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An assessment of microbiological quality criteria for reuse of treated wastewater in agricultural irrigation

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ABSTRACT

The reuse of treated wastewater is considered necessary but also effective solution in water-scarce areas of the world for the confrontation of increased water demand due to increasing population and per capita consumption. The application of treated wastewater reuse presupposes right planning based on the protection of public health and environment according to enacted specifications of wastewater treatment plant effluent quality and also gaining public acceptance. The guidelines in the USA vary from state to state. The guidelines of the State of California set more stringent criteria than those of WHO, but they are not the strictest in the world. In European level does not exist legislative regulation with regard to the reuse of treated wastewater and each country applies national or even regional directives. Therefore, it is necessary for European Union countries to legislate a directive for the encouragement but also the safe application of wastewater reuse programs. In this work, the main worldwide regulatory status for microbiological quality criteria is presented, that is applied in programs for wastewater reuse in agricultural irrigation.

Keywords: Wastewater; Reclamation; Reuse; Microbial quality; Agriculture

1. Introduction

The last fifty years the water demand has increased considerably. Growing urbanization in water-scarce areas of the world intensifies the increasing water demands for domestic, commercial, industrial and agricultural purposes. Also, climatic changes intensify the necessity to utilize new water resources. For more than a quarter century, the environmental engineering thesis for treated wastewater influence is that it should not be wasted into streams, lakes and seas to reduce pollution of surface water and groundwater but put to beneficial use as a water resource for beneficial purposes. So, water reuse is an alternative, effective and growing practice. In the USA the states of Florida, California, Texas and Arizona account for the majority of the water reuse. Several other states (Nevada, Colorado, Washington, etc.) have growing water reuse programs and regulations dealing with water reuse. But also in other countries in the world, such as Japan, Australia, Latin America, Sub-Saharan Africa, the Middle-East, the Mediterranean and the European Union countries there are many projects of wastewater reuse, mainly for agricultural use [1,2].

The term "wastewater reuse" is often used synonymously with the terms "wastewater recycling" and "wastewater reclamation", but they are three different terms. Wastewater or water reuse is the beneficial use of treated water. The Environmental Protection Agency of the United States (US-EPA) defines waste water reuse as "using wastewater or reclaimed water from one ap-

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plication for another application". Wastewater or water recycling is the use of wastewater that is captured and redirect back into the same water use scheme. Wastewater reclamation involves the treatment or processing of wastewater to make it reusable [2–6]. The most common reasons for establishing a wastewater reuse program is to utilize new water resources to satisfy the increasing water demands and to attain this target with the lowest cost possible and moreover to protect the population and the environment. Water reuse applications consist of seven categories, such as agricultural irrigation, landscape irrigation, industrial activities, groundwater recharge, recreational and environmental uses, non-potable urban uses and potable reuse, which is a water reuse challenge. Agricultural irrigation represents the largest current use of reclaimed water in the world and it offers significant future opportunities for water reuse in both industrialized countries and developing countries. It separates to agricultural reuse on food crops (not commercially processed and commercially processed food crops) and agricultural reuse on non-food crops (pasture for milking animals and fodder, fiber and seed crops) [7]. Most countries where wastewater irrigation is practiced have public health regulations to protect both the agricultural workers and the irrigated crops consumers. Epidemiological studies of untreated wastewater reuse concluded that the danger of infection was: high with intestinal nematodes; moderate with bacterial infections and diarrheas; minimal with viral infections and diarrheas, and hepatitis A; and high to nonexistent with trematode and cestode infections, schistosomiasis, clonorchiasis, and taeniasis, depending on local practices and circumstances [8].The World Health Organization (WHO) guidelines of 1989 were based on a number of available epidemiological studies [9]. In 2002, a critical review of epidemiological evidence on the health effects of wastewater and excreta use in agriculture for WHO were completed A summary of the results of this epidemiological review are presented in Table 1 [10–12]. In this work, the main worldwide regulatory status for microbiological quality criteria is presented, that is applied in programs for wastewater reuse in agricultural irrigation.

