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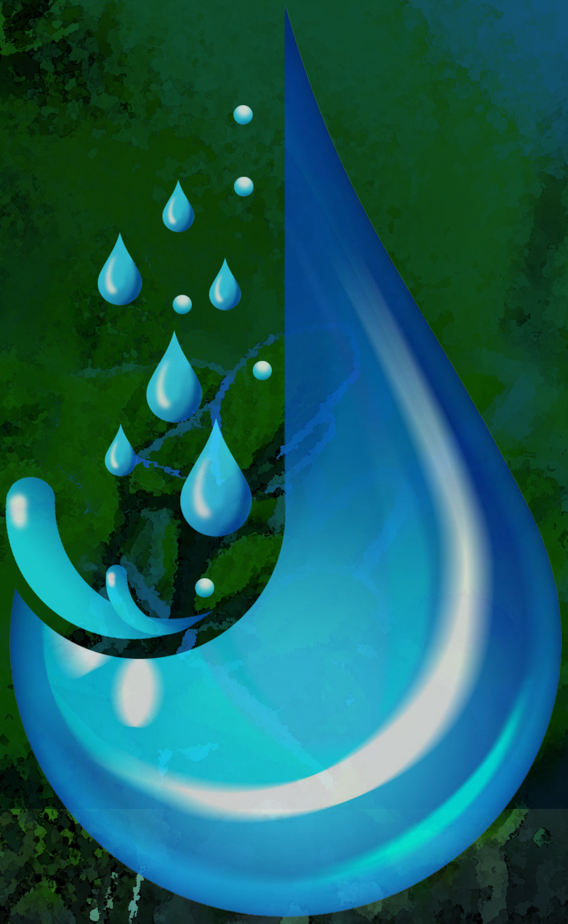

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Chapter 3

Water quality guidelines in agricultural water use

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Agricultural use of reclaimed water has a long history and accounts for a significant percentage of the reclaimed water used globally. The use of reclaimed water for agriculture is also widely supported by regulatory and institutional policies. In addition, the World Health Organization (WHO, 1989, 2006) has provided guidelines to reduce risks where farmers use untreated and/or diluted wastewater either intentionally or unintentionally.

Historically, water reuse standards were first developed for agricultural water reuse (e.g. in California in 1918), with different countries subsequently developing different approaches to protect public health and the environment. A major factor in the choice of regulatory strategy in many countries is economics, specifically the costs of treatment, monitoring and distribution of the recycled water. Some developed countries have opted for developing conservative low-risk guidelines or standards based on relatively costly technology and stringent water quality monitoring (e.g. Australia, California, the European Commission and the USEPA). However, the feedback from practice and health risk assessments demonstrates that health risk mitigation can also be achieved by means of additional health protection barriers and the use of less expensive technologies, as recommended by the WHO (2006) guidelines.

Many water reuse standards and guidelines are developed with farmer and consumer health protection in mind. Contact, inhalation and, in particular, ingestion of reclaimed water containing pathogenic microorganisms or toxic chemicals, can create the potential for adverse health effects in humans and animals. The most common health concern associated with non-potable wastewater reuse is the potential transmission of infectious disease by microbial pathogens. Waterborne disease outbreaks of epidemic proportions have been controlled to a large extent where treatment has gained good household coverage, but the potential for disease transmission through the water delivery system has not been eliminated. With a few exceptions, there are minimal health concerns associated with chemical constituents where reclaimed water is not intended to be consumed (Lazarova & Bahri, 2005).

3.1. Key water quality parameters for agricultural water reuse

The most common risks and adverse impacts of water quality in water reuse systems are summarized in Table 3.1. The major water quality parameters and compounds of concern are given with the associated risk category and potential adverse impacts, as well as the type of regulatory tools and guidelines available.

The presence of pathogens is the main health concern when (reclaimed) water is used for irrigation. Because it is not possible to monitor all pathogens and their viability, coliforms are successfully used as microbial indicators (Asano *et al.*, 2007). Thermo-tolerant (faecal) coliforms are the most common microbial indicator, as well as *Escherichia coli* (*E. coli*), the most common faecal coliform. In developed countries, one of the major human health concerns related to water reuse is intestinal parasitic infections (WHO, 2006), which has led to the use of helminth eggs or spores of sulfate-reducing bacteria as another indicator.

