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Crop development based assessment framework for guiding the conjunctive use of fresh water and sewage water for cropping practice—A case study

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ABSTRACT

Sewage dilution and formulated fertilization are cost-effective to avoid sewage-deriving phytotoxicity stress and excess fertilizer application in agricultural sewage irrigation practice. However, it is hard for us to fix the parameters of sewage dilution ratio (SDR) and fertilization formula exactly for the best management of sewage irrigation practice according to those published guidelines. This paper presented such an assessment framework. The assessment tools in the framework consist of four consecutive sewage irrigation experiments, which include germination test, seedling test and cropping test for assessing sewage-deriving phytotoxicity stress in different crop development stages, and DRIS test for diagnosing crop nutrient deficiency. The framework is further verified with crop kale (*Brassica oleracea* L. var. *acephala* D.C.) under different pre-set SDR values. The results of germination, seedling and cropping tests can significantly reflect the change of sewage-deriving phytotoxicity with both SDR gradient and crop development stages. Furthermore, the results of DRIS test show that sewage irrigation causes the deficiency of N and P nutrients relative to K nutrient in crop kale. Finally, according to these test results, SDR values and fertilization formula are optimized for guiding the conjunctive use of sewage and fresh water in cropping practice. The framework is thus a best management tool supplementary for those published guidelines to enhance the efficiency and feasibility of agricultural sewage reuse.

1. Introduction

Sewage water, including raw, primary and secondary-treated effluents, have already been widely reused for agriculture and horticulture (Emongor and Ramolemana, 2004; Singh et al., 2012; Al-Khamisi et al., 2013). The reused sewage water generally exerts both positive and negative effects on crops in crop–soil–sewage system; this is especially true for the cases of nutrient supplement and environment stress. Sewage irrigation can enhance the concentrations of nitrogen and phosphorus and other nutrient in soil (Thapliyal et al., 2013), while some water pollutants such as salts, nitrates, heavy metal and pathogens, etc., often accumulate in soil and lead to phytotoxicity and potential secondary environment pollution (Jordan et al., 2001; Friedman et al., 2007; Qadir et al., 2010; Xu et al., 2010). The principal mechanism for overcoming any difficulties relating to sewage irrigation is the pre-treatment of sewage water. Reverse osmosis membrane filtration is just one of the effective techniques to remove salt molecules and ions, but it is far too expensive to be economically viable for crop irrigation (Toze, 2006). Therefore, a cost-effective strategy to relief the sewage-deriving stress is recommended with conjunctive use of reclaimed water and groundwater (Al-Khamisi et al., 2013). In doing so, refined management is crucial to improve crop yields. For example, those management approaches, such as transplanting older seedlings, applying balanced nutrients, etc., have great potential for enhancing yield in stress-prone rainfed coastal areas and will help sustain rice yield while ensuring sustainability of the cropping system (Sarangi et al., 2015). However, sewage water is often applied directly to crops, meanwhile fertilizers are also applied empirically for high crop yield in sewage irrigation practice, and

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it can thus easily lead to unbalanced or excessive nutrient supplement and increasing possibility of leaching (Blum et al., 2013). In order to refine the engineering management of conjunctive use of sewage and fresh water for cropping irrigation, it is important for us to establish an in-situ assessment method for fixing some key engineering parameters, especially sewage dilution ratios (SDRs) and fertilization formula based on crop development stages.

On one hand, SDRs can be easily set through sewage-deriving stress test. Many methods have been developed to test the environment stress. Bioassay methods are popularly used because of its ease of use in getting situ and direct results. Regarding phytotoxicity bioassay, seed germination, early seedling growth and root elongation tests have been well developed into phytotoxicity bioassay methods and adopted by regulatory agencies (Gong et al., 2001; Plaza et al., 2005). Recently crop seed germination test has been reported as a bioassay to assess the phytotoxicity caused by wastewater (Rivera et al., 2013). On the other hand, fertilization formula can be prescribed through crop nutrition diagnosis. There have been three main methods developed for assessing the crop nutrient deficiency, and the Diagnosis and Recommendation Integrated System (DRIS) method is especially claimed to have certain advantages over other tools (Srivastava and Singh, 2008). The DRIS technique is based on a comparison of calculated elemental ratio indices with established norms, which are defined as the average values of foliar nutrient ratio pairs for high yield stands (Beaufils, 1973). DRIS identifies nutrient constraint early in crop growth and allows sufficient time for remediation of identified problem right in the same growing season (Walworth and Sumner, 1987). Apparently, assessment and management of toxicological risks is the key step when establishing sewage irrigation based production (Salgot et al., 2006). Currently, most of guidelines and risk management on agricultural sewage irrigation focus mainly on food and environmental safety (Levy et al., 2010). The above-mentioned biological and chemical testing methods can only assess the effects separately and thus can't provide cropping-specified data for analysis. This study intends to establish a crop development based assessment framework for conjunctive use of sewage and fresh water for agriculture irrigation.