2. The regulation status for wastewater reuse in agricultural irrigation

There is not a common regulation of wastewater reuse in the world due to the various climatic, geological and geographical conditions, the water resources, the type of crops and soils, the economic and social aspects and the country policies towards using wastewater treatment plants effluents for irrigation purposes. Most countries where wastewater agricultural irrigation is practiced have public health regulations to protect the agricultural

Table 1
Summary of health risks associated with the use of wastewater in irrigation [10–12]

Group exposed	Nematode infection	Bacteria/viruses	Protozoa
Consumers	Significant risks of *Ascaris* infection for both adults and children with untreated wastewater; no excess risk when wastewater treated to < 1 nematode egg/l except where conditions favour survival of eggs.	Cholera, typhoid and shigellosis outbreaks reported from use of untreated wastewater, sero-positive responses for *Helicobacter pylort* (untreated); increase in non-specific diarrhoea when water quality exceeds 104 FC/100 ml.	Evidence of parasitic protozoa found on wastewater. Irrigated vegetable surfaces but no direct evidence of disease transmission.
Farm workers and their families	Significant risks of *Ascaris* infection for both adults and children with contact with untreated wastewater, risks remain, especially for children when wastewater treated to < 1 nematode egg/l. Increased risk of hookworm infection to workers.	Increased risk of diarrhoeal disease in young children with wastewater contact if water quality exceeds 104 FC/100 ml: elevated risk of salmonella infection in children exposed to untreated water, elevated seroresponse to *Norovirus* in adults exposed to partially treated wastewater.	Risk of *Giardia intestinallis* infection was significant for contact with both untreated and treated wastewater, increased risk of amoebiasis observed from contact with untreated wastewater.
Nearby communities	Ascaris transmission not studied for sprinkler irrigation but same as above for flood or furrow irrigation with heavy contact.	Sprinkler irrigation with poor quality water 104 TC/100 ml, and high aerosol exposure associated with increased rates of viral infection; use of partially treated water 104 FC/100 ml or less in sprinkler irrigation not associated with increased viral infection.	No data for transmission of protozoan infections during sprinkler irrigation with wastewater.

workers, the populations living near irrigated fields and the irrigated crops consumers. Some countries and organizations have established reuse standards such as the State of California, the US-EPA and the WHO. Most of the developing countries and many European countries have adopted their own standards based on the standards referred above. There is not any common regulation of wastewater reuse at European level up today, except the Directive 91/271/EEC concerning urban wastewater treatment, where it is referred that treated wastewater shall be reused whenever appropriate. Also, in the Directive 60/2000/EE it is mentioned the necessity of exploitation of wastewater treatment plants effluents [13,14]. The first regulation on wastewater reuse for irrigation was developed in 1918 by the California State Health Department and it is considered as the most comprehensive one in regards to public health. Since 1960, the State of California has promoted wastewater reuse by drafting regulations and promoting research for irrigation, industrial and municipal reuse, groundwater recharge and potable reuse. In 2000, the State of California revised the Water Recycling Criteria (Title 22 regulations) (Table 2) [15,16].

In 1992 (and initially in 1980), the US-EPA developed the guidelines for water reuse, a comprehensive technical document, which has been revised recently (US-EPA 2004). These guidelines include a summary of state reuse requirements, recommended treatment processes, reclaimed water quality limits, monitoring frequencies, setback distances and other controls for various water reuse applications (Table 3). However, the guidelines in USA vary from state to state. States such as Arizona, California, Florida, Hawaii, Nevada, Texas and Washington have developed guidelines which provide successful reuse programs and long-term experience (Table 4 and Table 5). Treatment requirements range from secondary treatment and disinfection (state of Nevada) for irrigation of food crops to tertiary treatment and disinfection (states of Arizona, California, Florida, Hawaii and Washington). The agricultural use of reclaimed water for irrigation of non-food crops requires less stringent treatment and water quality limits than the reuse of food crops, as the prospect of human exposure to the water is reduced. In most of the states secondary treatment and disinfection is required, while the state of Hawaii requires something more, filtration [5].