Table 3.1. Water quality criteria for agricultural water reuse

Main objective for risk mitigation	Parameters of concern	Major parameters and compounds of concern	Main risks and adverse impacts	Type of regulatory tools and recommendations
Human and animal health protection and mitigation of health risks	Microbial parameters	Bacteria, viruses and protozoa Coliforms (total, faecal or *E. coli*) are the most common microbial indicator	Short-term microbial risk of infection	Major topic in water reuse regulations, guidelines and standards
	Chemical compounds	Heavy metals, organic micropollutants (pesticides, pharmaceuticals and health care products, endocrine disruptors, etc.)	Long-term biological risk of toxicity	Emerging issue Ongoing research
Environmental protection	Microbial and chemical compounds	Nitrate (groundwater), nitrate and phosphorus (eutrophication), residual chlorine (surface water), inorganic and organic micropollutants (soil and water resources)	Aquifer, surface water and soil pollution, Adverse impacts on biodiversity (flora and fauna)	Included in some wastewater treatment and reuse regulations and standards
Mitigation of agronomic impacts	Agronomic parameters and chemical compounds	SAR*, salinity, sodicity, toxic ions, trace elements (heavy metals and organic micropollutants), residual chlorine, nutrients, anions and cations (Ca^{2+}, Mg^{2+}, CO_3^{2-}, HCO^{3-}, C^{l-}, SO_4^{2-}), boron, etc.	Crop growth and quality, Soil properties	FAO and some national guidelines, some water reuse regulations
Mitigation of technical constraints	Chemical, biological and general parameters	Suspended solids, residual chlorine, redox potential, hardness, etc.	Biofilm growth and clogging of distribution and irrigation systems	FAO (1985, 1992), ISO water reuse guidelines (ISO 16075-3)

* SAR – sodium adsorption ratio.

Source: Authors' own elaboration.

As a rule, the environmental and agronomic risks from water reuse for irrigation relate to uncontrolled or high industrial wastewater discharge in municipal sewers (e.g. high concentrations of heavy metals or organic micropollutants). In coastal areas, the primary risk is high salinity and sodicity of wastewater caused by seawater intrusion in municipal sewers (e.g. high rates of infiltration, especially under bad weather and high tide conditions). Experience with biological wastewater treatment (e.g. activated sludge) shows that the large proportion of heavy metals and refractory organic micropollutants are concentrated in sludge. Consequently, the field application of polluted wastewater sludge and the reclamation of industrial wastewater represent a higher risk for agriculture. For this reason, French regulation (Légifrance 2010) on water reuse does not require the monitoring of trace contaminants if municipal sludge quality is in compliance with the regulation on sludge spreading in agricultural areas.

3.2. Definition of the main categories of water reuse for agricultural irrigation

Despite the complexity of existing use categories definitions, a general decision tree can be developed. The first stage is to determine whether a crop is considered edible or not. For edible crops, the next stage is to ascertain whether the crop is eaten cooked or raw. Here, cooking is viewed as an additional treatment (or barrier) favouring public protection. Direct contact between crops and reclaimed water is an additional important factor. It should be recognized, however, that the entire transmission chain should be considered. This includes factors such as the use (or not) of low-quality water to irrigate or wash food crops, the sale of such uncooked crops to markets, restaurants, and so on – all of which might present risks of pathogen transmission arising from crop handling or the contamination of cooking environments.

For those crops that are not edible, it is important to consider whether the area under irrigation is restricted or not. In restricted areas, the likelihood of public exposure is lower than in a non-restricted site. The risk of disease transmission is related to the quality of the reclaimed water and the degree of human contact with that water. Finally, sprinkler irrigation is associated with a higher risk than flood, furrow or drip irrigation, due to the potential for disease transmission from aerosols or windblown spray if a low level of disinfection is provided.

In many countries, crops eaten raw are generally considered to present the greatest potential for disease transmission associated with the use of reclaimed water for irrigation. However, this is not always the case. For example, some regulations recommend more stringent standards for public lawns than for crops eaten raw.

3.3. Key international and national water reuse regulations and guidelines

Water reuse standards or guidelines vary with the type of application, regional context and overall risk perception. In practice, these factors are expressed through different water quality and treatment requirements as well as criteria for operation and reliability. The most stringent guidelines and regulations operate on the basis of the precautionary principle, which demands high water quality and intensive treatment, leading to lower health risks without additional specific measures. However, similar health protection can be achieved by means of additional health protection barriers, as demonstrated by WHO (2006). This approach allows for the use of less expensive treatment and monitoring, which is within the reach of all countries, but struggles with its implementation where risk awareness is low (Drechsel, Qadir & Galibourg, 2022).

The application of additional health protection barriers and codes of good practices (the multi-barrier approach) could form an essential part of a risk mitigation strategy, as underlined by USEPA (2012). These kinds of measures are as important for farmers and operators as quality requirements for water especially where wastewater treatment is not able to achieve the latter.

