The Use of Wastewater in the Irrigation of Agricultural Soils and its Contamination Effect by Trace Elements: A Review

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Abstract

Wastewater reuse (either raw or treated) for irrigation of crops is a common widespread practice around the world. This water provides the soil with many nutrient elements. However, it also results to organic and metallic contaminants. This may have a significant effect on the physico-chemical characteristics of the soil and the crops contamination. It is a fact that constitutes a huge risk which is both sanitary and environmental. This paper focuses on explaining the effect of the use of wastewater in the irrigation of the agricultural soils and crops and their contamination by trace elements.

Keywords: Wastewater, trace elements, soil, irrigation

Introduction

Water demand is remarkably increasing in many countries around the world for various reasons like the growth of populations, the economy's prosperity, and the improvement of living standards. One of the most demanding fields, however, is agriculture, since it makes use of 67% of total water withdrawal which represents 86% of water consumption in 2000 as reported by UNEP (2005). According to the Food and Agriculture Organization, 277 million hectares of lands are irrigated out of 1.4 billion hectares of arable ones, which provides one-third of the world's food production (Gurel, 2007).

Using wastewater for irrigation is a considerably widespread practice in developing countries (Raschid-Sally et al., 2005; Scott et al., 2004). This can be explained particularly in terms of the demographic growth. Hence, this can also be seen due to an increase in water consumption per capita that leads consequently to a high quantity of wastewater production in both urban and rural areas. On the other hand, the high demand for food shows the need for a reliable irrigation practice to maintain or enhance the rate of food production, especially in the warm climate regions. 80% out of the 53 studied towns in Africa, Asia, South America and Middle East use the untreated wastewater or the partially treated one for irrigation (Raschid-Sally et al., 2009).

The reuse of wastewater (either raw or treated) in agriculture is a means to fix the growing problem of water scarcity in many arid and semi-arid countries and to face the climate change at a global scale. Despite the fact that it represents an important low-cost source of water compared to other sources (Bahri, 1999), it constitutes of a regular and permanent irrigation water source (Murtaza et al., 2008). This phenomenon is also expanding in many countries with the temperate climate like Japan, Australia, Canada, Belgium, England, and Germany (Gurel, 2007).

According to an investigation made in 2001, the total surface of irrigated lands by wastewater, either the treated or the partially treated ones, was estimated to be around 20 million hectares (Hamilton et al., 2007). As far as wastewater irrigation expansion is concerned, the recently obtained estimates (Thebo et al., 2017) demonstrates that the scale of the practice is at least 50% larger than previous, highly uncertain estimates. Thus, the result shows that 10% of the world's population consumed food produced in lands irrigated with wastewater during the early 90's (Smit & Nasr, 1992).

The use of wastewater in irrigation is more and more regarded due to the lower cost technical solutions for decreasing soils degradation, and also for intoducing new nutrient elements into the soil (Kiziloglu et al., 2008; Yadav et al., 2002; Xiong et al., 2001).

Consistence of Trace Elements in Wastewater

One of the major problems that both the developed and the developing countries are suffering from is water pollution which is caused by the pollution of wastewater by trace elements pollutants. Urban effluents always consist of the trace elements (Smith et al., 1996; Pescod, 1992). These trace elements have very high quantity that is largely superior to what potable water, rivers water, or sea water are supposed to contain (Juste et al., 1995). The most abundant ones are cadmium (Cd), copper (Cu), molybdenum (Mo), nickel (Ni), and zinc (Zn), which are all dangerous to the health of humans and animals; in addition, it can also affect, in the long-term, the irrigated crops due to their accumulation in the soil (Hamilton et al., 2007).

Trace elements content in wastewater differs from one another depending on its origin and the nature of urban activities (Smith et al., 1996; Rattan et al., 2005). Generally, the trace elements in commercial and industrial wastewater is much more superior than that noticed in the domestic one (Smith et al., 1996; Juste et al., 1995).

