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Wastewater retreatment and reuse system for agricultural irrigation in rural villages

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ABSTRACT

Climate changes and continuous population growth increase water demands that will not be met by traditional water resources, like surface and ground water. To handle increased water demand, treated municipal wastewater is offered to farmers for agricultural irrigation. This study aimed to enhance the effluent quality from worn-out sewage treatment facilities in rural villages, retreat effluent to meet water quality criteria for irrigation, and assess any health-related and environmental impacts from using retreated wastewater irrigation on crops and in soil. We developed the compact wastewater retreatment and reuse system (WRRS), equipped with filters, ultraviolet light, and bubble elements. A pilot greenhouse experiment was conducted to evaluate lettuce growth patterns and quantify the heavy metal concentration and pathogenic microorganisms on lettuce and in soil after irrigating with tap water, treated wastewater, and WRRS retreated wastewater. The purification performance of each WRRS component was also assessed. The study findings revealed that existing worn-out sewage treatment facilities in rural villages could meet the water quality criteria for treated effluent and also reuse retreated wastewater for crop growth and other miscellaneous agricultural purposes.

Key words | agricultural irrigation, membrane filtration, nanobubble, ultraviolet disinfection, wastewater retreatment and reuse

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INTRODUCTION

The world population is expected to grow from 6.5 billion in 2010 to 9.5 billion in 2050, and the steadily increasing demand for manufactured goods pressures limited fresh water resources that are rapidly becoming unsustainable. A water crisis in South Korea was caused by imbalanced seasonal precipitation distribution (approximately two-thirds of annual precipitation occurred between June and September), less rainfall throughout the year (only 13% of global average, 2,591 m^3), and high population density (Korean Development Institute 2011). Therefore, the search for alternate water resources is more critical than ever and reuse of treated wastewater is the most recommended alternative, particularly for irrigated agriculture.

In Korea, the wastewater reuse rate was 7.14 million tons per year, ~10.8% (8.5% for agricultural irrigation) of the total amount of wastewater treated and discharged, and this trend is continuously increasing (Ministry of Environment 2009). With small-scale sewage facilities in rural villages, South Korea's public sewage system has a daily sewage treatment capacity of 50–500 m^3/day to prevent water pollution in agricultural districts. Even though rural treatment capacity is far less than that of wastewater treatment facilities (83,066.8 m^3/day) in medium-sized cities, it plays a role in water pollution prevention and supplies good-quality water resources.

Lee & Son (2009) found 50% of 932 small-scale sewage facilities exceeded the biological oxygen demand (BOD) standard. Many small-scale sewage facilities in rural villages require renovation due to age, upgrades to bring the facility in compliance with new wastewater treatment standards, uncertain sewage production, and increasing population connecting to a facility. Older facilities are likely not to meet current phosphorus and bacteria discharge requirements, which eventually cause water pollution from untreated and/or inadequately treated effluents.

Despite the fact that treated wastewater contains useful nutrients for crop growth, health-related problems may develop from dietary accumulation of heavy metals, such

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as Cd, Cr, Cu, Zn, and others. Therefore, wastewater reuse implementation has been restricted in Korea, and the Ministry of Construction & Transportation and Ministry of Environment proposed wastewater recycling and reuse water quality criteria (Ministry of Environment 2009).

Choosing the right wastewater treatment technology is most important in reuse system planning, to decrease or eliminate human health and environmental risks. A combination of biological, chemical (coagulants and flocculants), and physical (filtration, sedimentation, and flotation) removal processes are typical in wastewater treatment. There are also broad technologies available, including sequencing batch reactor, membrane filtration, and ultraviolet (UV) disinfection.

Filter applications have emerged as a promising alternative to conventional advanced physical–chemical treatment, which usually includes chemical coagulation, flocculation, and granular-medium filtration. Filtration is a cost-comparable application for removal of microorganisms, organic substances, ions and dissolved solids (Cleasby *et al.* 1989). UV irradiation emerged in France and the USA as a viable chlorination alternative with comparable, and often more effective, disinfection efficiency for virus and bacteria control. Memarzadeh *et al.* (2010) found that UV irradiation is a highly efficient and cost-competitive advanced disinfection process. The micro- and nanobubble process has promise in wastewater aeration by creating the 'permanent' benefit of gas exchange (CO_2 dosing and O_2 stripping) and no longer requiring large open tanks to achieve this (Lichtwardt & Murphy 2001; Zimmerman *et al.* 2011). In contrast with conventional flotation using coarse bubbles in wastewater systems, the smaller bubble size enormously influenced kinetics and oxidation process efficiency (Bartrand 2007).