Regarding microbial parameters and health protection, current agricultural water reuse regulations and guidelines vary significantly in terms of selected key water quality parameters, threshold levels and monitoring requirements. Table 3.2 illustrates the microbial water quality and treatment requirements of the most important cornerstone water reuse guidelines and regulations followed in many countries.

Concerning trace elements, agronomic and physico-chemical parameters and compounds, the FAO guidelines (Ayers & Westcot, 1985; Pescod, 1992) constitute the key document of reference for the water reuse standards, guidelines and regulations of other organizations and countries. These parameters are of critical importance for the implementation of safe agricultural water reuse practices due to their influence on crops quality and yield, as well as soil properties and productivity.

Table 3.2. Comparison of common water quality criteria for agricultural irrigation of selected guidelines and regulations

Class	Parameter	**WHO** (1989)	**WHO** (2006)	**FAO** (1992[a])	**USEPA** (2012)	**California** (2000)	**Australia NRMMC** (2006)	**ISO 16075-1 to 4** (2015, 2016, 2020)	**European Union** (2020)
		Guidelines	*Guidelines*	*Guidelines*	*Guidelines*	*Regulation*	*Guidelines*	*Guidelines*	*Regulations*
Unrestricted irrigation of food crops/consumed raw	**Microbial indicator**	Faecal coliforms	*E. coli*	Faecal coliforms	Faecal coliforms	Total coliforms (TC)	*E. coli*	Thermo-tolerant coliforms	*E. coli*
	Coliforms, number (cfu or MPP) per 100 mL	≤1 000 crops eaten raw ≤200 for public lawns	10 to 10^5 *E.coli* depending on treatment, additional health barriers and type of crops	≤1 000 (more stringent (<200) for public lawns)	Not detected (daily, seven-day median, 14 max)	≤2.2 (daily, seven-day median, 23 max in 30 days, 240 max)	≤1 (weekly)	≤10 (weekly, 100 max, 95 percentile)	≤10 (weekly, 90 percentile)
	Helminths, eggs/L	≤1	≤1	≤1[b]	NS	NS	NS[d]	NS	NS
	BOD_5, mg/L	NS	NS	NS	≤10 (weekly)	NS	NS[e]	≤5 (average, 10 max)	≤ 10 (weekly)
	Total suspended solids TSS, mg/L				NS				
	Turbidity, NTU				≤2 (online, av. 24 h, 5 max) Membranes ≤0.2 any time	≤2 (online, av. 24 h, 5 max) Membranes ≤0.2 (max 0.5)		≤3 (average, 6 max)	≤5
	Chlorine residual				>1 mg/L (on-line)	>1 mg/L		optional (0.2 to 1 mg/L)	NS
	Log removal requirements (pathogens)	NS	6-7 logs in total via various combinations of pathogen barriers, water treatment and natural die-off	NS	NS	5 log of MS2 bacteriophages of disinfection process	6 log viruses 5 log for bacteria and protozoa	NS	>5 log *E. coli* >6 log coliphages[h] >4 log *Clostridium perfringens*[i]
	Minimum treatment requirements	Stabilisation ponds	List of treatment and non-treatment pathogen barriers which can be combined to achieve the health-based risk reduction target	Series of stabilization ponds	Secondary treatment, filtration, disinfection	Tertiary treatment + disinfection; chlorination Ct 450 mg. min/L	Secondary treatment, filtration and disinfection[f]	Secondary treatment, filtration and disinfection[g] multi-barrier approach supported	Secondary treatment, filtration, disinfection , post-treatment barriers
Others	Coliforms / 100 mL	NS	Restricted irrigation: 3-4 log units removal requirement	NS	Processed/non-food crops ≤200 FC (median, 800 max)	NS	Commercial food crops, pastures, fodder ≤100 to ≤1 000 *E. coli*	≤200 *E. coli for* processed food crops, ≤1 000 for non-food crops (+ 1 log max)	
	Legionella		NS	NS	NS		NS	<1 000 cfu/L if risk of aerosolization (twice a month)	
	Helminths, eggs/L	≤ 1	≤ 1	≤ 1[c]				≤ 1 for categories C, D and E	≤ 1 for pastures or fodder[j]

NS: Not specified

a Based on the WHO 1989 guideline.

b *Ascaris* and *Trichuris* species and hookworms, during the irrigation period.

c For pastures, fodder, cereals and orchards.

d For highest exposures, the verification monitoring also includes *Clostridium perfringens*, somatic and F-specific bacteriophages (weekly), as well as adenovirus and *Cryptosporidium* oocysts (monthly).

e The state regulations in Australia require 10 mg/L of BOD_5 and TSS for category A, the highest exposure and highest water quality.

f A number of specific operational parameters are recommended depending on the given treatment process.

g Different treatment processes are specified for each treatment step.

h Total coliphages or alternatively F-specific or somatic coliphages.

i Spore-forming sulfate-reducing bacteria can be used as an alternative.

j The monitoring frequency depends on the initial count of helminth eggs.