Most of the species of the Cruciferae family are well known as very important agriculture and/or horticulture crops, they are therefore of particular interests for agriculture environment risk evaluation. Kale (*Brassica oleracea* L. var. *acephala* D.C.) is one of them which is commonly used as an important potted flower and as a favorable vegetables in "baby" green salad due to its high levels of lutein and β-carotene, which is good for human health (Lefsrud et al., 2007). Its seeds are easy to obtain and germinate. The crop kale will be employed as material to carry out the experiments illustrating the assessment framework. The overall objectives of this study are: (1) To develop a crop development based framework to diagnosis crop stress and balance fertilization, and further to give some in-situ risk management recommendation for conjunctive use of sewage and fresh water in agricultural irrigation practice; (2) To verify the feasibility of the bioassay through a case study with crop kale.

2. Materials and methods

2.1. Assessment framework

Cropping management strategy generally changes with crop development stages, such as germination, seedling and maturity. Sewage irrigation may bring about phototoxicity to crop plants in all stages, while potential crop nutrient deficiency often occurred in maturity stage. Three bioassays, germination test, seedling test and cropping test, are designed for assessing crop phytotoxicity in the above three crop development stages, and a nutrient diagnosis method is established based on DRIS for assessing crop nutrient deficiency in maturity stage. The assessment framework has been shown in Fig. 1a, and the assessment can be implemented by following four steps:

Step I: Establishing assessment index system

Assessment index system of the framework include crop assessment indices and engineering-operating indices, the former mainly consist of Crop Stress Indicators (CSIs) and Crop Nutrition Indicators (CNIs), and the later of Sewage Dilution Ratio (SDR) and Sewage water quality indices (WQIs), see Fig. 1a. CSIs reflect the effects of sewage-deriving stress on the germination and crop growth, e.g., germination rate, root elongation, seedling and crop biomass (or yield). On the other hand, CNIs including macro- or micro- nutrients, and here we focus on the three macro-nutrients such as total nitrogen (TN), total phosphorus (TP) and total potassium (TK). CNIs can't be directly used to assess crop nutrient status before being transformed into Nutrient Imbalance Indices (NIIs). More details on NIIs see Step IV.

Step II: Phytotoxicity bioassay

Three bioassays, germination test, seedling test and cropping test, are designed to assess the crop phytotoxicity in germination, seedling and maturity stages, respectively, see Fig. 1a. Three random potting experiments are carried out for the bioassays through treating seed, seedling and mature crop plants with different SDR levels of sewage water. The potting medium and sewage-irrigating regime are implemented according to local cropping practice. SDR levels are generally suggested to set 4 values ranging from 0% (fresh water) to 100% (undiluted sewage water). Germination test method is modified from ISO guidelines (ISO, 2012) and seedling test and cropping test methods from OECD (2006). The three bioassays are conjunctively carried out in triplication during the periods of seed germination, seed germination to seedling transplantation and seedling transplantation to harvest. Meanwhile the responding values of CSIs or CNIs should be monitored for the next step of assessment. More details see Sections 2.2.2 and 2.2.3.

Step III: Crop nutrient diagnosis

Crop nutrient diagnosis test is arranged to assess the nutrient deficiency of adult crop under sewage irrigation condition. Here the method is slightly modified from the developed DRIS method (Gregoire and Fisher, 2004), see Table 1. In using the DRIS method, three crop macro-nutrient data, foliar TN, TP and TP, should be determined for the two types of populations, one is abnormal population (low-yielding group), the other is non-abnormal population (high-yielding group) (Beaufils, 1973), and all the experiment are arranged in triplication. In this assessment framework, the high-yielding group is achieved through treating the transplanted seedling with fertilizer and fresh water, and the low-yielding ones are just those treatment groups in cropping test. Up to the harvesting day, plants of all treatments are sampled to determine the CNIs and crop yield for calculating NIIs. More details see Step IV and Section 2.2.4.

Step IV: Risk assessment and management recommendation

Apparently, those pollutants impacting human health, such as heavy metals and pathogens, should be deeply concerned first of all in agricultural sewage irrigation. Many local or regional sewage reuse guidelines can present us strategies to assess and control these risks (WHO, 1989). As a supplementary tool of the published guidelines, this assessment framework focuses on optimizing SDRs and fertilization formula based on crop development stage. Normalized CSIs (NCSIs) are suggested so as to assess those phytotoxicity intensities scaled by different CSIs. NCSIs are calculated by $1–CSI_{m\%}/CSI_{0\%}$. Here $CSI_{m\%}$ means the CSI value of the crop in m% SDR treatment. It results in a positive correlation between the NSCI values and the intensity of crop stress. Through analyzing the correlationship between SDRs and NCSIs, SDR values are optimized