We developed a new advanced wastewater retreatment and reuse system (WRRS) especially for old, small-scale sewage facilities in rural villages. This WRRS system consisted of three components: filters, UV light, and nanobubbles. The specific study objectives were (1) to assess the WRRS's ability to meet standards and improve the irrigation water quality, (2) to quantify the treatment efficiencies of each WRRS processing element, and (3) to conduct a greenhouse experiment to investigate any environmental and health-related risks from three irrigation water sources.

MATERIALS AND METHODS

Description of study site and WRRS

The small-scale sewage facility located in Sangju-city (Gyeongbuk Province, South Korea) is a typical aerobic digestion wastewater treatment system equipped with modified sequencing batch reactor, settling and aeration tanks, clarifier, digester, etc. Collected wastewater enters this facility and the daily treatment capacity is ~300 m^3 (500 m^3 of the facility's maximum capacity). This facility often experiences pollutant overload during the heavy rainfall season and on weekends.

The WRRS developed in this study was 184 cm high × 170 cm long × 97 cm wide and had three processing elements to remove residual suspended solids (SS), BOD, and total coliforms. As shown in Figure 1, these elements were filters (membrane filter (MF), autoscreen filter, and carbon filter (CF)); UV disinfection; nanobubbling.

Primary treated wastewater was pumped from a sewage facility discharge tank and injected into the WRRS collection tank using an inlet pump (Wilo Pumps Ltd, Busan, South Korea) with a maximum discharge capacity of 2,100 L/h. Wastewater passed through a pre-filtration membrane (PREFLOW I^{TM}, Chungsoo Technofil Inc., Hwaseong, South Korea), an autoscreen filter to remove residual SS,

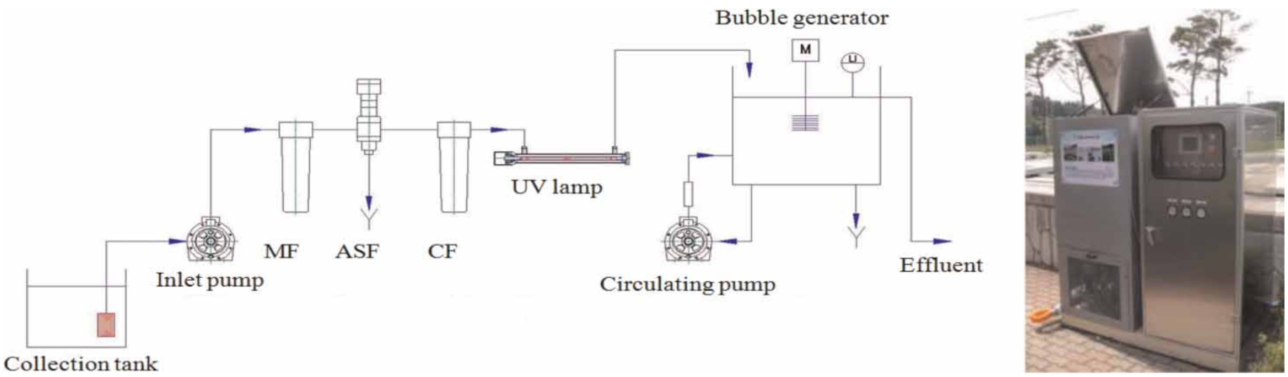

Figure 1 | Process chart of WRRS installed on a sewage facility discharge tank.

and a CF (CLEANFLOW^{TM}, Chungsoo Technofil Inc., South Korea) to deodorize unfavorable smell.

A flow-through UV disinfection element was covered by stainless steel for rust proofing. A quartz pipe 24.5 mm in diameter and 700 mm long with a UV lamp (Phillips Inc., Andover, Massachusetts, USA) inside was the element, and a modulating valve controlled the light intensity. The quartz pipe was designed with a programmable timed washing device to prevent fouling. The UV disinfection process was continuous (24 h/day), using 88 mW s/cm^2 of UV light.