The World Health Organization (WHO) published guidelines for wastewater reuse, which are mainly based on a number of available epidemiological studies and focused on the needs of developing countries. In 1989, the main features of the WHO guidelines for wastewater reuse in agriculture were the wastewater quality and treatment goals, the restrictions on crops to be irrigated with wastewater ("restricted irrigation", which excludes salad crops and vegetables eaten uncooked and "unrestricted irrigation", which includes such crops), the selection of irrigation methods providing increased health protection, and the protection of exposed populations (consumers, farm workers, populations living near irrigated fields) against excess infection (Table 6) [9].

In 2006, these guidelines were revised. In the WHO 2006 guidelines for restricted and unrestricted irrigation there are health-based targets which are based on a standard metric, disability adjusted life years (DALYs) (Table 7). DALYs are a measure of the health of a population or burden of disease due to a specific disease or risk factor. DALYs attempt to measure the time lost because of disability or death from a disease compared with a long life free of disability in the absence of the disease. Fur-

Table 2
California water recycling criteria [16]

Category of reclaimed water	Total coliform MPN/100 ml	Turbidity, NTU	Suitable uses
Disinfected tertiary[a]	<2.2	2 average 5 maximum	All water uses that are not for potable use or food preparation.
Disinfected secondary-2.2	<2.2	na[d]	All uses except irrigation of parks and playgrounds,[b] food crops coming in contact with reclaimed water, nonrestricted impoundments
Disinfected secondary-23	<23	na[d]	Same restrictions as disinfected secondary-2.2, except no food crop irrigation, no nonrestricted impoundment, and no watering of yards
Undisinfected secondary[c]	na[d]	na[d]	Drip or surface irrigation of fodder, fiber, seed orchard, and tree crops and sugar beets (commercially processed food crops)

[a] Filtered through natural undisturbed soils or filter media,such as sand or diatomaceous earth.
[b] Urban areas such as parks, playgrounds, school yards, residential yards, and golf courses associated with residences.
[c] Undisinfected wastewater means wastewater in which the organic matter has been stabilized, is nonputrescible,and contains dissolved oxygen.
[d] na= not applicable

Table 3
EPA suggested guidelines for water reuse [5]

Agricultural reuse – food crops not commercially processed[12] Surface or spray irrigation of any food crop, including crops eaten raw	• Secondary[1] • Filtration[2] • Disinfection[3]	• pH = 6–9 • ≤ 10 mg/l BOD[4] • ≤ 2 NTU[5] • No detectable fecal coli/100 ml[6,7] • 1 mg/l Cl_2 residual (minimum)[8]	• pH – weekly • BOD – weekly • Turbidity – continuous • Coliform – daily • Cl_2 residual – continuous	• 50 ft (15 m) to potable water supply wells	• The reclaimed water should not contain measurable levels of viable pathogens[11] • A higher chlorine residual and/or a longer contact time may be necessary to assure that viruses and parasites are inactivated or destroyed. • High nutrient levels may adversely affect some crops during certain growth stages.
Agricultural reuse – food crops commercially processed[12] Surface irrigation of orchards and vineyards	• Secondary[1] • Disinfection[3]	• pH = 6–9 • ≤ 30 mg/l BOD[4] • ≤ 30 mg/l TSS • < 200 fecal • coli/100 ml [6,9,10] • 1 mg/l Cl_2 residual (minimum)[8]	• pH – weekly • BOD – weekly • TSS – daily • Coliform – daily • Cl_2 residual – continuous	• 300 ft (90 m) to potable water supply wells • 100 ft (30 m) to areas accessible to the public (if spray irrigation)	• If spray irrigation, TSS less than 30 mg/l may be necessary to avoid clogging of sprinkler heads. • High nutrient levels may adversely affect some crops during certain growth stages.
Agricultural reuse – non-food crops Pasture for milking animals; fodder, fiber and seed crops.	• Secondary[1] • Disinfection[3]	• pH = 6–9 • ≤ 30 mg/l BOD[4] • ≤ 30 mg/l TSS • < 200 fecal • coli/100 ml [6,9,10] • 1 mg/l Cl_2 residual (minimum)[8]	• pH – weekly • BOD – weekly • TSS – daily • Coliform – daily • Cl_2 residual – continuous	• 300 ft (90 m) to potable water supply wells • 100 ft (30 m) to areas accessible to the public (if spray irrigation)	• If spray irrigation, SS less than 30 mg/l may be necessary to avoid clogging of sprinkler heads. • High nutrient levels may adversely affect some crops during certain growth stages • Milking animals should be prohibited from grazing for 15 d after irrigation ceases. A higher level of disinfection, e.g., to achieve ≤ 14 fecal coli/100 ml, should be provided if this waiting period is not adhered to.