Source: Authors' own compilation.

3.3.1. WHO water reuse guidelines

The first set of World Health Organization water reuse guidelines were published in 1973 and included recommended criteria for several uses, including crop irrigation and potable reuse. In 1985, WHO and other international organizations sponsored a meeting of experts to review the use of reclaimed water for agriculture and aquaculture, in particular in arid and developing countries. The experts concluded that the health risks for those applications were minimal and the current guidelines were overly restrictive. Consequently, revised guidelines were developed and published (WHO, 1989). Compared to the original WHO guidelines, the revised version proposed less stringent maximum concentration levels for food crops eaten raw with respect to faecal coliforms, with the recommended threshold limit increasing from 100 FC/100 mL to 1 000 FC/100 mL (Table 3.2). A more stringent standard of 200 FC/100 mL was suggested for the irrigation of public lawns. The technology recommended for water reuse was stabilization ponds or any equivalent treatment processes. Several countries have used the WHO 1989 guidelines as the basis for their agricultural reuse standards. In the absence of recommendations for suspended solids in the WHO guidelines, national standards have typically fixed TSS concentrations at between 10 mg/L and 30 mg/L.

After in-depth reviewing of the epidemiological evidence linking disease transmission to irrigation with reclaimed water led to a third edition of the WHO-FAO-UNEP guidelines for the safe use of wastewater in agriculture (WHO, 2006). This edition benefited from scientific advances in microbiological risk assessment and drew on the Australian Water Reuse Regulations (NRMMC, 2006).

Rather than relying on water quality thresholds, as was the case with the 1973 and 1989 editions, the revised 2006 WHO-FAO-UNEP guidelines adopt a comprehensive risk assessment and risk management framework. This risk assessment framework identifies and distinguishes different vulnerable communities (e.g. agricultural workers, consumers, and members of communities where wastewater-fed agriculture is practised), and considers the trade-offs between potential risks and nutritional benefits in a wider development context. Accordingly, the WHO-FAO-UNEP approach recognizes that conventional wastewater treatment may not always be feasible, particularly in resource-constrained settings, and offers alternative (multi-barrier) measures that can reduce the health risks, in particular for consumers of wastewater irrigated crops.

The performance targets developed by WHO-FAO-UNEP in 2006 for unrestricted and restricted irrigation provide adequate health protection, and attain the health-based target of ≤10^{-6} DALY

Disability adjusted life year) per person per year. This tolerable health risk can be achieved through various options and combinations of treatment, irrigation methods, low- and high-rate growing crops, types of crop, and additional health protection barriers such as natural die-off, product washing, peeling or cooking, and so on. For example, the microbial concentration levels for verification monitoring recommended for unrestricted irrigation of food crops (Table 3.2) vary from 10 *E. coli*/100 mL (treatment only) to 10 000 *E. coli*/100 mL (drip irrigation of high-growing crops).

However, the increased complexity of the 2006 edition, with its emphasis on quantitative microbial risk assessment (QMRA) to determine local health-based targets, has limited its widespread adoption, as it was not the case with the previous 1989 edition (Scott *et al.*, 2010; Drechsel, Qadir & Galibourg, 2022). To provide assistance with implementation, WHO has developed a step-by-step health risk-based Sanitation Safety Planning approach for managing and monitoring sanitation systems (WHO, 2022).

In addition to risks from pathogen contamination, wastewater may contain chemical contaminants from industrial discharge or stormwater runoff. The 2006 WHO-FAO-UNEP guidelines provide maximum tolerable soil concentrations of various toxic chemicals based on human exposure through the food chain. With regard to irrigation water quality, WHO refers to the FAO guidelines, which focus on plant growth requirements and limitations (Ayers & Westcot, 1985; Pescod, 1992) through the food supply chain.