A nanobubbler generator with linear flow and multiple air paths combined an impeller generator (Motor 0.4 KW × 2P, velocity control of inverter, 3,600 rpm) and a piping generator (220 V, 1.2 HP, maximum discharge capacity 9,600 L/h, Han-Il Corp., South Korea). It raised the air/water mixing ratio to 30% and uniformly distributed nanobubbles within a 90 cm (width) × 97 cm (length) × 107 cm (depth) tank. Daily maximum processing capacity was 28,800 L and the nanobubble generating pressure was 4 kg/cm^2. An average nanobubble was 100 nm in diameter and the rate was 4 L/min.

Wastewater sampling and analysis

During the study, effluents from the small-scale sewage facility and the WRRS were collected weekly and compared. Treatment efficiencies of each WRRS processing element were also evaluated. Wastewater samples were analyzed for physiochemical properties including pH, electrical conductivity (EC), SS, dissolved oxygen (DO), BOD, chemical oxygen demand (COD), nutrients (total nitrogen (TN) and total phosphorus (TP)), and pathogenic indicator organisms (total coliforms). To evaluate the WRRS performance, samples were collected for water quality evaluation at three steps in the retreatment process: the collection tank, after filtration, and the final effluent after application of UV and the nanobubbler generator. All wastewater quality components were analyzed according to *Standard Methods for the Examination of Water and Wastewater* (APHA 1999).

Greenhouse experiment irrigated with controls and WRRS effluent

The greenhouse experiment was conducted 16 September–14 December 2011, using 0.1 m^3 cultivation pots 1,000 mm (L) × 600 mm (W) × 310 mm (H). Potting soil up to 200 mm deep was placed in each pot and lettuce seeds were sown (Figure 2).

The experimental design applied three water sources to three replicate pots, for a total of nine experimental pots. Tap water was a control water source, and treated and retreated wastewaters were treatments. All water samples were periodically collected and analyzed for physiochemical properties, as described above, and also for macrocations (Ca, K, Mg, and Na) and heavy metals (Cd, Cu, Cr, Pb, and As).

A surface drip irrigation system was installed to directly apply the water to the soil surface and avoid water contact with plant surfaces. Plants were distributed randomly within pots and watered at the same time each day with a predefined amount of source water from the seedling stage until full maturity (harvesting). Throughout the growing period, from 3 to 30 L of water was irrigated to each pot depending upon the growth condition. A total of 90.8 L of water and no chemical fertilizer were applied during the study. Mechanical shading evenly distributed sunlight throughout the experimental blocks and the greenhouse remained under local ambient air temperature and relative humidity.

Soil and plant quality analysis

A commercially available bed of soil was used (Dongbu Hitech, Inc., Bucheon, South Korea) with 40–55% of water content, 55–65% of moisture holding ability, 0.2–0.4 Mg/m^3 of bulk density, pH of 5.5–7.0, $<$1.2 dS/m of EC, 200–350 mg/L of mineral nitrogen, 200–400 mg/L of P_2O_2, and $>$10 cmol$^+$/L of cation-exchange capacity. No hazardous components (Cd, Cr, Cu, Pb, and As) or pathogenic organisms were detected in the bed soil.

Soil samples were collected before, during, and after the experiment. Air-dried samples were analyzed for chemical properties (pH, EC, TN, P_2O_5, Ca, Mg, K, and Na) and heavy

Figure 2 | Experimental apparatus equipped with a drip irrigation system.

metals (Cd, Cr, Cu, Pb, and As). Lettuce samples were used to compare wet weight, leaf length, leaf width, and dry weight. For quality analysis, sampled lettuce leaves were dried for 48 hours at 70–75 °C, pulverized and then analyzed for TN, P_2O_5, CaO, K_2O, MgO, Na_2O, Cd, Cr, Cu, Pb, and As. The chemical components of the water, soil, and plant samples were analyzed using the standard methods for the examination of environmental pollution (Ministry of Environment 2004) and the standard method APHA-AWWA-WEF (1995).