The Effects of Wastewater Irrigation on Soils Agronomic Properties

It is quite obvious that the quality of the soil depends on their intrinsic characteristics, the geo-chemical and climatic environment, and man's use (Arshad & Coen, 1992). As a result, the quality of the irrigating water frequently used affects the physico-chemical properties of the soil.

pH

Almost all authors agree that soils pH depends on wastewater pH used for irrigation (Khan et al., 2008; Yadav et al., 2002; Kiziloglu et al., 2008; Qichlaqi et al., 2008). Many authors noticed that there is a decrease in the pH of the soil after being irrigated with wastewater (Chary et al., 2008; Rattan et al., 2005; Shahalam et al., 1998; Solis et al., 2005) (Table 1**)**. Rattan et al. (2005) registered a significant decline of 0,4 units, while Shahalam et al. (1998) and Kiziloglu et al. (2008) registered a decline of 0,6 units. Furthermore, using a slightly acid water for irrigation would not have any significant effect on the variation of soils pH (Khan et al., 2008; Sinha et al., 2006). The pH decrease may be caused, on the one hand, by a release of exchangeable cations during a process of an organic material mineralization brought by wastewater (Kiziloglu et al., 2008). On the other hand, the supply with wastewater may reduce the content of active limestone (responsible for the alkalinity) in those soils (Solis et al., 2005).

Table 1. pH evolution of soils irrigated by wastewater

References	pH		
	Irrigation sewage	Bearing soil	Soil irrigated by Wastewater
(Shahalam et al., 1998)	8.6	8.4	7.7
(Yadav et al., 2002)	7.4	8.5	8.1
(Rattan et al., 2005)	5.8 - 6.5	7.9	7.5
(Khan et al., 2008)	/	8.0	7.9
(Kiziloglu et al., 2008)	8.55	7.52	6.85
(Madyiwa et al., 2002)	/	4.6	5.4
(Sinha et al., 2006)	7.26	8.16	8.26
(Al-nakshabandi et al., 1997)	7.4	7.9	8.1
(Qishlaqi et al., 2008)	8.4-9.8 (9)	7.29	8.6

Some authors, had reported that the soils pH had significantly increased due to the irrigation with wastewater (Madyiwa et al., 2002; Qishlaqi et al., 2008; Al-nakshabandi et al., 1997) (Table 1) reaching 1.3 unit as it was shown in the study of Qishalaqi et al. (2008). However, this is caused by the basic nature of wastewater used for irrigation (pH average 9). The latter which is loaded with basic cations is responsible for soils alkalization (Madyiwa et al., 2002). The pH increase may reflect the lime nature of the mother rock, even if a weak dissociation of $CaCO_3$ may increase the pH too.

In addition, limestone soils buffer effect may prevent soil acidification, and hence keep the soils pH neutral (Chen et al., 2007).

Soil Organic Matter Content

Irrigation using wastewater leads to an increase of soil's organic matter content and thus contributes to its fertility (Rattan et al., 2005; Yadav et al., 2002; Qishlaqi et al., 2007; Lucho-Constantino et al., 2005). The rate of enrichment may vary according to the content of organic matter in wastewater. Within 20 years, Rattan et al. (2005) and Qishlaqiet al. (2008) have estimated the enrichment of the surface horizons of irrigated soils between 20 and 60% varying according to the nature of the soil itself. The duration of irrigation seems to be positively effective based on the organic matter content (Lucho-Constantino et al., 2005).

Soil Salinity

Generally speaking, wastewater salinity (salt concentration) varies according to its origin. Industrial wastewater salinity is much higher than the one of municipal wastewater (Hamilton et al., 2007). The physical and mechanical properties of the soil just like the particle dispersion, aggregate stability, and soil permeability and its structure are very reactive to the nature of ions present in irrigation water (Pescod, 1992). Salts accumulation in the superior horizons of soil presents a high risk of the spreading of wastewater (Duan et al., 2010). Solis et al. (2005) has noticed that long term irrigated soils with wastewater consisted of an important accumulation of salt (mainly in Na).

