://doi.org/10.1016/j.jenvman.2019.05.157
57. Alegbeleye OO, Singleton I, Sant'Ana S (2018) Sources and contamination routes of microbial pathogens to fresh produce during field cultivation: a review. Food Microbiol 73:177–208. https://doi.org/10.1016/j.fm.2018.01.003
58. Rock CM, Brassil N, Dery JL, Carr D, Mclaine JE, Bright KR, Gerba CP (2019) Review of water quality criteria for water reuse and risk-based implications for irrigated produce under the FDA food safety modernization act, produce safety rule. Environ Res 172:616–629. https://doi.org/10.1016/j.envres.2018.12.050
59. Rubino P, Tarantino E (2015) In: Te.R.R.A. project. Innovazioni Tecnologiche e di Processo per il Riutilizzo irriguo delle acque Reflue urbane e Agroindustriali ai fini della gestione sostenibile delle risorse idriche. A cura di Rubino P. e Lonigro A. Edizione di Pagina, Bari, pp 183–192
60. Libutti A, Gatta G, Gagliardi A, Vergine P, Pollice A, Beneduce L, Disciglio G, Tarantino E (2018) Agro-industrial wastewater reuse for irrigation of a vegetable crop succession under Mediterranean conditions. Agric Water Manag 196:1–14. https://doi.org/10.1016/j.agwat.2017.10.015
61. Ribeiro TAP, Paterniani JES, Coletti C (2008) Chemical treatment to Unclogg dripper irrigation systems due to biological problems. Sci Agric 65(1):1–9
62. Xu J, Wu L, Chang AC, Zhang Y (2010) Impact of long-term reclaimed wastewater irrigation on agricultural soils: a preliminary assessment. J Hazard Mater 183:780–786. https://doi.org/10.1016/j.jhazmat.2010.07.094
63. Tarchouna LG, Merdy P, Raynaud M, Pfeifer HR, Lucas Y (2010) Effects of long-term irrigation with treated wastewater. Part I: evolution of soil physico-chemical properties. J App Geochem 25:1703–1710. https://doi.org/10.1016/j.apgeochem.2010.08.018

64. Gloaguen TV, Forti MC, Lucas Y, Montes CR, Gonçalves RA, Uwe H, Melfi AJ (2007) Soil solution chemistry of a Brazilian Oxisol irrigated with treated sewage effluent. Agric Water Manag 88:119–131. https://doi.org/10.1016/j.agwat.2006.10.018
65. Mandal UK, Warrington DN, Bhardwaj AK, Bar-Tal A, Kautsky L, Minz D, Levy GJ (2008) Evaluating impact of irrigation water quality on a calcareous clay soil using principal component analysis. Geoderma 144(1–2):189–197. https://doi.org/10.1016/j.geoderma.2007.11.014
66. Baldock JA, Skjemstad JO (2000) Role of the soil matrix and minerals in protecting natural organic materials against biological attack. Org Geochem 31(7–8):697–710. https://doi.org/10.1016/S0146-6380(00)00049-8
67. Saviozzi A, Levi-Minzi R, Riffaldi R (1990) Cinetica della decomposizione nel terreno del carbonio organico delle acque di vegetazione. Agrochimica 34:1–2
68. Disciglio G, Gatta G, Tarantino A, Frabboni L, Tarantino E (2014) Use of treated municipal wastewater on artichoke crop. Int J Agric Byosyst Eng 8:224–229
69. Ayers RS, Westcot DW (1989) Water quality for agriculture. Irrigation and drainage paper no. 29. FAO, Rome, p 163
70. Rhoades JD, Loveday J (1990) Salinity in irrigated agriculture. In: Steward BA, Nielsen R (eds) Irrigation of agricultural crop, vol 30. ASA Monograph, London, pp 1089–1142
71. Libutti A, Monteleone M (2012) Irrigation management in Mediterranean salt affected agriculture: how leaching operates. Ital J Agron 7-5:28–35. https://doi.org/10.4081/ija.2012.e5
72. Libutti A, Monteleone M (2017) Soil vs. groundwater: the quality dilemma. Managing nitrogen leaching and salinity control under irrigated agriculture in Mediterranean conditions. Agric Water Manag 186:40–50. https://doi.org/10.1016/j.agwat.2017.02.019
73. Monteleone M, Libutti A (2012) Salt leaching due to rain in Mediterranean climate: is it enough? Ital J Agron 7-6:36–43. https://doi.org/10.4081/ija.2012.e6
74. Campi P, Stellacci AM, Navarro A, Vitti C, Mastrorilli M (2015) In: Te.R.R.A. project. Innovazioni Tecnologiche e di Processo per il Riutilizzo irriguo delle acque Reflue urbane e Agroindustriali ai fini della gestione sostenibile delle risorse idriche. A cura di Rubino P. e Lonigro A., Edizione di Pagina, Bari, pp 231–246
75. Surdyk N, Cary L, Blagojevic S, Jovanovic Z, Stikic R, Vucelic-Radovic B, Zarkovic B, Sandei L, Pettenati M, Kloppmann W (2010) Impact of irrigation with treated low quality water on the heavy metal contents of a soil-crop system in Serbia. Agric Water Manag 98(3):451–457. https://doi.org/10.1016/j.agwat.2010.10.009
76. Siebe C, Fischer WR (1996) Adsorption of Pb, Cd, Cu and Zn by two soils of volcanic origin under long term irrigation with untreated sewage effluent in Central Mexico. J Plant Nutr Soil Sc 159:357–364
77. Simmons RW, Pongsakul P (2002) Toward the development of an effective sampling protocol to "rapidly" evaluate the distribution of Cd in contaminated, irrigated rice based agricultural systems. In: Transactions of the 17th world congress of soil science, Bangkok, 14–21 August 2002. Vienna, international union of soil science. WHO guidelines, 2006
