Utilization of artificial recharged effluent for irrigation: pollutants’ removal and risk assessment
Liangliang Wei, Kena Qin, Qingliang Zhao, Kun Wang, Felix Tetteh Kabutey and Fuyi Cui

ABSTRACT
The reclaimed water from soil aquifer treatment (SAT) column was reused for irrigation as the source water, pollutants’ removal and health risk assessment was analyzed via the comparison with secondary and tertiary effluents. The effect of the SAT pre-treatment on the qualities and growth of different crops (Lachca sativa – lettuce, Brasica rapa var chinensis – pak choi, Cucumis sativus – cucumber, Brassica oleracea – cabbage, and Zea mays – maize) were evaluated. Experimental results demonstrated that the tertiary and SAT treatments had no significant effect on the crop qualities, and could efficiently decrease the accumulation of heavy metals (especially for SAT pre-treatment). Moreover, the carcinogenic risk of the chemical carcinogens for the 1.5 m SAT effluent irrigation declined roughly an order of magnitude as compared with the secondary effluent, and three to four orders of magnitude decreasing of the virus risk. These findings are significant for the safe and cheap reuse of secondary effluent for irrigation purposes.

INTRODUCTION
Water shortage is a serious environmental issue in arid and semi-arid regions that requires the exploration of water reuse options (Bakopoulou et al. 2011; Wei et al. 2012). To solve the water crisis throughout the world, rainfall, deep groundwater, seawater, etc., have been recognized as new alternative water resources (Elimelech & Phillip 2011; Erban et al. 2017; Jung et al. 2015). However, exploitation of the above water resources is always restricted by the local, economic and technological conditions, which limits their further application (Busch & Mickols 2004; Henriques et al. 2015). Considering that municipal wastewater treatment plants (WWTP) produce stable and abundant flows during different seasons, development of secondary effluent as an attractive alternative for water reuse is practically urgent (Kalkan et al. 2011; Zucker et al. 2015). Thus, how to efficiently recharge and then reuse the secondary effluent is rapidly becoming a necessity for many municipalities throughout the world (Wei et al. 2009). Generally, the traditional reuse approaches of secondary effluent include mainly agricultural irrigation, industrial processing, cooling water, toilet flushing, wetland habitat creation, restoration and maintenance, groundwater recharging, landscape water replenishment, among others (Bunani et al. 2015).

China is one of the largest agricultural countries in the world and the amount of water used for agriculture irrigation accounts for about 70% of the total water consumption (Li et al. 2010; Zhao et al. 2014). However, the lack of water sources constrains the development of agriculture (especially for northwest China), and the increase in population and shrinking of water supplies has strengthened this water shortage (Huang et al. 2012). Recently, the search for a renewable water source, such as secondary effluent, for agricultural irrigation is considered to be practically applicable. However, a relatively high level of heavy metals,
persistent organic pollutants, salt ions, and other elements, as well as a certain amount of pathogenic bacteria have provided limits to its direct agricultural reuse (Rizzo et al. 2014). Earlier work by Lado et al. (2012) demonstrated that a significant accumulation of total organic matter, Cu, Ni, Zn and B in the top 1.0–1.5 m soil layer during long-term irrigation (>7 yr) with secondary treated wastewater, might be potentially toxic to some sensitive crops. Friedman et al. (2007) observed that higher levels of nitrogen and Mn were accumulated in celosia and phosphorus in sunflower during irrigation with secondary-treated municipal effluents. Recent work by Bakopoulou et al. (2011) pointed out that secondary effluents produced in the Thessaly region are suitable for irrigation reuse, especially for crops which are not used raw by humans; however, the seasonal and site-specific inhibition of growth on the plants were noted. Oron et al. (2006) stated that a UF/RO system would significantly improve the water quality of the secondary effluent, and minimize the health risk of agricultural products which had been irrigated with reclaimed wastewater. Generally, the existence of heavy metals, salinity, sodium, residual chlorine and other containments could partially affect plant growth, and consequently negatively affect the crop characteristics and soil properties. To effectively remove these hazardous pollutants in the secondary effluent, pre-treatments such as coagulation, ozone oxidation, granular activated carbon adsorption and membrane filtration have been applied as tertiary treatments (Bixio & Wintgens 2006; Kalkan et al. 2011; Pramanik et al. 2015). Generally, the above-mentioned pre-treatments are expensive and need chemical additions or regeneration steps. Therefore, less expensive and environmentally friendly methods for secondary effluent pre-treatment are desired.