In general terms, the reuse of water in irrigation must have a weak or an average degree of salinity (electricity conductivity should be between 600 and 1700cm^{-1}) according to Feigin et al. cited in Hamilton (2007). However, wastewater frequently exceeds the precedent value (Al-nakshabandi et al., 1997; Yadav et al., 2002; Biggs & Jiang , 2009; Murtaza et al., 2008; Sinha et al., 2006), which presents a big salinity risk to soils irrigated with this water. Biggs and Jiang (2009) recorded an increase in electricity conductivity ranging between 6,2 to 8,4 times superior to one of soils irrigated with underground water.

CEC and Exchangeable Cations

Wastewater usually increases cations exchange capacity. This is explained mainly in terms of an influx of organic matter and exchangeable cations (Hamilton et al., 2007; Qishlaqi et al., 2008; Biggs & Jiang, 2009). Irrigation using wastewater enhances the concentration of exchangeable cations (Na, K, Ca, Mg) and available trace elements. It was calculated that a blade of residual water of 100mm may bring to a hectare amounts varying from 16 to 62 kg of nitrogen, from 2 to 69 kg of potassium, from 4 to 42 kg of phosphorus, from 18 to 208 kg of calcium, from 9 to 100 kg of magnesium, and from 27 to 182 kg of sodium (Faby & Brissaud, 1997).

Wastewater spreading causes exchangeable cations accumulation in arable layers (Hamilton et al., 2007). Qishlaqi et al. (2008) recorded an important quantity of Ca in the arable layer (higher than 2500 $mg.kg^{-1}$). Biggs and Jiang (2009), on the other hand, have noticed an accumulation of Na cations, which is an average of 20 to 22 times superior compared to lands irrigated with underground water. This latter causes soils sodisation (a high Na^+ proportion comparing to soils Ca^{2+} and Mg^{2+}), which in return leads to the destruction of the soil structure by the dispersion of clay aggregates (Agassi et al., 2003). This, therefore, is a fact that explains the decrease in permeability and porosity of soils' superficial layers (Faby & Brissaud, 1997).

Soils' cations composition differs according to wastewaters cations and the sites of soils exchange. An example is Mg^{2+} and K^+ cations which are connected more to clay fraction compared to Na^+ cations (Biggs & Jiang, 2009).

Trace Elements Concentrations in the Soil

The spreading of raw wastewater is potentially dangerous to soils because of its consistency in the transportation of toxic elements like trace elements. This is because wastewater is considered to be the main source of anthropogenic trace elements in the soil. Using it for irrigation constitutes an important source of trace elements for the soils too. Even if many authors reported that wastewater irrigation does not cause a significant trace elements accumulation in the surface horizon (Cebula,1980; Ramirez-Fuentes et al., 2002), there are, however, many noticed cases of contamination by trace elements (Xiong et al., 2001; Schirado et al., 1986; Schalscha & Ahumada, 1998; Jiries et al., 2002; Flores et al., 1997; Chen et al., 2007; Wu & Cao, 2010). Long term irrigation with municipal effluent water increases the soils metal concentrations (Schirado et al., 1986; Sharma et al., 2007; Flores et al., 1997; Chary et al., 2008; Wu & Cao, 2010). Qishlaqi et al. (2007) have noticed a high concentrations of lead (Pb) in the arable layer caused mainly by the high value of organic matter. According to Alloway (1995), if any soil that is exposed to an important value of organic matter is brought either by wastewater or mud, the organic matter is going to be as a source of both organic and inorganic pollutants (trace elements). Also, it is going to be a major absorbent of contaminants. In many investigations, it had been proved, however, that there is a positive correlation between the organic matter and metals present in the soil (Qishlaqi et al., 2008; Flores et al., 1997).