The pH was measured using an EA 940 ion analyzer (Orion, Houston, TX, USA) and EC was measured using a Model 162 conductivity meter (Orion, Houston, TX, USA). The percentages of TN, P_2O_5, and available P_2O_5 were estimated by macro Kjeldahl, Vanadate (Wilde *et al.* 1972), and Lancaster methods (Alban *et al.* 1964), respectively. Heavy metals and cations in rainwater were measured using inductively coupled plasma optical emission spectroscopy (GBC Integra XMP, Dandenong, Australia) and inductively coupled plasma mass spectroscopy (HP, Agilent 7500cs, Santa Clara, USA) (APHA-AWWA-WEF 1995; Ministry of Environment 2004), respectively.

Statistical analysis

The experiment was repeated three times with means calculated. Using 5% as the level of significance, statistical analysis was subjected to analysis of variance followed by Duncan's multiple range tests (SAS9.1, SAS Institute Inc., Cary, NC, USA).

RESULTS AND DISCUSSION

Quality improvement of retreated wastewater using WRRS

The eight water quality components were compared among the control (tap water), Treatment 1 and Treatment 2 (treated and retreated wastewater) water resource from the sewage facility. Figure 3 shows that effluent BOD and total coliform exceeded water quality standards in the small-scale sewer facility effluents. Museums and tourist attractions located nearby caused high BOD and total coliform concentrations, particularly during weekends and holidays.

Retreated wastewater passed through the filter, UV, and nanobubbler system, as shown in Figure 4, improved water quality by 3–100% (representing a ratio of quality items before and after the WRRS, i.e. a ratio of WRRS-IN and WRRS-OUT). Suspended solids in retreated wastewater were reduced by carbon and MFs, and DO dramatically increased in the nanobubbler generator. In addition, UV sanitization reduced, or removed, total coliforms in retreated wastewater.

Each WRRS treatment process in Figure 5 showed water quality improvement (3–50% for filtration and 4–100% for UV/nanobubble, respectively). The total coliform reduction was greatest, followed by BOD, TN, TP, COD, and EC. Performance of filtration and UV/nanobubble varied depending upon water quality parameters, as shown in Figure 5. This indicates physical filtration effectively removed particulate phosphorus and total coliforms embedded in or attached to the surface of particles, and UV/nanobubble use enhanced the overall wastewater treatment performance.

Plant growth response for different irrigation waters

Lettuce growth rate was measured over time and triplicate measurements were taken of leaf number, leaf length, leaf width, and dry weight; averages were reported. At the early stage of cultivation, there was no distinct difference between control and treatments, but over time, significant differences were observed in number of leaves, dry weight, and wet weight, but not in leaf length and width (Table 1).

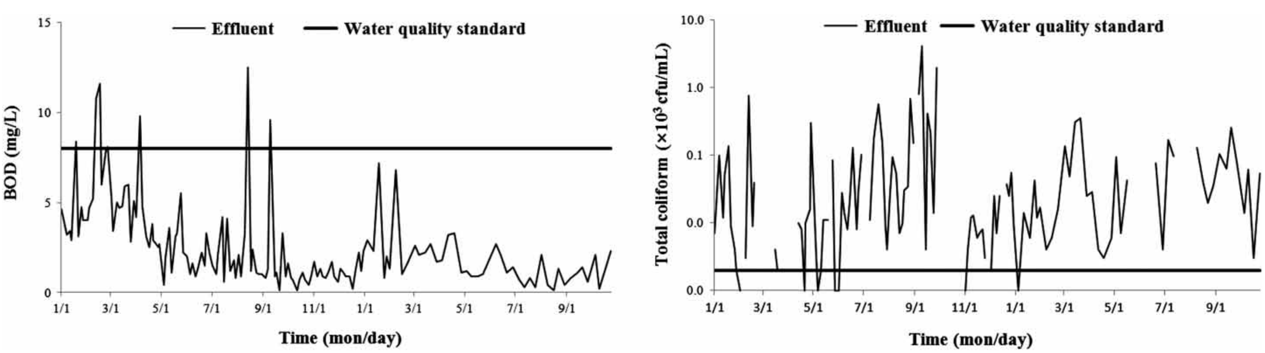

Figure 3 | Time-variant change of influent and effluent quality from a sewage facility (2010–2011).

