Multidisciplinary approach on reclaimed water use projects in agriculture

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Abstract

Countries more exposed to water scarcity could play a central role in the adoption and success of effective land and water management policies. In this respect, they require new technological capacity and innovative solutions to increase water sources available for agricultural activities in order to have major food and avoid health crises.
Although reclaimed water is commonly and successfully used in many countries, water reuse face numerous barriers. Therefore, for the preservation of profitable intensive agriculture that respects the environment, are needed innovative agricultural projects incorporating state of the art technologies in water reuse with multidisciplinary studies.
The developed work show the multidisciplinary approach on reclaimed water use projects in agriculture through an integrated methodology, generating novel strategies to describe and quantify the interactions of the use of saline reclaimed water for horticultural crops irrigation in agriculture.

Keywords: reclaimed water, agriculture, water scarcity, precise irrigation

1. Introduction

The next decades a large percentage of the world population will live in areas with water scarcity and poor water quality due to climate change and increasing population pressure, thus agriculture will face the challenge of supplying the increasing demand for food resulting from the forecasted population growth rates. One strategy for maintaining or increasing productivity under resource scarcity is to make greater use of marginal quality lands and waters. Irrigated agriculture worldwide (2.7 times more productive than rainfed agriculture) will play a crucial role in the food production system as well as in the use of non-conventional water resources such as saline ground water and saline reclaimed water. In implementing such a strategy, key factors for sustainability are soil salinity and water quality.

In the Mediterranean Region, irrigated agriculture contributes 75% to the final production. The continued use of these water resources for irrigation will probably put the agro-systems and the environment at risk from salinization, soil compaction and undesirable ions toxicity. Soil secondary salinization affects an estimated 1 to 3 million hectares in the enlarged EU, mainly in the Mediterranean countries. It is regarded as a major cause of desertification. A new strategy of water management it could be a key method for desertification prevention. Actually, there is a need for technologies that increase water use efficiency and make additional (non-conventional) water sources available for fertigation, thereby decreasing water scarcity and the discharge of water and nutrients to the environment.

Countries more exposed to water scarcity could play a central role in the adoption and success of effective land and water management policies. In this respect, they require new technological capacity and innovative solutions to increase water sources available for agricultural activities in order to have major food and avoid health crises.

Although reclaimed water is commonly and successfully used in many countries (e.g. Israel, USA, Australia), in the EU, water reuse face numerous barriers. Among them, safety risks, economic concerns and social acceptance can be currently defined as the main barriers considering that 1) safety risks have been traditionally linked to the use of improperly treated wastewater; 2) cost is probably the first driven force in fresh produce production; and 3) public acceptance of reclaimed water by the public varied according to its potential use.

2. Objectives

The main aim of this paper is to show a success multidisciplinary approach on reclaimed water use projects in agriculture laying the foundations of a novel and more efficient crop production management by enabling the saline reclaimed water use for irrigation. To achieve this main aim, the following methodology was implemented: evaluate the horticultural crops performance, determination of the water use efficiency (WUE), establish new agronomic thresholds, use plant uptake models to evaluate the short and long-term effects of reclaimed irrigation water and verify under Mediterranean field conditions. Finally, the integration of new tools as GIS, environmental value and public perception into the water resource use studies. All of this, working at different size levels.

3. Research pilot plants at plot level

In the Region of Murcia was established a network of experimental plots in different Mediterranean locations and different Mediterranean types of crops, where be assessing the effect of using reclaimed water from nearby wastewater treatment plant in combination with deficit irrigation strategies, on the physiology, performance, quality and safety of crops. The evaluation of the effects on the long and medium term effect on soil salt accumulation as well as the influence of the use of this water on the drainage fractions and groundwater pollution is being studied. In these experimental platforms, the effects of treated wastewater are compared with results obtained with conventional water usually used by farmers. The last goal would be to try to optimize the use of such reclaimed water, showing that such use may be a strategy aimed at optimizing the use of water especially in areas with limited conventional water resources.