Evolution of Trace Elements Concentration according to the Depths

Irrigation using wastewater increases trace elements concentrations in the superior horizons of soils (Flores et al., 1997; Mutraza et al., 2008; Dère, 2006; Qishlaqi et al., 2007; Sharma et al., 2007). Dère (2006) has reported that after 100 years of experiences, the use of raw wastewater in irrigation led to an increase in trace elements contents exogenously of 98% out of the total content of surface horizons (plowed ones). In the investigation led by Flores et al. (1997) which was about irrigation of soils with raw wastewater, they noticed an important accumulation of trace elements in the surface horizons between 0-10 cm. This corresponds to an enrichment varying between 31 and 49% for Cd, 14 and 73% for Pb, and between 21 and 55% for Zn compared to the beneath horizons (50-60 cm depth). For the most profound horizons, the enrichment is much more important (90-100 cm depth), varying between 49 and 144% for Cd, 19 to 587% for Cu, 100 to 418% for Pb, and between 31 and 120% for Zn.

Thus, according to Ayers and Westcot (1994), more than 85% of trace elements, brought by wastewater used for irrigation, was accumulated in the surface horizon of the soil.

Dère (2006) reveals, in her study about the pollution of sandy Luvisols in Parisian region after 100 years of an intensive irrigation with wastewater, that there is an important migration of Ni, Zn, Cu, and Cd towards the depths (40-100 cm). She even observed that exogenous stocks (brought by raw wastewater) in this horizon represents 45% for Ni, 31% for Zn, 14% for Cu, and 10% for Cd out of Exogenous stock of ETM present in the solum. Metal infiltration and leaching in the depth are two procedures that leads to the contamination of underground water (Li et al., 2003).

In general, ETM migration to the depth depends mainly on (Dére 2006):

- The Considered Elements (Zn, Pb,…): Trace elements mobility depends on their form in a solution, which controls their similitude with the horizon constituents of the soil. Zn and Ni occur predominantly in a cationic form, where the Cu is in cationic form or forming a complex element with a dissolved organic matter. Qishlaqi et al. (2007) have noticed that Pb is less mobile and this is what causes its accumulation in the arable (surface) layer. Also, it matches and corresponds to Dére's study, in which she observed a total absence of exogenous Cr and Pb under plow horizon (0-40cm) on the opposite of Ni, Zn, Cu, and Cd that migrate to the solum depth. Fitamo et al. (2007) have investigated the two kinds of soils (Fluvisol and vertisol) in the region of Adis Ababa, and noted that Zn is a little mobile in vertisol soil, while Cr is a little mobile in both soils.

- Chemical Characteristics of Soil Horizons: The most important obstacles for trace elements are the organic matter, carbonates, clayey minerals, and iron and manganese oxyhydroxides. It seems that trace elements brought by wastewaters are fixed by the organic matter (Qishlaqi et al., 2007; Flores et al., 1997; Dère, 2006).

- Physical Properties of Soil Horizons (Structure, Permeability): In Dére's investigation (2006), the content of Zn in the sandy clay horizon is related to the horizon's permeability.

- Hydraulic function of the soil constitute a non-negligible fact in the redistribution of trace elements exogenous in the inferior horizons (Dère , 2006).

Evolution of Trace Elements Concentration through Time

Many investigations have shown a linear connection between the content of the soil and the period of time of irrigation with wastewater (Lucho-Constantino et al., 2005; Flores et al., 1997; Dére, 2006; Xiong et al., 2001).

Trace elements accumulation is a common phenomenon noticed also in soils irrigated with water in which the average of trace elements does not exceed the one of water predestined for irrigation (Rattan et al., 2005).

Based on the concentration of trace elements and the amount of irrigation water used yearly, Murtaza et al. (2008) have estimated that wastewater irrigation causes an annual input of an area between 0.88 and 0.96kg ha^{-1} for cadmium. With such an input, the studied samples of soils reach the limited threshold requested of trace elements content in agricultural soils after a decade of irrigation.