3.3.2. FAO guidelines

The most commonly cited FAO health protection recommendations were developed on the basis of the WHO 1989 guidelines (Pescod, 1992), and took into account the epidemiologic studies. Depending on the risk of contact, three water quality categories were defined: (A) Irrigation of crops likely to be eaten uncooked, sports fields and public parks; (B) Irrigation of cereal crops, industrial crops, fodder crops, pasture and trees; and (C) localized irrigation. Faecal coliforms were used as a microbial indicator only for category A (≤1 000 FC/100 mL, Table 3.2), where helminth eggs were introduced for the irrigation of pastures, fodder, cereals and orchards. These guidelines were indirectly superseded when FAO, as part of UN-Water, adopted the WHO (2006) guidelines as the official position of the United Nations.

General physico-chemical parameters (suspended solids, biological oxygen demand BOD, etc.) were not specified in the FAO guidelines, but agronomic parameters and trace elements that could have adverse impacts on crops and soils were well defined and used as a basic reference worldwide (Ayers & Westcot, 1985; Pescod, 1992).

The parameters of agronomic significance (see Table 3.1) include a number of specific properties of water that are relevant to the yield and quality of crops and the maintenance of soil productivity, as well as protection of the environment and irrigation systems. As emphasized by Pescod (1992), the FAO water quality classifications are only indicative guidelines and their application must be adjusted to local conditions. In fact, the suitability of water for irrigation depends greatly on the climatic conditions, the physical and chemical properties of the soil, the salt tolerance of the crop grown and the management practices. The quality of irrigation water is of particular importance in arid zones where extremes of temperature and low relative humidity result in high rates of evaporation with consequent deposition of salt, which tends to accumulate in the soil profile.

As shown in Table 3.3, the FAO classification for irrigation water includes three groups of potential crop yield problems based on salinity, sodicity, toxicity and miscellaneous hazards: no impact, slight to moderate impact and severe impact (Ayers & Westcot, 1985).

The most important agronomic parameter is the salinity of irrigation water, expressed either as total dissolved solids (TDS, mg/L) or as electrical conductivity (ECw), and measured in dS/m (Table 3.3). In general, TDS over 2 000 mg/L or conductivity higher than 3 dS/m could represent a significant quality problem for irrigation. In fact, dissolved salts increase the osmotic pressure of soil water and, consequently, lead to an increase of the energy which plants must expend to take up water from the soil. As a result, respiration is increased and the growth and yield of most plants decline progressively as osmotic pressure increases.

Compared to 1985 (Ayers & Westcot, 1985), in 1992 FAO slightly increased the maximum threshold limit for salinity from 2.7 dS/cm to 3.0 dS/cm (Pescod, 1992). On the basis of research and practical observations, the classification of saline water has been reconsidered, with the maximum threshold value increasing from >3 mS/cm to >6 mS/cm (Rhoades *et al.*, 1992; Lazarova & Bahri, 2005). FAO has since produced the updated salt tolerance value for major crops in FAO Irrigation and Drainage

Table 3.3. FAO guidelines for parameters with agronomic significance for agricultural irrigation

	Parameter			Pescod, 1992; Ayers & Westcot, 1985		
				No impact	**Slight to moderate impact**	**Severe impact**
Impact on crop growth	**Salinity**					
	Electrical conductivity, ECw dS/m			<0.7 (<1.0)	0.7 (1.0) to 3.0 (2.7)	>3.0 (>2.7)
	Total dissolved solids, TDS, mg/L			<450	450 to 2 000	>2 000
	Sodicity – effect of sodium ions expressed by SAR* versus ECw					
Impact on infiltration rate	SAR	0 to 3	ECw	>0.7	0.7 to 0.2	<0.2
		3 to 6		>1.2	1.2 to 0.3	<0.3
		6 to 12		>1.9	1.9 to 0.5	<0.5
		12 to 20		>2.9	2.9 to 1.3	<1.3
		20 to 40		>5.0	5.0 to 1.9	<1.9
	Specific ion toxicity					
Impact on crop growth	Sodium Na+, surface irrigation sprinkler irrigation			SAR <3 <3 meq/L	SAR 3 to 9 >3 meq/L = 69 mg/L	SAR >9
	Chloride Cl^-, surface irrigation sprinkler irrigation			<4 meq/L = 113 mg/L <3 meq/L	4 to 10 meq/L (to 15) >3 meq/L = 85 mg/L	>10 meq/L = 282 mg/L (>15)
	Boron			<0.7 mg/L (<1)	0.7 (<1) to 3.0 mg/L	> 3.0 mg/L
	Trace elements, maximum concentration, mg/L Cd, Mo – 0.01 ; Se – 0.02; Co – 0.05; As, Be, Cr, V – 0.1; Cu, Mn, Ni – 0.2; F – 1.0; Zn – 2.0; Li – 2.5; Al, Fe, Pb – 5.0					
Miscellaneous effects	Nitrogen, mgN/L			<5	5 to 30	>30
	Bicarbonates HCO_3^-, meq/L			<1.5 = 91.5 mg/L	1.5 to 8.5 (7.5)	>8.5 = 519 mg/L (>7.5 = 456 mg/L)
	pH				6.5 to 8.0	
	Parameters related to **clogging potential** in drip irrigation					
Clogging of drippers	Suspended solids, mg/L			<50	50 to 100	>100
	Dissolved solids, mg/L			<500	500 to 2 000	>2 000
	Manganese Mn, mg/L			<0.1	0.1 to 1.5	>1.5
	Iron Fe, mg/L			<0.1	0.1 to 1.5	>1.5
	Hydrogen sulphide H_2S, mg/L			<0.5	0.5 to 2.0	>2.0
	Bacterial count, number/mL			<10 000	10 000 to 50 000	>50 000