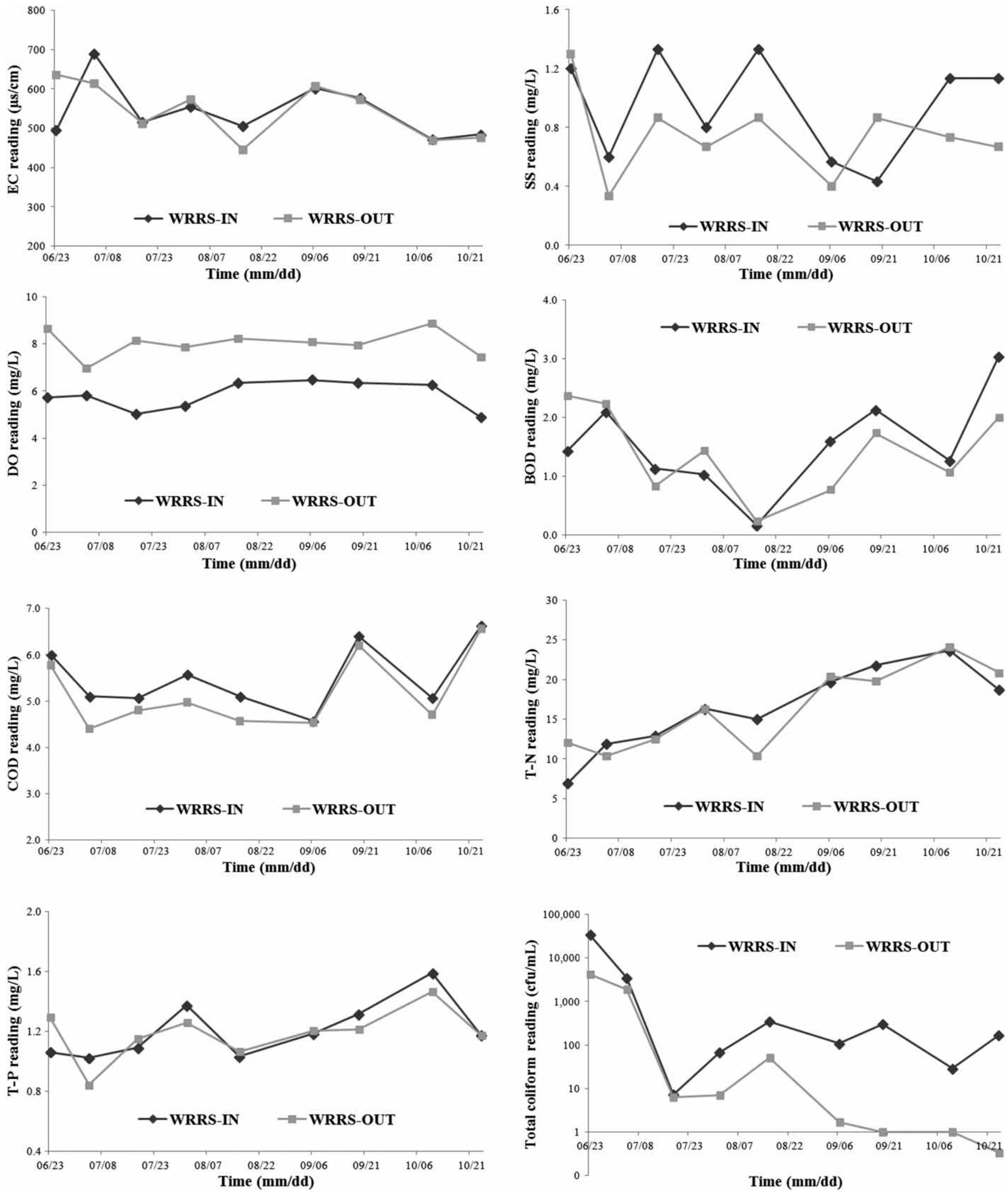

Figure 4 | Performance comparison of WRRS-retreated wastewater from sewage treatment system.

Overall, lettuce irrigated with retreated wastewater (Treatment 2) exceeded the size of lettuce irrigated with treated wastewater (Treatment 1) and tap water (Control). This might be caused by three reasons: (1) an increase of DO, (2) the large specific surface area of the nanobubbles, and (3) negative electronic charges on the nanobubbles.