3.1 Long-term research experimental farm on salty reclaimed water. Fruit trees (citrus).

The first investigation approximation into reclaimed water was on lemon trees (Pedrero and Alarcón, 2009). The aim of this work was to study the effects of reclaimed water on lemon tree performance. In particular, this research was to compare two sources of treated wastewater, one obtained with a secondary treatment (Cartagena) and the other with a tertiary treatment blending with well water (Campotejar), and to study their effects on soil chemical properties, on the leaf mineral status, crop production and fruit quality and safety. The main results obtained shown that the possibility of blending reclaimed water with well water is a good solution to avoid the problems associated with wastewater use in agriculture. The high salinity, Cl and B concentration were the main restrictions associated with treated wastewater used in the experiment. The fruit-quality indexes (weight, firmness, soluble solids, pH, total acidity and maturity index,..) were significantly better in the plots irrigated with secondary treated wastewater (Pedrero et al., 2012a). The soil microbiological analysis revealed an absence of faecal coliforms, Escherichia coli and helminth eggs in the experimental plots irrigated with tertiary treated wastewater, but with secondary treated wastewater the soil accumulation of faecal coliforms exceeded health standards (Pedrero et al., 2012a).. In both cases, the use of reclaimed water as irrigation water for lemon trees did not represent a microbial risk for lemon fruit.

The second investigation approximation was on an experimental plot conducted at a commercial orchard located in Campotejar (Murcia) Spain (Fig. 1). In this case, the study was more complex because of was conducted with three different irrigation water qualities and two different irrigation doses applied. The experimental plot of 0.5 ha is cultivated with 7-year young `Star Ruby´ grapefruit trees (Citrus Paradisi Macf) grafted on Macrophylla rootstock [Citrus Macrophylla] and 0.5 ha with 11 years "Orogrande" mandarin trees grafted on Carrizo rootstock. The irrigation head is equipped and supplied with three irrigation water sources; the first (TW) was pumped from the Tajo-Segura water transfer (EC ≈ 1 dS m^{-1}) ,the second water sources (RW) was pumped from the " North of Molina de Segura" wastewater treatment plant (WWTP) (EC ≈ 3-4 dS m^{-1}), and the third one was delivered by the irrigators' association of Campotejar (IW) (1≈EC≈4 dS m^{-1}), this time-variable quality water depends on the proportional mix of the available water resources needed to cover the actual irrigation demand (underground water, transfer water and reclaimed water). The treatment in the WWTP is a conventional activated sludge with ultraviolet tertiary treatment. Two irrigation treatments were carried out for each water source. The first was a control treatment (C) irrigated through-out the growing season to recover 100% of the soil water lost by ETc. The second was a regulated deficit irrigation treatment (RDI) irrigated similarly to C, except during the second stage of fruit growth when it received 50% of the water applied to the control. The stage selected to apply the RDI was identified for being unsusceptible to moderate water stress (Gonzalez-Altozano et al., 2003). In our case, this stage extended over a time period of 55–65days between late June and late August. No leaching fraction was added to the irrigation doses.

Little is known about the interaction between deficit irrigation and saline water. For this reason, the main objectives of the second study during the first four years, were to evaluate the combined effects of different irrigation water qualities (Tajo Segura water transfer canal, irrigators association and reclaimed water) and the regulated deficit irrigation strategies on mandarin tree crop performance under Mediterranean climate conditions and their effects on plant physiology and leaf mineral status, soil chemical properties and water content, yield and fruit quality. Yield reductions were not significant between treatments, although a tendency to reduced number of fruit was detected in the reclaimed water treatments (Pedrero et al., 2012b). This reduction was more pronounced under combined conditions of reduced irrigation quality water and regulated deficit irrigation (Mounzer et al., 2013). The combined effects of RDI strategies and of using reclaimed water can increase some fruit quality parameters such as vitamin C on mandarin trees. Plant water relations and vegetative growth were not significantly affected by the use of reclaimed water. However, water stress in the RDI treatments induced some reductions in the stem water potential that immediately were recovered when deficit period disappeared (Pedrero et al., 2012b; 2012c).

Although no leaf toxic visual symptoms were seen during the experiment, a tendency was identified in terms of salts accumulation in the soil during last season in RW-RDI treatment. In this sense, it is important to remark that in arid and semi-arid areas, the combination of RDI strategies and reclaimed water-use can be affected in the long-term because of the salts and boron accumulation (Pedrero et al., 2014a;2015b).

During the next 5 years (2010-2015), research studies on the same pilot farm have continued on evaluating different indicators on salt stress, establishing phytotoxicity thresholds for Na, Cl and B and evaluating salt accumulation at leaf level. After evaluating the validity of three indicators (gas exchange parameters, stem water potential and leaf chlorophyll content), results showed the need of seasonal measurements of leaf chlorophyll content as an important diagnostic indicator of salt stress on field crops of grapefruit (Romero-Trigueros et al., 2014a). Additionally, it was observed salt accumulation at leaf level that could eventually lead to possible risks, establishing thresholds at which a reduction in yields occurs at Na: 0.1 g/100 g, Cl: 0.6 g/100 g and B: 100 ppm. In fact, recent research showed that irrigation water sources with high level of boron could affect citrus production with similar thresholds (Grattan et al. 2015).