*SAR – sodium adsorption ratio, which reflects the amount of sodium relative to calcium and magnesium, expressed in meq/L

Source: Authors' own elaboration.

Paper 61 on agricultural drainage water management in arid and semi-arid areas (FAO, 2002) as well as in the FAO AquaCrop model (2017) that accommodated the yield response of herbaceous crops to water and is particularly well suited to conditions in which water and salinity are limiting factors. It is important to emphasize that FAO and some national water reuse guidelines and regulations provide lists of crops classifications according to their tolerance and sensitivity to salinity. Salt tolerance also depends on the type, method and frequency of irrigation (see Chapter 5).

It is important to emphasize that FAO and some national water reuse guidelines and regulations provide lists of crops classifications according to their tolerance and sensitivity to salinity. Salt tolerance also depends on the type, method and frequency of irrigation (see Chapter 5). Sodium is a unique cation because of its effect on soil properties. When present in the soil in exchangeable form, sodium causes adverse physical-chemical changes, particularly to soil structure, which results in the dispersion of particles and, consequently, in reduced infiltration rates of water and air into the soil. The most reliable index of the sodium hazard of irrigation water is the sodium adsorption ratio (SAR). A threshold value of SAR of less than 3 indicates no restriction on the use of recycled water for irrigation, while severe damage could be observed when the SAR exceeds 9, in particular for surface irrigation. At a given SAR, the infiltration rate decreases when salinity increases. Therefore, SAR and ECw should be used in combination to evaluate the potential adverse impact (see Chapter 5).

Many ions which are harmless or even beneficial at relatively low concentrations may become toxic to plants at high concentrations. This effect may be a consequence of direct interference with the metabolic processes or indirect effects on other nutrients, which might be rendered unavailable. Toxicity normally results in impaired growth, reduced yield, changes in the morphology of the plant and even its death (see Chapter 5). The most common phytotoxic ions that may be present in municipal effluents in concentrations high enough to cause toxicity are boron (B), chloride (Cl) and sodium (Na). Each can cause damage individually or in combination. Boron can become toxic at levels only slightly greater than those required by plants for good growth. Specific lists of crops tolerance and sensitivity to these three toxic ions are provided by FAO (Ayers & Westcot, 1985) and other publications (see Chapter 5).

In addition to sodium, chloride and boron, many trace elements are toxic to plants at low concentrations. Trace elements are not normally included in routine analysis of regular irrigation water, but attention should be paid to them when using treated municipal effluents, particularly if contamination with industrial wastewater discharges is suspected. These include (Table 3) aluminum (Al), beryllium (Be), cobalt (Co), fluoride (F), iron (Fe), lithium (Li), manganese (Mn), molybdenum (Mo), selenium (Se), tin (Sn), titanium (Ti), tungsten (W) and vanadium (V). Heavy metals include also a special group of trace elements that have been shown to create definite health hazards when taken up by plants, as for example arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg) and zinc (Zn). According to the recommendations of the US National Academy of Sciences (Asano *et al.*, 2007), distinction is made between permanent irrigation of all soils with low maximum concentration levels, and up to 20 years irrigation of fine-textured neutral to alkaline soil, where higher concentrations of trace elements can be tolerated.

In addition to adverse effects on crops and soil properties, reclaimed water quality could lead to a number of technical constraints, such for example clogging of localized irrigation, e.g. drippers and sprinkler noses. Table 3 illustrates also the FAO water quality requirements to prevent clogging in localized irrigation systems (Pescod, 1992). High content of suspended solids, iron, manganese and bacterial growth are the most common water quality parameters inducing emitter clogging.