78. Dere C, Cornu S, Lamy I (2006) Factors affecting the three-dimensional distribution of exogenous zinc in a sandy Luvisol subjected to intensive irrigation withdraw wastewaters. Soil Use Manag 22(3):289–297. https://doi.org/10.1111/j.1475-2743.2006.00044.x
79. Lucho-Constantino CA, Prieto-Garcia F, Del Razo LM, Rodriguez-Vazquez R, Poggi-Varaldo HM (2005) Chemical fractionation of boron and heavy metalsin soils irrigated with wastewater in Central Mexico. Agric Ecosyst Environ 108:57–71. https://doi.org/10.1016/j.agee.2004.12.013
80. Bao Z, Wenyong W, Honglu L, Honghan C, Shiyang Y (2014) Impact of long-term irrigation with sewage on heavy metals in soils, crops, and groundwater – a case study in Beijing. Pol J Environ Stud 23(2):309–318
81. Dang Q, Tan W, Zhao X, Li D, Li Y, Yang T, Li R, Zu G, Xi B (2019) Linking the response of soil microbial community structure in soils to long-term wastewater irrigation and soil depth. Sci Total Environ 688:26–36. https://doi.org/10.1016/j.scitotenv.2019.06.138

82. Cheng P, Wang Y, Liu T, Liu D (2017) Biofilm attached cultivation of *Chlorella pyrenoidosa* is a developed system for swine wastewater treatment and lipid production. Front Plant Sci 8:1594. https://doi.org/10.3389/fpls.2017.01594
83. Venglovsky J, Martinez J, Placha I (2006) Hygienic and ecological risks connected with utilization of animal manures and biosolids in agriculture. Livest Sci 102:197–203. https://doi.org/10.1016/j.livsci.2006.03.017
84. Rubino P, Lonigro A (2015) In: Te.R.R.A. project. Innovazioni Tecnologiche e di Processo per il Riutilizzo irriguo delle acque Reflue urbane e Agroindustriali ai fini della gestione sostenibile delle risorse idriche. Linee guida per il riuso irriguo delle acque reflue depurate, p 271
85. Lopez A, Pollice A, Laera G, Lonigro A, Rubino P (2010) Membrane filtration of municipal wastewater effluents for implementing agricultural reuse in southern Italy. Water Sci Technol 62:1121–1128. https://doi.org/10.2166/wst.2010.393
86. Pollice A, Lopez A, Larera G, Rubino P, Lonigro A (2004) Tertiary filtered municipal wastewater as alternative water source in agriculture: a field investigation in southern Italy. Sci Total Environ 324(1–3):201–210. https://doi.org/10.1016/j.scitotenv.2003.10.018
87. Qaryouti M, Bani-Hani N, Abu-Sharar TM, Shnikat I, Hiari M, Radiadeh M (2015) Effect of using raw waste water from food industry on soil fertility, cucumber and tomato growth, yield and fruit quality. Sci Hortic 193:99–104. https://doi.org/10.1016/j.scienta.2015.07.002
88. Al-Lahham O, El Assi NM, Fayyad M (2003) Impact of treated wastewater irrigation on quality attributes and contamination of tomato fruit. Agric Water Manag 61(1):51–62. https://doi.org/10.1016/S0378-3774(02)00173-7
89. Al-Hamaiedeh A, Bino M (2010) Effect of treated grey water reuse in irrigation on soil and plants. Desalination 256:115–119. https://doi.org/10.1016/j.desal.2010.02.004
90. Singh R, Gautam N, Mishra A, Gupta R (2011) Heavy metals and living systems: an overview. Indian J Pharmacol 43:246–253. https://doi.org/10.4103/02537613.81505
91. Uddin MJ, Khanom S, Al Mamun S, Parveen Z (2015) Effects of irrigation water on some vegetables around industrial areas of Dhaka, Bangladesh. J Sci Res 28(2):151–159. https://doi.org/10.3329/bjsr.v28i2.26785
92. Odoemena KK, Rowshon KMD, Binti CMH (2019) Advances in utilization of wastewater in agricultural practice: a technical note. Irrig Drain. https://doi.org/10.1002/ird.2384
93. Commission Regulation (EC) No 1881/2006 of 19 December 2006: setting maximum levels for certain contaminants in foodstuffs. Official Journal of the European Union (L. 264). http://eur-lex.europa.eu/legal-content. Accessed 22 Jan 2017
94. Pendias AK, Pendias H (1992) Elements of group VIII. In: Trace elements in soils and plants. CRC Press, Boca Raton, pp 271–276
95. Ewers U (1991) Standards, guidelines and legislative regulations concerning metals and their compounds. In: Merian E (ed) Metals and their compounds in the environment: occurrence. Analysis and biological relevance. VCH, Weinheim, pp 458–468
96. FAO/WHO (2001) Food additives and contaminants. FAO/WHO food standards program, ALINORM 01/12A, Joint Codex Alimentarius Commission, Rome
97. Pescod M (1992) Wastewater treatment and use in agriculture, FAO irrigation and drainage paper 47, Food and Agriculture Organization, Rome
98. Durán-Álvarez JC, Jiménez-Cisneros B (2014) Beneficial and negative impacts on soil by the reuse of treated/untreated municipal wastewater for agricultural irrigation – a review of the current knowledge and future perspectives. In: Hernandez-Soriano MC (ed) Environmental risk assessment of soil contamination