The overall ranking of the percent elemental concentration in different irrigation water sources was: Ca > Na >

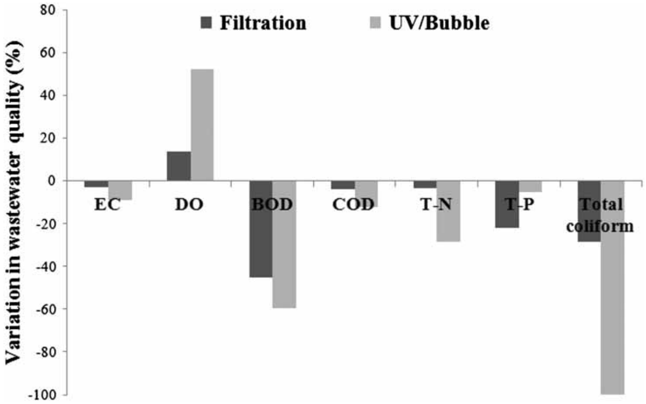

Figure 5 | Effect of water quality improvement using WRRS.

K ≈ Mg (tap water), Na > Ca > K ≈ Mg (treated wastewater), and Na > Ca > Mg ≈ K (retreated wastewater), respectively (data not shown). Concentrations of Na, Ca, Mg, and K were significantly ($p < 0.05$) greater in treated, and retreated, wastewaters than in tap water. This differs from a previous study by Adeyeye (2005) where the general pattern of cations was ranked: Mg > Na > K > Ca, and caused by the wastewater properties. We found an increase in cations (Na, K, Ca, and Mg) in soil irrigated with treated and retreated wastewaters before the experiment began, and after the final harvest. Thus, irrigation with wastewater generally increased soil fertility. However, the effect was clearly seen in plant fortification, growth and yield, and soil nutrient status.

Heavy metal concentrations in soil and lettuce

Harvested lettuce leaves and soils were analyzed for differences in physicochemical properties and residual heavy metals among the control and two treatments. The magnitude of heavy metals detected in soil from each irrigation source was ranked in order: Cr > As > Pb > Cu (Control), Cr > As > Pb > Cu (Treatment 1), and Cr > As > Pb > Cu (Treatment 2). On the other hand, the magnitude of heavy metals detected in lettuce irrigated with different water sources was ranked in order: Cu > Pb > Cr > As (Control), Cu > As > Cr > Pb (Treatment 1), and Cu > As > Pb > Cr (Treatment 2).

Table 2 | Maximum permissible concentrations of metals in soil and plant

Metal	Soil	Plant	Metal	Soil	Plant
Cd	3	0.2	Pb	300	5.0
Cr	400	NA	As	NA	NA
Cu	50	40.0			

Sources: USEPA (ppm) for soil, WHO/FAO/Indian standard (mg/kg) for plant.

Following the criteria proposed by USEPA for soils, and the WHO/FAO/Indian standard for plants (Table 2), the grand mean values of Cd, Cr, Cu, Pb, and As were within the safe limit and not in the toxic range (Maninder *et al.* 2011). Heavy metal accumulation in soil and subsequent uptake by lettuce revealed that the mean levels of all the metals were not significantly different among the control and two treatments (Figure 6) and residual cadmium was not detected in any soil or lettuce samples.

It was interesting that the residual metal concentration in soil and uptake by lettuce varied from metal to metal, depending upon irrigation sources, and did not follow any particular pattern. This is because heavy metals existing in soils and plant uptake are influenced by variable reactions, such as adsorption, ionic exchange, redox reaction, precipitation, and dissolution (Igwe *et al.* 2005).