In recent years, FAO started collaborating with the U.S. Food and Drug Administration on the application of Whole-Genome-Sequencing (WGS) to study pathogens and track their path from water to food in order to prevent food contamination at its source. By incorporating water quality into food safety considerations and applying genomic surveillance to this process, WGS is enabling countries to address water and food quality as an integrated issue. The approach allows to improve supply chain controls and to support more efficient and safe food production . It also allows to monitor water quality forearly pathogen detection . The COVID-19 pandemic made the world realize the critical role WGS has in environmental monitoring .

3.3.3. United States Environmental Protection Agency (USEPA) guidelines

The revised 2012 USEPA guidelines follow three earlier editions (1980, 1992, 2004) and were developed in collaboration with the United States Agency for International Development (USAID). They aim to make the water reuse process easier to implement, based on information drawn from databases in different states and global experience. Recent innovations in treatment technologies, best practices and public outreach strategies are presented and illustrated in chapter 9 with a number of case studies from around the world. The 2012 edition maintains the highly stringent requirements for microbial parameters (e.g. no detectable faecal coliforms in 100 mL) and the high level of treatment, which includes secondary treatment, filtration and disinfection for food crops irrigation (see Table 3.2). The USEPA reuse guidelines are intended to be used as Federal recommendations for water reuse criteria, but states have the authority to develop even more stringent criteria (but not lesser than Federal guidelines).

3.3.4. California Water Recycling Criteria

The State of California has been a leader in the development of comprehensive water reuse regulations, with the California Department of Health Services revising its criteria most recently in 2000 (State of California, 2000). California's Water Recycling Criteria, also known as the Title 22 Water Reuse Criteria, provide a very comprehensive set of water quality and other requirements, and have served as the basis for similar criteria in other states and countries. These criteria have been considered as among the most stringent and restrictive of their type, but have also been recommended for their very comprehensive and easy-to-implement approach. Similar to the USEPA guidelines, the state criteria require a high level of disinfection for almost total coliform inactivation (<2.2 TC/100 mL, Table 3.2) for unrestricted food crop irrigation. In this case, total coliforms are used as the principal microbial indicator, and are considered as conservative compared to faecal coliforms and *E. coli*. In addition, a specific treatment process is required for the production of high-quality recycled water that includes – after conventional secondary treatment – at a minimum filtration and disinfection at levels that meet state process requirements.

The California Water Recycling Criteria also include conservative requirements for water quality monitoring, treatment train design and process operation. For example, the turbidity requirements for Title 22 treatment (conventional tertiary treatment with disinfection) state that turbidity should be less than 2 NTU (max 5 NTU), and if membranes are used, the turbidity cannot exceed 0.2 NTU more than 5 percent of the time within a 24-hour period or exceed 0.5 NTU at any time.

In California, specific laws and regulations mandate water reuse under certain conditions (State of California, 1998). For example, Section 13550 of the California Water Code states that the use of potable domestic water for non-potable uses, including, but not limited to, cemeteries, golf courses, highway landscaped areas, and industrial and irrigation uses, is considered a waste or an unreasonable use of the water if reclaimed water is available that meets certain conditions (i.e. adequate quality, reasonable cost, and no adverse effect on public health and environment).

3.3.5. Australian Regulation for Water Recycling

In 2006, the Australian Environment Protection and Heritage Council in conjunction with the Natural Resource Management Ministerial Council issued the "Australian Guidelines for Water Recycling: Managing Health and Environmental Risks" (NRMMC, 2006). Developed on the basis of existing state regulations designed to address water crises and improve the management of health and environmental risks, these guidelines cover a broad range of applications, including agricultural and landscape irrigation, urban uses, managed aquifer discharge, and stormwater harvesting and recycling. They include a comprehensive risk assessment developed for health and environmental risks using DALYs for human risks, as explained previously for the WHO guidelines (2006).
In principle, the guidelines recommend qualitative microbial risk assessment, although for some pathogens or contaminants, it may be possible to carry out a quantitative microbial risk assessment, in order to provide a numerical estimate of risks. This risk assessment approach consists of the following steps: (i) define a tolerable maximum additional burden of disease, (ii) derive tolerable risks of disease and infection, (iii) determine the required pathogen reduction to ensure that the tolerable disease and infection risks are not exceeded, (iv) determine how the required pathogen reductions can be achieved, and (v) put in place a system for verification monitoring. Preventive measures are recommended to lower the identified risks to acceptable levels.