On grapefruit, deeply studies have been done because trees were receiving saline reclaimed water from they were planted. I was studied the use nutritional and structural traits measurements at leaf level and isotopic measurements to assess the sustainability in the medium to long term. From this study, it was hypothesized that (i) the positive correlation between leaf *δ15N* content and leaf salt content suggested that causal links exist between *δ15N* and salt stress; (ii) excess of nitrates provided by the reclaimed irrigation water were lost in the ecosystem through leaching, denitrification, etc., enriching the medium with *δ15N* and increasing δ15N value in plants. Therefore, it has been demonstrated the usefulness of isotopic discrimination measure to predict crop sustainability in the medium to long term when using water sources of different quality combined with deficit irrigation strategies (Romero-Trigueros et al., 2014b).

It is interesting to know that the lowest relative yields occurred in the RW-RDI and TW-RDI treatments, where ECe values were highest. In addition, the threshold at which yield is reduced in this research (2 dS m^{-1}) compared to the TW-C treatment coincides with the values proposed by Ayers and Westcot (1989) for citrus (ECe= 1.7 dS m^{-1}), 25 years before. Non-microbiological risks were observed by the use of reclaimed water for citrus trees production during the experiment (Pedrero et al., 2012a; 2012b) as was

reported by different authors (Pereira et al., 2011; Reboll et al., 2000; Zekri et al., 1993;1994).
Actually, two new treatments have been added to the experimental design in Campotejar. 1) The Dual-Water treatment will be irrigated to restore 100% ETc using the following criteria: Fresh water from the Tajo-Segura canal (EC ≤ 1 dS m^{-1}) will be used whenever the actual ETc is higher than 3 mm/day. Under our experimental conditions in Murcia, this period may extend from mid-May till mid-August. Reclaimed saline water (EC > 4 dS m^{-1}) will be utilized during the remaing period. i.e. when the daily ETc is lower than 3 mm. and 2) Regulated saline irrigation will be irrigated similar to the control treatment (100% ETc) with fresh water except during the second stage of fruit growth when saline treated water will be used for irrigation. The objective is to test new management practices to substitute the deficit stress by osmotic stress during the non-critical fruit growth stage.

Fig 1. Research citrus experimental farm in Campotejar (Molina de Segura, Murcia)

3.2 Agricultural and Water Research Platform at Roldán-Balsicas WWTP

The Agricultural and Water Research Platform from CEBAS-CSIC situated inside of the wastewater treatment plant Roldán-Balsicas (37º47´48.88´´N,0º57´33.63´´O), is based on
Almost 700 m^2 with a plastic greenhouse, screen and heating system, irrigation and different automatisms.

3.2.1 Horticultural crops experiments under greenhouse

The study was carried out on a plastic greenhouse with screen and heating system, irrigation and different automatisms, in the Wastewater Treatment Plant (WWTP) of Roldan-Balsicas, Murcia, Spain (Fig. 2). Plants were grown under greenhouse conditions to determine the effects of different irrigation water sources and growing media on growth, yield and fruit quality. Crops (tomato, pepper and zucchini) were grown in two commercial culture systems, rock wool and coconut fiber and two irrigation water qualities, irrigation community (CW) and reclaimed water from the Roldan Wastewater treatment plant (RW). The water is supplied by drip irrigation with three compensated pressure drips per bag, each with a flow rate of 3 Lh^{-1} and spaced 0.3 m. A total of 1080 plants were distributed into the 680 m^2 greenhouse surface. During the three years of experiments, one of biggest benefit was that the use of reclaimed water for irrigation was a significant saving of mineral fertilizers (N - P_2O_5 - K_2O - CaO) (6, 5, 8 y el 40%, respectively) for both substrates (Pedrero et al., 2014b). After the analysis performed in plant and fruit, it was concluded that the use of reclaimed water for hydroponic tomato and pepper crop irrigation, is suitable under conventional agricultural practices (hydroponics, drip irrigation, polyethylene greenhouse, etc....) and the most important, offers a microbiological food safety.