1. Secondary treatment processes include activated sludge processes, trickling filters, rotating biological contactors, and many stabilization pond systems. Secondary treatment should produce effluent in which both the BOD and SS do not exceed 30 mg/l.
2. Filtration means the passing of wastewater through natural undisturbed soils or filter media such as sand and/or anthracite.
3. Disinfection means the destruction, inactivation, or removal of pathogenic microorganisms by chemical, physical, or biological means. Disinfection may be accomplished by chlorination, ozonation, other chemical disinfectants, UV radiation, membrane processes, or other processes.
4. As determined from the 5 d BOD test.
5. The recommended turbidity limit should be met prior to disinfection. The average turbidity should be based on a 24 h time period. The turbidity should not exceed 5 NTU at any time. If SS is used in lieu of turbidity, the average SS should not exceed 5 mg/l.
6. Unless otherwise noted, recommended coliform limits are median values determined from the bacteriological results of the last 7 days for which analyses have been completed. Either the membrane filter or fermentation tube technique may be used.
7. The number of fecal coliform organisms should not exceed 14/100 ml in any sample.
8. Total chlorine residual after a minimum contact time for 30 min.
9. The number of fecal coliform organisms should not exceed 800/100 ml in any sample.
10. Some stabilization pond systems may be able to meet this coliform limit without disinfection.
11. It is advisable to fully characterize the microbiological quality of the reclaimed water prior to implementation of a reuse program.
12. Commercially processed food crops are those that, prior to sale to the public or others, have undergone chemical or physical processing sufficient to destroy pathogens.

Table 4
Guidelines for agriculture reuse; food crops of reclaimed water in states of the USA [5]

	Arizona	California	Florida	Hawaii	Nevada	Texas	Washington
Treatment	Secondary treatment, filtration and disinfection	Oxidized, coagulated, filtered and disinfected	Secondary treatment, filtration and high-level disinfection	Oxidized, filtered and disinfected	Secondary treatment and disinfection	NS[1]	Oxidized, coagulated, filtered and disinfected
BOD_5, mg/l	NS	NS	20 $CBOD_5$	NS	30	5	30
TSS, mg/l	NS	NS	5	NS	NS	NS	30
Turbidity, NTU	2 (avg) 5 (max)	2 (avg) 5 (max)	NS	2 (max)	NS	3	2 (avg) 5 (max)
Coliform per 100 ml	Fecal	Total	Fecal	Fecal	Fecal	Fecal	Total
	None detectable (avg)	2.2 (avg)	75% of samples below detection	2.2 (avg)	200 (avg)	20 (avg)	2.2. (avg)
	23 (max)	23 (max in 30 d)	25 (max)	23 (max in 30 d)	400 (max)	75 (max)	23 (max)

[1]NS – not specified by state regulations

Table 5
Guidelines for agriculture reuse; non-food crops of reclaimed water in states of the USA [5]