As with the USEPA and California water quality requirements, a very high level of disinfection is required for almost total coliform removal (<1 *E. coli*/100 mL for irrigation of food crops consumed raw; see Table 3.2). The threshold limits for commercial food crops vary from <100 to <1 000 *E. coli*/100 mL depending on the treatment train). In addition, verification monitoring is proposed to demonstrate adequate log removal of not only bacteria, but also viruses and protozoa (defined by means of the microbial health risk assessment). Risk assessment and monitoring requirements are highly restrictive and conservative compared to other regulations. Chemical and agronomic parameters are also included.

3.3.6. ISO Standards on water reuse

In 2015, the first ISO standard on water reuse for irrigation was issued in three parts covering the main steps of project development (ISO 16075-1 to 3, 2015). Part 1 contains guidelines for the development and the execution of projects intending to use treated wastewater for irrigation taking into consideration the parameters of climate and soil. Part 2 is focused mostly on wastewater treatment and water quality, while Part 3 is providing comprehensive recommendations for the management of distribution system and irrigation material. Part 4 was published a year later and is covering water quality and soil and aquifer monitoring to mitigate health and environmental risks (ISO 16075-4). WHO (2006) and the State of California Water Recycling Regulations (2000) were used as the basic reference points for the development of this standard.

ISO defined five categories of water quality for irrigation of which category A requires almost total disinfection (≤10 *E. coli*/100 mL, Table 2) for irrigation of crops consumed raw. The recommended treatment to achieve this quality is the conventional combination of secondary treatment, filtration and disinfection. In 2020, the second edition of ISO 16075-2 broadened the options available for risk reduction to include different barriers from farm to fork based on WHO (2006) and USEPA (2012).

In 2018, ISO issued a comprehensive guideline on health risk assessment for non-potable reuse, including agricultural irrigation, based on qualitative health risk assessment (ISO 20426).

3.3.7. European Commission Water Reuse Regulation

The Water Reuse Regulations of the European Commission were published in 2020 to harmonize minimum water quality and monitoring requirements for the safe reuse of treated urban wastewaters in agricultural irrigation (EU regulation 2020/741). Risk management provisions are included to assess and address potential health and environmental risks, as well as permit requirements. The regulation defined four categories of water quality on the basis of existing guidelines and regulations of member states and leading international standards (Australia, ISO, WHO). For the highest reclaimed water quality, cat. A, which is used for the irrigation of all food crops consumed raw and all irrigation methods, a restrictive threshold is required of ≤10 *E. coli*/100 mL or under the detection limit (see Table 3.2). A relatively conservative threshold is also required for cat. B of ≤100 *E. coli*/100 mL for the irrigation of food crops consumed raw, where the edible part is produced above ground and is not in direct contact with reclaimed water, processed food crops and non-food crops, including those used to feed milk- or meat-producing animals. Cat. C is used for the same applications, but in the case of drip irrigation higher concentration is authorized of ≤1 000 *E. coli*/100 mL. In addition, verification of the log removal of bacteria, viruses and protozoa is required for cat. A, the most stringent category. While the guideline is referencing the multi-barrier approach supported by WHO (2006) and ISO 16075-2 (2020), its recommendation focus is on barriers to achieve the EU water quality threshold, not like WHO (2006) on health-based targets.

3.4. Conclusion

The development and enforcement of water reuse standards is an essential step in the social acceptance of water recycling. However, in some cases, regulations could represent a challenge and a burden for water reuse, as for example in the case of very restrictive requirements based on the precautionary principle. For example, health risk-based regulations for irrigation, such as those developed in Australia and used as the basis for the new European regulations, require an additional health risk assessment (qualitative or Quantitative Microbial Risk Assessment, QMRA) and validation of log removal of treatment technologies, in addition to water quality monitoring. These new requirements lead to significantly higher permit and operation costs, without any guarantee of lower health risks or better process reliability. A recent review performed by leading experts (Olivieri *et al.*, 2014) demonstrated that agricultural water reuse following the treatment-based approach used for years in the United States, in particular in California, do not increase public health risks and that modifying the standards to make them more restrictive will not improve public health.

Water reuse standards must be adapted to the country's specific conditions (administrative infrastructure, economy, climate, etc.), and should be economically viable and coordinated with the country's water conservation strategy. Regulated and well-managed irrigation under WHO guidelines (or similar standards) can protect public health and the health of farm workers at affordable cost. While the WHO (2006) supported multi-barrier approach is increasingly accepted, like in the 2020 versions of the ISO and EU guidelines, water quality targets continue to have priority where they can be achieved, compared to the broader concept of the WHO (2006) supported health-based targets.

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