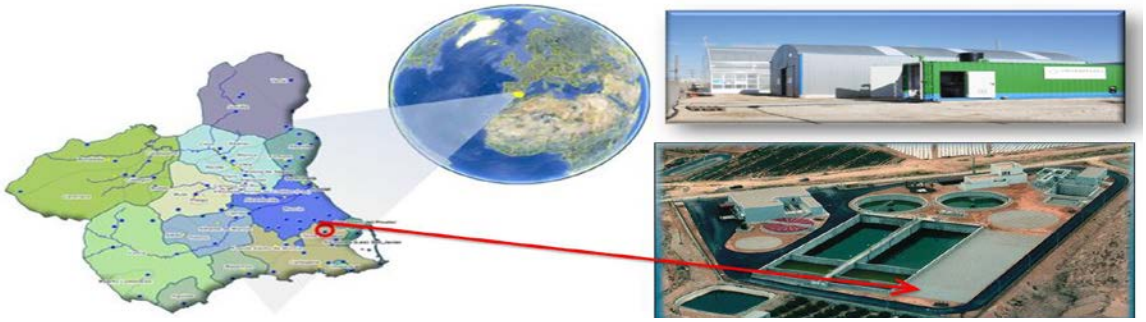

Fig 2. Agricultural and Water Research Platform at Roldán-Balsicas WWTP

3.2.2 Agricultural system microbiological safety

Health and environmental aspects are particularly sensitive issues and important prerequisites, since wastewater effluent will not be used and/or be accepted to replace conventional or possibly other non-conventional water sources for irrigation, unless it is adequately treated and safely applied (Gerba and Rose, 2003). Systematic monitoring of indicator microorganisms, such as Escherichia coli, can help identifying potential risk factors for faecal contamination in the agricultural environment.

On horticultural crops under greenhouse conditions, deeply microbiological studies were developed. On pepper study in Roldan greenhouses, levels of E. coli in irrigation water (both reclaimed and surface water), water sprayed in humidifiers to regulate ambient humidity, and pepper fruits were assessed. Additionally, the role of fertilizer solutions as a potential vector of contamination was investigated. One interesting result showed that regarding the fertilizer solutions, E. coli was detected more frequently and in higher levels in the fertilizer solution richer in micronutrients (Gil et al., 2014). These results suggested that there is a low risk of contamination in this agricultural system despite of the combination of risky irrigation water sources (reclaimed and surface water) and the hydroponic grown system. Nevertheless, especial care should be taken regarding the microbiological quality of the agriculture solutions that contact directly the edible parts of the crop (Gil et al., 2014; Allende et al., 2016).

Finally, the election of the quantification technique for microbiological indicator, have been demonstrated on a zucchini experiment under greenhouse. The suitability of two E. coli quantification techniques (plate count and qPCR) was examined for irrigation water and fresh produce. E. coli levels using qPCR assay were significantly higher than that obtained by plate count in all samples of irrigation water and fresh produce. However, differences in the water characteristics influenced the suitability of qPCR as a tool to predict potential contamination in irrigation water (Truchado et al., 2016).

The next approach, will be studies based on the Quantitative Microbial Risk Assessment (QMRA). QMRA is one of the preferred tools for determining those risks. In point of fact, QMRAs overcome limitations of other approaches (e.g. epidemiological studies), such as costs and logistics (De Keuckelaere et al., 2015). QMRA is considered as a data-intensive approach that requires several inputs. These are categorized by De Keuckelaere et al. (2015) as: “(1) prevalence and concentration of microorganisms of concern; (2) transmission routes (how the pathogens enter the food chain); (3) growth, removal, survival, and/or inactivation of microorganisms; (4) consumer behavior; and (5) dose–response relationship”.

4. Pilot plant irrigation at district level. Miraflores irrigators community

Such pilot plants could be used as demonstration platforms where continuously assess the quality of irrigation water used, and will be assessed, bases on trials carried out on plot, the use of this reclaimed water in the different crops of the study area. The last goal is to optimize this new water resource at a higher scale of production, assessing the effects of reclaimed water on plant and soil, but also estimating how the reservoirs, water pipes systems and all the associated infrastructures with the distribution could affect the quality of the effluent. The project “Feasibility study of using reclaimed water from the WWTP of Jumilla in the Miraflores irrigators community” was developed in 2012 (Nicolás et al., 2012), assessing the irrigation community of Miraflores (Jumilla, Murcia) about the best management practices to use the reclaimed water in their different crops and irrigation infrastructure. During the second phase of the project, the main objective was the management and control of reclaimed water from the Jumilla WWTP in Miraflores. For that porpoise, continuous measurement with probes (pH, electrical conductivity, turbidity, nitrates and phosphates) to analyze and interpret water quality from the water reuse law to and agricultural point of view, have been done. The information is collected to a head programmer to close the valve, when water conditions are deficient and do not comply with the requirements of RD 1620/2007 quality 2.1. level. Also, training courses on agricultural use of reclaimed water for irrigators have been developed.