	Arizona	California	Florida	Hawaii	Nevada	Texas	Washington
Treatment	Secondary treatment and disinfection	Secondary-23, Oxidized and disinfected	Secondary treatment, basic disinfection	Oxidized, filtered and disinfected	Secondary treatment and disinfection	NS[1]	Oxidized and disinfected
BOD_5, mg/l	NS	NS	20 $CBOD_5$	NS	30	5	30
TSS, mg/l	NS	NS	20	NS	NS	NS	30
Turbidity, NTU	NS	NS	NS	2 (max)	NS	3	2 (avg) 5 (max)
Coliform per 100 ml	Fecal	Total	Fecal	Fecal	Fecal	Fecal	Total
	200 (avg)	23 (avg)	200 (avd)	2.2 (avg)	200 (avg)	20 (avg)	23 (avg)
	800 (max)	240 (max in 30 d)	800 (max)	23 (max in 30 d)	400 (max)	75 (max)	240 (max)

[1]NS – not specified by state regulations

thermore, in the WHO 2006 guidelines on the restricted irrigation, additional microbiological quality criteria are proposed to corresponding of the WHO 1989, which recommended only for human intestinal nematodes ≤ 1 egg/l and there was not any recommendation for the reduction of other pathogenic microorganisms or E. coli. More actually, in the WHO 2006 guidelines, the effluent quality is proposed to has a concentration of ≤ 10^4 E. coli per 100 mL for labour-intensive agriculture (developing countries), while for highly mechanized agriculture (industrialized countries) that of ≤ 10^5 E. coli per 100 mL. So, in unrestricted irrigation the microbiological criteria of quality are less stringent than those in the WHO 1989 guidelines. In the WHO 2006 guidelines the 6–7 log unit pathogen reduction can be achieved by treatment to a lower quality (≤ 10^4 E. coli per 100 mL, as in the case of restricted irrigation), but moreover supplemented by post-treatment health-protection control measures, such as post-harvest pathogen die-off, produce washing, produce disinfection, etc. (Table 8) [9,17].

In Table 9, the comparative microbiological quality criteria for agricultural irrigation reuse of the main worldwide regulatory status are presented.

Table 6
Guidelines for the use of treated wastewater in agriculture[a] [9]

Category	Reuse conditions	Exposed group	Intestinal nematode[b] (arithmetic mean no. egg/l)[c]	Faecal coliforms (geometric mean no. per 100 ml)[c]	Wastewater treatment expected to achieve the required microbiological guideline
A	Irrigation of crops likely to be eaten uncooked, sports fields, public parks[d]	Workers, consumers, public	≤1	≤1000	A series of stabilization ponds designed to achieve the microbiological quality indicated, or equivalent treatment
B	Irrigation of cereal crops, industrial crops, fodder crops, pasture and trees[e]	Workers	≤1	No standard recommended	Retention in stabilization ponds for 8-10 days or equivalent helminth and faecal coliform removal
C	Localized irrigation of crops in category B if exposure to workers and the public does not occur	None	Not applicable	Not applicable	Pretreatment as required by irrigation technology, but not less than primary sedimentation

[a] In specific cases, local epidemiological, sociocultural and environmental factors should be taken into account and the guide lines modified accordingly.
[b] *Ascaris* and *Trichuris* species and hookworms.
[c] During the irrigation period.
[d] A more stringent guideline (200 faecal coliforms per 100 ml) is appropriate for public lawns, such as hotel lawns, with which the public may cone into direct contact.
[e] In the case of fruit trees, irrigation should cease two weeks before fruit is picket, and no fruit should be picked off the ground. Sprinkler irrigation should be used.

Table 7
Health based targets for wastewater use in agriculture [17]

Exposure scenario	Health-based target (DALY per person per year)	$\log_{10}$ pathogen reduction needed [a]	Number of helminth eggs per liter
Unrestricted irrigation	≤10–6 [a]		
Lettuce		6	≤1 [b,c]
Onion		7	≤1 [b,c]
Restricted irrigation	≤10–6 [a]		
Highly mechanized		3	≤1 [b,c]
Labour intensive		4	≤1 [b,c]

[a] Rotavirus reduction. The health based target can be achieved, for unrestricted irrigation by a 6–7 log unit pathogen reduction (obtained by a combination of wastewater treatment and other post-treatment health-protection measures), for restricted irrigation it is achieved by a 2–3 log unit pathogen reduction.
[b] When children under 15 are exposed, additional health protection measures should be used(e.g. treatment to ≤ 0.1 egg/L, protective equipment such as gloves, shoes, etc.).
[c] The mean value of ≤ 1 egg/L should be obtained for at least 90% of samples.