Assadian et al. (1998), on the other hand, have estimated that after 50 years of irrigation with wastewater, trace elements' intake is 10kg ha^{-1}, which represents 31% of surface soils metals charge.

Location of Trace Elements in Soils Irrigated with Wastewater

Flores et al. (1997) investigation on the chemical fraction, shows that the mobile and exchangeable fractions do not exceed 4,5% of metal stock. On the other hand, dominant fractions are the organic and carbonate ones, to which Pb is more connected to 71%. This is followed by the other metals (Cd, Zn, Cu) with an average varying between 42 and 46%. The Organic fraction is the most important for the following four trace elements, Cu (between 14 and 65%), Cd (between 20 and 46%), Pb (between 34 and 52%), and Zn (between 16 to 61%).

Fitamo et al. (2007) have noticed that almost all metals are mainly connected to the non-risidual fraction, whereas Zn and Cr are connected to the residual fraction (non labile). According to Dére's study (2006), Zn was the only metal to connect with the exchangeable fraction with an important proportion of 20% in the plow horizon, probably explained in relation to its form. Hence, it is the form and the nature of the metal, in addition to the soils properties (physical, chemical, biological and mineral), that determine trace elements mobility and availability in the non-residual fractions (Fitamo et al., 2007).

Chen et al. (2007) have reported that after 25 years of suspension of irrigation using wastewater, Zn is connected to the reducible fraction (iron oxide) followed by the residual fraction. On the other hand, mobile, exchangeable, and carbonate fractions represent 50% of Cd total stock. For Fitamo et al. (2007), Cd, Cu, Zn, and Pb are all connected mainly to reducible and carbonate fractions.

Generally, chemical speciation studies of irrigated soils with wastewater, all indicate and reveal that trace elements are found in a moderately mobilisable form.

Availability of Trace Elements

Trace elements passage through the soils solution is controlled by the form (speciation) under which they are during the solid phase: exchangeable, absorbed, forming a complex with the surface constituents of the soil, or co-precipitated. Organic matter, carbonates, clay minerals, and iron and manganese oxy-hydroxid are the main constituents involved in trace elements retention (Adriano et al., 2004). Trace elements, routed in the soil via wastewater, would not all have an assimilable or bioavailable forms, but their chemical form will depend also on the intrinsic conditions of the soil like the pH, Eh, the organic matter, the clay rate, the cation exchange capacity CEC, and the total organic carbon TOC (Solis et al., 2005).

Many authors have observed that Cd phytoavailability depends on the soil physicochemical properties more than its total concentration in the soil. On the other hand, exchangeable Ca brought by wastewater contributes in the insoluble complex formation of Pb in the arable layer, which reduces its availability in the soil's solution. This, inturn, explains the negative relation between Ca exchangeable content and Pb availability (Qilshaqi et al., 2008). A continuous supply of nitrogen by wastewater may contribute in the enhancement of the bioavailability and plants' absorption of trace elements (Sharma et al., 2007).

Trace elements high concentration in the soils does not necessarily means their phytoavailibility (Liu et al., 2005). Furthermore, Qishlaqi et al. (2008) have observed that only 1,3 to 7,7% and 0,07 to 1,69% of Pb total content and Ni are phytoavailable due to the combined effect of the organic matter (fixing) and the alkaline pH. The study led by Chary et al. (2008), executed on the soil alongside of Musi river (India), have demonstrated that 70 to 77% of lead is connected to non-mobile fractions because of the high content of these soils with the organic matter brought by wastewater.