5. Simplified treatments for agricultural water reuse

On the Agricultural and Water Research Platform at Roldán-Balsicas WWTP, a number of European research projects have been developed in the 5 years running, both with the agricultural testing of different prototypes of wastewater treatment ("Intelligent Reclaim Irrigation System" (IRIS) and “Low-cost water desalination and sensor technology compact module” (DESERT)) (Fig. 3), and the agronomic development of irrigation programming tools with water of different qualities and database in soil, plant and environment ("Professional online irrigation system of expert programming" (OPIRIS), KBBE.2013.1.4-07 EU). The objective of IRIS project was to convert wastewater compounds into renewable sources for agriculture. The technology convert raw domestic wastewater into irrigation water containing fertilizers, CO_2 and biogas which will be used in greenhouse production. On DESERT project, the main aim is more ambitious because introduces a new approach and vision of agriculture, creating an innovative concept as a smart system combining sustainable technology on water treatment and water quality sensors, tuned to the local situation.

These simplified treatments for agricultural water reuse can contribute to mitigate the negative effects of intensive surface and groundwater abstraction, improving water quality and increasing farmers' income through saving costs of energy and reducing the water and fertilizers needs.

Fig 3. Simplified treatments for agricultural water reuse at Roldán-Balsicas WWTP

6. Tools for planning and management reclaimed water projects

6.1 Public acceptance and education of reclaimed water use

Successful implementation of a water reuse project depends not only on its economic and environmental feasibility, but mainly on the support of the general public, who, ultimately, pays for, and might be affected by the reuse project. Within this economic assessment all environmental benefits – including non-market benefits – should be included to ensure an efficient and sustainable allocation of the water resource. A specific study to estimate the non-market benefits that society attaches to the use of reclaimed water for agricultural purposes, which is expected to play a growing role in areas where conventional water resources are scarce, was developed in Murcia. It was shown that the use of reclaimed water for irrigation has significant non-market environmental benefits (mean willingness to pay of €5.13 per month per household, which adds up to a total annual value of €23.3 million) (Alcón et al., 2012).

This study, being the first of its kind in Spain and among the first in Europe, is believed to help policy makers with the implementation of water management measures to achieve the Water Framework Directive environmental objectives in an efficient, sustainable and equitable manner.

6.2 Geographical Information Systems (GIS) and new technologies

Geographical Information Systems (GIS) based on multi-criteria analysis, can be used as a tool in the planning and management of water reuse projects helping in the identification of potential sites for reclaimed water use. The first work was developed in the Beira Interior Region (Portugal) with the aims at identifying potential sites for reclaimed water use, using a GIS-based multi-criteria analysis (Pedrero et al., 2011). A constructed wetland (CW) system located in the northwest part of the Beira Interior region was used as the source of reclaimed water.

The same methodology improved, was developed in the northwest part of the Region of Murcia (Spain) for optimization of the use of reclaimed water through the integration of the water resources management. After analyzing all the criteria established, of the total area studied (237,960 ha), only 2.7% (6,442 ha) was considered optimal for aquifer recharge (Pedrero et al., 2013) (Fig.4). So, after two different works on different locations, the application of multi-criteria analysis resulted in a final, optimal map showing areas appropriate for the infiltration of reclaimed water.

New technologies in agriculture as the use of hyper spatial sensing techniques, was also studied on reclaimed water studies to evaluate the effects on spectral properties and leaf traits of citrus orchards. After a long period of applying saline reclaimed water on citrus trees in Campotejar, reclaimed water did not affect either NIR–NDVI or anatomy traits, but these techniques are suitable for detecting chlorophyll dynamics (Contreras et al., 2013).