Table 8
Pathogen reductions achievable by various post-treatment health-protection control measures [17]

Control measure	Pathogen reduction (log units)	Comments
Localized (drip) irrigation		
Low-growing crops	2	Root crops and crops that grow just above, but partially in contact with the soil (lettuce)
High-growing crops	4	Crops that the harvested parts are not in contact with the soil (tomatoes)
Pathogen die-off	0.5–2/d	Die-off on crop surfaces after irrigation and before consumption. The value depends on climate, time, crop, type, etc.
Produce washing with water	1	Washing salad crops, vegetables and fruit with clean water
Produce disinfection	2	Washing salad crops, vegetables and fruit with a weak disinfectant solution and rinsing with clean water
Produce peeling	2	Fruits, root crops
Produce cooking	6–7	Immersion in boiling or close-to-boiling water until the food is cooked ensures pathogen destruction.

Table 9
Microbiological quality criteria for agricultural irrigation reuse [5,16,17]

Guidelines	Types of reuse	Treatment requirements	Reclaimed water quality	Comments
California (2000)	Spray, drip or surface irrigation of all food crops	Tertiary disinfection (1)	< 2.2 total coliforms (TC)/100 mL	(1) Filtered through natural undisturbed soils or filter media
	Spray, drip or surface irrigation of no food crops	Secondary-23 disinfection	< 23 TC/100 mL	
US-EPA (2004)	Surface or spray irrigation of any food crop	Secondary filtration disinfection (2)	No detectable fecal coliform (FC)/100mL	(2) In most of the states except the states of California and Washington (coagulation in addition) and the state of Nevada (secondary and disinfection only)
	Surface irrigation of food crops commercially processed	Secondary disinfection	<200 FC/100 mL	
	Non food crops irrigation	Secondary disinfection(3)	<200 FC/100 mL	(3) In most of the states except the state of Hawaii, which moreover requires filtration
WHO (2006)	Restricted irrigation (no food crops)	A series of stabilization ponds designed to achieve the microbiological quality indicated or equivalent treatment	≤10^4 E. coli /100 mL(4) ≤10^5 E. coli /100 mL(5)	(4) Labour-intensive agriculture (5) Mechanical agriculture
	Unrestricted irrigation (all food crops)	Identical as the previous case, plus post-treatment health-protection control measure (6)	6–7 log unit pathogen reduction	(6) Table 8

3. Conclusions

The guidelines in the USA vary from state to state. In some states of the USA and countries of South Africa agricultural reuse for irrigation of food crops is prohibited, but in others it is allowed only with the limitation that the crop will be processed and not eaten raw. The guidelines of the state of California set more stringent criteria than those of WHO, but they are not the strictest in the world. The WHO 2006 guidelines set more stringent requirements for wastewater treatment than those in the WHO 1989 for restricted irrigation reuse, while for unrestricted irrigation they are less stringent, since the treatment level is the same as for restricted irrigation, but supplemented by post-treatment health-protection control measures. So, a very important outcome is extracted from the WHO 2006 guidelines. The treatment requirements for restricted and unrestricted irrigation would be identical, that means treatment cost for unrestricted irrigation is lower and thus this treatment level is more probable to be feasible and practicable. Also, the WHO 2006 guidelines introduce the concept of DALYs for health-based targets which define a level of health protection that is relevant to each hazard. A value for the additional disease burden ≤ 10–6 DALY loss per person per year (pppy) is recommended for the safe wastewater reuse in agricultural irrigation. In European level does not exist legislative regulation with regard to the reuse of treated wastewater and each country applies national or even regional directives. Therefore, it is necessary for European Union countries to legislate a directive that would be based on the standards referred above for the encouragement but also the safe application of wastewater reuse programs.

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