Generally speaking, an alkaline soil that is superior to 8 is known to limit trace elements mobilization, hence reducing their absorptions (Sharma et al., 2007). Trace elements availability enhances with the raise of soil acidity. Indeed, trace elements concentration in plants is negatively correlated with solution pH (Adams et al., 2004; Qilshaqi et al., 2008). pH increase reduces the absorption and concentration of Cd in the leaves of lettuce (Xue & Harrisson,1991) and also the one of colza (Eriksson, 1989) and other farmings. The combination of a high pH level, the organic matter, and limestone may decrease the trace elements phytoavailability (Murtaza et al., 2008). For Qilshaqi et al. (2008), it depends mostly on the physicochemical properties of the soil rather than their total concentration in the soil. Nevertheless, a high rate of water nutritious elements may lead to a relatively high rate of growth, which results in a sample relatively rich of trace elements (Sharma et al., 2007; Qilshaqi et al., 2008).

Among the set of trace elements, Cadmium is considered to be the most health threatening metal due to wastewater irrigation. Largely available to plants, situated with high concentrations in plants edible parts, it is very dangerous to man (Hamilton et al., 2007; Mapanda et al., 2007). On the other hand, Zaranyika et al. cited in Mapanda et al. (2007) have proved that Cu^{2+} has a good affinity with the organic matter and it easily form complexes, and thus reduces its availability for plants.

In Sharma et al. (2007) study, the sample of Cd, Zn, Cr, and Mn was more important during summer season. This is a fact explained mainly in relation to a release of trace elements after the relatively high decomposition of organic matter (McGrath et al., 1994) and also the high rate of plants transpiration (Ingwersen & Streck, 2005).

Mobility and availability of trace elements are controlled by numerous chemical and biochemical processes as dissolution–precipitation, adsorption-desorption, complex formation-dissociation, and the oxydoreduction. Each process depends on the reactions of soil and the rhizosphere effect (He et al., 2005).

Content of Trace Elements in Plants

The transfer of trace elements to plants irrigated with wastewater may cause trace elements accumulation in plants' tissues, and in some cases,the content of these metals may reach phytotoxicity thresholds (Faby & Brissaud, 1997). In many cases, plants content of trace elements exceeds by large its content in control plants or guideline concentration as denoted by Xiong et al. (2001), Mapanda et al. (2007), Yadav et al. (2002), Qishlaqi et al. (2008), Sharma et al. (2007), Rattan et al. (2005), and Chary et al. (2008).

According to the references, the most irrigated plants with wastewater are vegetables which accumulate the large amount of trace elements in their tissues (Sharma et al., 2007; Sinha et al., 2006).

Despite the physiological characteristics of plants, the heavy metal content incultures depends also on the physical and chemical nature of the soil, which controls the bioavailability of trace elements. This later depends on many facts like: soil temperature, moisture, organic matter, pH, and nitrogen availability (Sharma et al., 2007; Qishlaqi et al., 2008). Many investigations have denoted that a high content of trace elements in the soil does not necessarily reflect their high concentration in cultures.

Murtaza et al. (2008) have found that cultivated plants in soils, consisting of a content of Cd inferior to the threshold values, may accumulate this metal with a very important concentrations exceeding the allowed levels.

According to Kabata-Pendias (2004), the soil-plant transfer of trace elements involves the interaction of many parameters: the plants features, features of the soil, the nature of contamination and the environmental facts,etc...

Conclusion

In developing countries, fields and gardens bordering the different conurbations are irrigated with urban wastewater containing relatively weak trace elements content. However, it is the long term (continuous) irrigation using wastewater that causes the accumulation of these toxic metals. Accumulation takes place in the surface horizon of the soil and is responsible for plants and animals metabolic disorders and hence contaminating the foodchains.

Despite the varying dangerous risks on health and environment, direct or indirect use of wastewater in agricultural irrigation in many developing countries is still planned.

Also, despite the general low concentration of trace elements in the treated effluents, the impact of this water ;however,remains a major concern to the environment. Since trace elements generally accumulate in the soil, and because of the biochemical conditions, they pass into the soil solution. They are more or less absorbed by plants and affect the quality of the agricultural products intended for both humans and animals which causes serious health problems.

This review was conducted to demonstrate the effect of trace elements resulting from wastewater irrigation and their contamination of soils and plants which represent not only a significant environmental risk, but also a potential health risk.

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