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Research article

Agricultural reuse of municipal wastewater through an integral water reclamation management

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ABSTRACT

The DESERT-prototype, a state-of-the-art compact combination of water treatment technologies based on filtration and solar-based renewable energy, was employed to reclaim water for agricultural irrigation. Water reclaimed through the DESERT-prototype (PW) from a secondary effluent of a wastewater treatment plant, as well as conventional irrigation water (CW) and the secondary effluent (SW) itself, were employed to cultivate baby romaine lettuces in a greenhouse in Murcia (Spain), by means of drip and sprinkler irrigation methods, thus establishing six treatments. Assessments of physicochemical and microbiological quality of irrigation water, as well as agronomic and microbiological quality of crops from all treatments, showed that results associated to PW complied in all cases with relevant standards and guidelines. In contrast, results linked to SW and CW presented certain non-compliance cases of water and crop microbiological quality. These assessments lead to conclude that the DESERT-prototype is an appropriate technology for safe water reclamation oriented to agricultural production, that can be complemented by a proper irrigation method in reaching safety targets.

1. Introduction

Water scarcity is a main issue currently affecting a large part of the global population (Eslamian, 2016). Along with this reality, agriculture stands out as the economic sector with the highest water demands, representing about 70% of global freshwater withdrawals worldwide (Eslamian, 2016; The World Bank Group, 2016). Moreover, 28% of the global cropland and 56% of the global irrigated cropland are located in areas under high (40–80%) or extremely high (>80%) water stress, based on the ratio of water withdrawal over available water (Gassert et al., 2013). In this sense, water reclaimed from municipal wastewater has become one of the major and less expensive non-conventional water sources for agriculture (Drechsel et al., 2015; Eslamian, 2016), which is, with roughly 20 out of 200 million Ha of irrigated land worldwide (Jaramillo and Restrepo, 2017), the largest reclaimed water consumer (Lazarova et al., 2013), and one of the economic sectors in which its use shows its real benefits (Younos and Parece, 2016).

Agricultural irrigation with reclaimed water brings several advantages: reduction of pressure over freshwater sources (Eslamian, 2016; Parsons et al., 2010), presence of nutrients that reduce the use of synthetic fertilizers (Lyu et al., 2016; Pedrero et al., 2013b; Vicente-Sánchez et al., 2014; Vivaldi et al., 2015), higher yields than freshwater-irrigated counterparts (Vergine et al., 2016; Vivaldi et al., 2015), amongst others. Contrariwise, water reclamation mismanagement may also arise negative impacts for both the environment and human health (Eslamian, 2016; Lazarova et al., 2013). Probably the most recognized and characterized concern is the presence of pathogens that may enter the food chain (Castro-Ibáñez et al., 2015; López-Gálvez et al., 2016b). Furthermore, crops and soils may be affected due to increasing salinity (Jiménez and Asano, 2008; Pedrero et al., 2010), phytotoxic elements can

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affect growth of crops reducing yields (Parsons et al., 2010; Pedrero, 2010), and the structure of soils may result damaged due to high sodicity levels (Jiménez and Asano, 2008; Pedrero, 2010).

There are several studies focused on the effects of different reclaimed water sources over tree crops (Nicolás et al., 2016; Pedrero et al., 2013a, 2013b; Pedrero and Alarcón, 2009; Vivaldi et al., 2015), as well as horticultural crops (Cirelli et al., 2012; Hoque et al., 2010; López-Gálvez et al., 2016b, 2014). From the latter, health risks associated to the intake of raw-eaten leafy greens irrigated with reclaimed water, such as lettuces, take particular attention (Castro-Ibáñez et al., 2015; Ceuppens et al., 2015; Makkaew et al., 2016; Sales-Ortells et al., 2015). In this respect, several studies highlight the relevance of irrigation methods in reducing health risks (López-Gálvez et al., 2016b; Qadir et al., 2010; Uyttendaele et al., 2015). Irrigation methods are one of the most relevant interventions within the World Health Organization (WHO) 'multiple-barrier approach', which offers, besides wastewater treatment, strategies at key points that aims to a safe agricultural production, avoiding recontamination and cross-contamination within the farm-to-fork cycle (Al-Baz et al., 2008; Drechsel et al., 2015, 2010; WHO et al., 2006).

Despite the wide amount of studies remarking its obvious advantages, reclaimed water is still a largely underused resource: barely 15% of the generated wastewater and 41% of the treated wastewater are destined worldwide for agricultural irrigation in around 20 million Ha (Jaramillo and Restrepo, 2017; Valipour and Singh, 2016). Besides, a major problem in many countries is the lack of appropriate criteria and realistic standards for using reclaimed water (Paranychianakis et al., 2015). In some cases, specific criteria and guidelines are adapted from other contexts, thus being not correctly oriented to local realities (Fulazzaky, 2010, 2009; Jeong et al., 2016; Norton-Brandão et al., 2013), whereas in other cases appropriateness of water for different uses still needs to be verified (Fulazzaky, 2013). A broad range of water reclamation technologies is available nowadays, being virtually able to achieve any required quality (Lazarova et al., 2013). However, the trend on agricultural-oriented water reclamation is the fit-to-purpose combination of technologies, mainly filters and membranes following a conventional (primary or secondary) treatment (Wang et al., 2011), whose aims are: regulation of salinity levels to the crops' needs, retention of valuable nutrients in the reclaimed water, and reduction of pathogenic loads to safe levels for irrigation (De La Cueva Bueno et al., 2016; Lazarova et al., 2013; Norton-Brandão et al., 2013). Low-cost compact technologies, suitable for rural croplands, can be obtained by coupling solar energy able to tackle with the costs that energy demand of high-pressure membranes implies (De La Cueva Bueno et al., 2016; Lazarova et al., 2013). Furthermore, incorporation of fertigation equipment to these compact, off-the-grid reclamation trains, would offer an ultimate solution to agricultural needs, such as the case of the DESERT-prototype (see supplementary information) of the DESERT project (Water JPI, 2016).