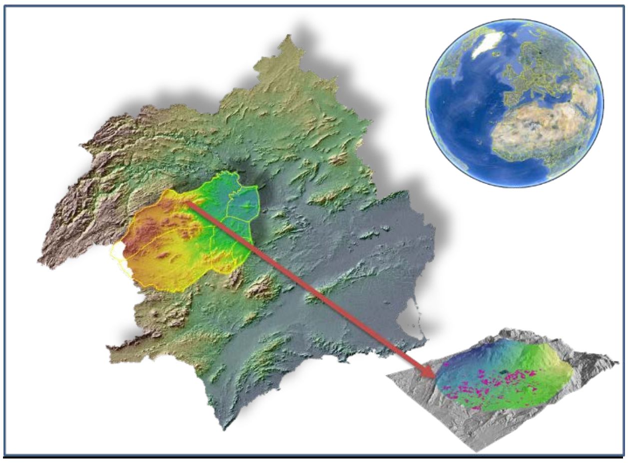

Fig 4. Multi-criteria analysis with GIS. On purple, the optimal area for aquifer recharge.

6.3 Models on medium to long term saline reclaimed water application

The use of new model predictions helps to determine the impact of using saline reclaimed water for citrus irrigation. The model for simultaneous salt and water uptake by plants can be coupled to groundwater models in order to predict the salt budget of ecosystems and to manage agriculture in arid zones as the Mediterranean Region. During collaboration with Denmark Technical University (DTU), It has been demonstrated to be a useful tool to measured water uptake of growing plants and salt concentrations in solution simultaneously, and in parallel with toxic effects on the plants. The model used is a coupled model based on a coupling of a tipping Buckets water and solute transport model for soil water balance model at the surface and plant uptake model (based on transpiration) substituted with an uptake factor F for exclusion of salt, which is based on measured data for willow tree in the laboratory (Trapp et al., 2008). The comparison of measured and simulated data has value for both - inconsistencies in data can be seen, but also model short-comings. A calibration and validation of the model was done and the verification of the model under Mediterranean field conditions with other compounds will be done in a near future.

On the other hand, Fuzzy logic is a very flexible model since it is capable to handle both qualitative and quantitative, correlated or completely uncorrelated variables, used widely (De Gruijter, et al., 2011; Shahmoradi, et al., 2013; Aroba, et al.,2007; Skarlatos, et al., 2013; D'Ercole, et al., 2000; Geographic Information Systems for Irrigation Management in Southwest Europe, 2012; Skarlatos, et al., 2004). It seems that the rule-based fuzzy modeling is a promising approach because can be applied in many topics of agriculture as selection a site for wastewater treatment plant (Shahmoradi, et al., 2013), or studied the effect of wastewater evapotranspiration on citrus cultivation (Skarlatos, et al., 2014). In collaboration with the colleges from Hellenic Open University (Patras, Greece), a study to show the long term effects of different irrigation water qualities under Mediterranean conditions though a Mamdani fuzzy modeling scheme, was done.

The application of fuzzy modeling showed that the fuzzy model can describe well the effect of the irrigation in the mandarin cultivation. This is because the models take into account a large number of parameters, whatever the degree of correlation between them. The division of the fuzzy model into sub models enables us to compare the effect of irrigation on individual characteristics of the system, such as the quality of the leaves, and soil. The model showed that the overall effect of watering with irrigation community water gives the best results, although, as the water quality from this treatment is not always the same because of the different water sources dotation, intensive soil status monitoring is needed to avoid the salt accumulation and a reduction in the physical soil properties. Sensitive indicators of soil status are therefore critical to allow monitoring of the effect of the application of these water sources. Among them, labile forms of soil organic carbon and variation in biological soil properties can be more efficient in highlighting also slight changes in soil quality status (Zang et al., 2015).

7. Conclusions

The developed work show the multidisciplinary approach on reclaimed water use projects in agriculture through an integrated methodology. This long-term multidisciplinary work at the crossover of environmental sciences, biology, chemistry, economic, agriculture and engineering, has generated novel strategies to describe and quantify the interactions of the use of saline reclaimed water for horticultural crops irrigation in agriculture. This approach will result in better understanding of the short and long-term effects of using saline reclaimed water in horticultural crops irrigation and will be a key challenge in promoting the expansion of water recycling for agricultural purposes, ensuring field sustainability and public safety. It will have a strong impact in the agriculture, but also in other fields where water management is of relevance. Therefore, for the preservation of profitable intensive agriculture that respects the environment, are needed innovative agricultural projects incorporating state of the art technologies in water reuse with multidisciplinary studies on salinity and toxic effects on crops at field, laboratory scale and long-term prediction, necessary to establish new reclaimed irrigation water strategies for the conservation of the natural environment.

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