Table 1 | Comparison of plant growth in response to different irrigation sources

Date	Treatment[a]	No. of leaf (ea/plant)	Leaf length (cm)	Leaf width (cm)	Dry weight (g)	Fresh weight (g)
27 September (after planting)	Control	5.8 a[b]	10.84 a	7.40 a	0.19 a	2.80 a
	Treatment 1	5.9 a	11.41 a	7.84 a	0.20 a	3.14 a
	Treatment 2	6.0 a	10.99 a	8.01 a	0.21 a	3.13 a
4 October (during the crop growth)	Control	7.8 ab	17.65 a	11.57 b	0.58 b	11.43 b
	Treatment 1	8.7 a	18.33 a	12.93 a	0.77 a	14.77 a
	Treatment 2	7.7 b	17.32 a	12.52 a	0.61 ab	12.07 b
10 October (during the crop growth)	Control	11.2 b	20.92 b	20.33 a	1.59 a	38.25 a
	Treatment 1	12.5 a	22.73 ab	18.98 a	1.68 a	40.47 a
	Treatment 2	12.8 a	24.48 a	18.90 a	1.72 a	42.88 a
14 October (after crop harvesting)	Control	13.7 b	23.45 a	19.72 a	2.43 b	63.05 b
	Treatment 1	14.5 ab	23.48 a	21.97 a	3.16 a	80.92 a
	Treatment 2	15.5 a	24.0 a	21.23 a	3.43 a	91.08 a

[a]Treatment 1 (treated wastewater), Treatment 2 (retreated wastewater using WRRS).
[b]Mean separation within columns by Duncan's multiple range test, 5% level.

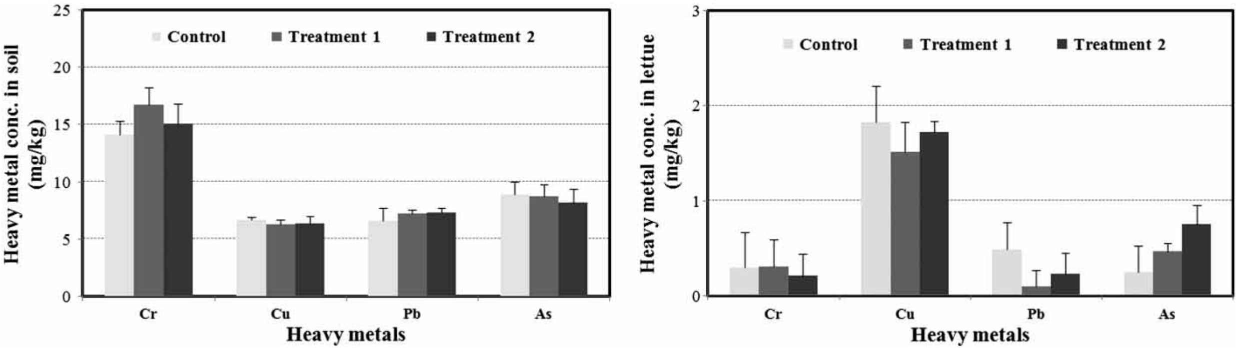

Figure 6 | Comparison of heavy metals in soil and lettuce irrigated by different water sources.

CONCLUSIONS

Water demand already exceeds supply in many parts of the world facing water shortages during the next decade. Wastewater treatment operators are seeking alternatives to conventional chlorination and de-chlorination prior to reuse as irrigation or discharge into aquatic environments. New technologies that improve water treatment capabilities and reduce energy consumption are poised for significant growth due to increased demand for water. Membrane filtration, UV disinfection, and nanobubble oxidation have recently received much attention because no chemicals are added and energy use is relatively low.

The WRRS process we developed outperformed the existing sewage facility, and retreatment reduced the magnitude of EC, SS, BOD, COD, TN, TP, and total coliforms in wastewater discharge from 3 to 100%. Dissolved oxygen increased up to 62% in retreated wastewater samples. This implies that WRRS integrated with MFs, UV light, and nanobubble generator would effectively improve wastewater quality discharged into neighboring streams and lakes and meet the water quality standard for agricultural irrigation.

The amounts of major nutrients and exchangeable cations in treated and retreated wastewater were higher than in tap water, which was relevant to their increases in soil and plants. Comparison of crop yield among different irrigation water treatments showed a 7.4% increase from treated wastewater irrigated plots and an 11.7% increase from retreated wastewater irrigated plots as compared with tap water irrigated plots. Residual values in soil and plant were far less than the permissible limits and safe for agricultural irrigation. Overall, this study revealed that the implementation of WRRS with pre-existing sewage facilities could reduce UV sanitization and chemical application at wastewater treatment facilities, ensuring the availability of water for food, and is economically and environmentally beneficial for sustainable agriculture.

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