To foster and increase the practice of irrigating with reclaimed water while effectively coping with the associated risks, it is necessary to involve different factors beyond reclamation technologies: irrigation methods, quality of waters, type and quality of crops, risk assessments, amongst others (Cirelli et al., 2012; Valipour and Singh, 2016). However, there is a severe lack of literature addressing irrigation of reclaimed water for horticultural production from a holistic point of view, encompassing the aforementioned factors (Norton-Brandão et al., 2013). In this context, the goal of the present study is to evaluate, from an integral perspective and under the scope of current standards and guidelines, the effects that different (conventional and non-conventional) irrigation sources and methods may have over physical, chemical and microbiological qualities of soil-cultivated lettuces.

2. Materials and methods

2.1. Experimental set up

Baby romaine lettuces (*Lactuca sativa* var. *romana*) were grown between November 2016 and January 2017 (60 days), in a 680 m^2 greenhouse located in the *Roldán, Lo Ferro y Balsicas* municipal wastewater treatment plant (WWTP) facilities in Murcia, Spain (latitude 37° 47′ 48″ N, *longitude* 0° 57′ 36″ W). Inside the greenhouse, average temperature, relative air humidity, and daily transpiration were 15 °C, 67%, and 0.5 L m^{-2}, respectively. The crops were cultivated on silty clay loam with average pH and electrical conductivity (EC) values of 7.6 and 1.7 dS m^{-1}, respectively. Lettuce was the selected crop because its growth and nutritional composition is largely influenced by salinity stress (Kim et al., 2008). Furthermore, it is a highly representative horticultural crop for assessing safe agricultural production: it is the most common raw-eaten vegetable and its leafy configuration may protect pathogens from light and desiccation, thus promoting their persistence (Petterson et al., 2001).

2.2. Irrigation water sources and methods

Three types of water were used for irrigation: 1) water reclaimed through the DESERT-prototype (PW), 2) conventional irrigation water (CW), and 3) the secondary effluent (SW) from the WWTP. PW was reclaimed after feeding SW to the DESERT-prototype, whose reclamation train consists of two 130 μm disk filters, one 0.08 μm capillary ultrafiltration (UF) membrane module, one granular activated carbon filter, and four composite polyamide multi-pass reverse osmosis (RO) membrane elements, powered by eight 54.7 V monocrystalline-cell photovoltaic (PV) panels. CW was provided by an irrigation community, and is a mix of different conventional and non-conventional sources: Tajo-Segura water transfer (88.7%), Segura river basin (3.0%), reclaimed water from WWTPs (6.7%) and Mojón desalination plant (1.6%) (C.R.C.C., 2017). This water was mainly used for agronomic quality control due to its appropriate salinity levels. SW was obtained from the WWTP, after a treatment that consisted of pre-treatment (coarse screen, fine screen, sieving, degritter and degreaser), double-stage activated sludge with prolonged aeration, and secondary clarifier. SW was employed as a model of water with low microbiological quality. Irrigation waters were fertilized based on their initial concentration of nutrients. In terms of $N - P_2O_5 - K_2O$, the fertilization throughout the experiment was 60.4 − 20.0 − 75.5 kg ha^{-1} (balance 1 − 0.33 − 1.25), respectively.

The total irrigated water amount of 1163 m^3 ha^{-1} was applied through two irrigation methods: drip irrigation (DI) and sprinkler irrigation (SI), with a flow of 2 and 40 L h^{-1}, per dripper and micro-sprinkler, respectively. These were chosen because they are the most representative systems for growing vegetables (FAO, 2017), and due to their opposite ways of exposing crops to irrigation waters, leading to different consequences regarding microbiological risk (Jiménez and Asano, 2008; Uyttendaele et al., 2015). To ensure that irrigation demands of lettuces were fully covered, soil moisture was kept at field capacity. Moisture tension at 15 cm-depth (root zone) was daily monitored using ceramic cup tensiometers (Irrometer, USA), resulting in a range of 10.6–12.9 kPA.

Combining the three waters (PW, CW, SW) and the two irrigation systems (DI, SI), six treatments were set: PW-DI, PW-SI, CW-DI, CW-SI, SW-DI, SW-SI, with four replicates each (Figure 1 of supplementary data). A total of 144 lettuces were planted per each treatment plot (spacing of 12 plants m^{-2}), on ridges using a