Soil aquifer treatment (SAT) is an artificial water recharge technique frequently used to renovate domestic effluents for potable and non-potable purposes (Xue et al. 2013; Schaffer et al. 2015). The water quality is substantially improved via the integrated functions of biological, chemical, and physical processes in the aquifer (Hübner et al. 2014). To this end, the SAT system may be an alternative approach to the treatment of secondary effluent, and it has the advantages of lower cost, easier operation and greater efficiency. The SAT system can store the reclaimed water in the aquifer layer, with no evaporation losses and also can achieve inter-seasonal and inter-year storage (Dillon et al. 2006). Although several studies in the past years have attempted to explore secondary effluent as a water resource for agriculture irrigation, to the authors’ knowledge seldom do researchers mention the application of SAT as a pretreatment for secondary effluent irrigation.

The goal of this work was to: (1) study the effect of SAT pre-treatment on water quality for irrigation; (2) evaluate the effect of SAT pre-treatment on production of typical agricultural crops; and (3) assess the possible health risk of reusing the reclaimed water for irrigation.

MATERIALS AND METHODS

Experimental water quality

Secondary effluent was obtained from the Taiping WWTP, Harbin (China). Collection of secondary effluent was performed at least once a month between February 2012 and August 2014. The secondary effluent had a pH value of 7.2 ± 0.1, chemical oxygen demand (COD) of 45.1 ± 5.2 mg/L, dissolved organic carbon (DOC) of 10.1 ± 1.3 mg/L, ultraviolet light adsorption at 254 nm (UV-254) of 14.3 ± 2.1 m⁻¹, with suspended solids (SS) of 13.9 ± 6.2 mg/L, ammonia of 10.2 ± 2.1 mg N/L, nitrate of 21.7 ± 2.1 mg N/L, chlorine of 121.7 ± 7.1 mg/L, SO₄²⁻ of 59.0 ± 8.1 mg/L, total hardness of 157.2 ± 15.1 mg CaCO₃/L, and TP of 1.2 ± 0.3 mg/L. The tertiary effluent was obtained from the pre-treatment of the secondary effluent by ferric chloride coagulation/sand filtration.

SAT system set-up and operation

Laboratory-scale soil column system which simulated aquifer conditions in a series of three 55 cm columns (diameter 10 cm) was constructed and operated for a period of more than two years, which was operated with a cycle of 16 h wetting/8 h drying. The influent was pumped upwards through the column at a desired flow rate of 15 mL/h controlled by a peristaltic pump. A complete description of the operation parameters of the SAT system is given in Xue et al. (2007). Experimental soil samples were collected from the dry bed of Songhua River in Harbin (potential recharge sites). After
air drying, soil samples with particles greater than 2 mm were sieved out, then packed into the columns and further compacted to field density. The soil samples had an average pH of 8.2, organic carbon content (OC) of 2.9%, cation exchange capacity of 7.4 cmol/kg, and soil composition of 49.3% sand, 44.5% silt, and 6.2% clay, respectively.

Simulation of agricultural irrigation of crops

Secondary, tertiary (coagulated-filtrated) and the SAT effluents were used for irrigation purposes, with tap water as a control. Five different types of crops, namely (*Lachca sativa* – lettuce, *Brasica rapa var chinensis* – pak choi, *Cucumis sativus* – cucumber, *Brassica oleracea* – cabbage, and *Zea mays* – maize) were used for irrigation purposes, with tap water as a control. Five different types of crops, namely (*Lachca sativa* – lettuce, *Brasica rapa var chinensis* – pak choi, *Cucumis sativus* – cucumber, *Brassica oleracea* – cabbage, and *Zea mays* – maize) were selected as experimental objects, in which the lettuce and pak choi (common names) were used for studying the effect of different irrigation regimes on the inhibition/promotion of the growth and yields of vegetables, while cucumber, cabbage, and maize (common names) were used for evaluating accumulation of heavy metals in the crops.

After irrigation, the soil samples were air-dried, crushed and passed through a 2-mm sieve for further analysis. Soil pH and electrical conductivity were determined from suspension with a 1:1 soil:water ratio according to US Environmental Protection Agency (EPA) methods 9050 and 9045C, respectively. Calcium carbonate (CaCO₃) was measured with a calcimeter. Soil elements (K, Ca, Mg, Na, Cu, Fe, Mn, Zn, Ni, Cr, and Pb) were extracted after digestion with 3:1 (V/V) concentrated HCl-HNO₃ and measured by atomic absorption spectrophotometer (ICP-AES, Optima 5300DV, Perkin Elmer, USA).

Phytotoxicity of the irrigated water samples on crops’ growth

The phytotoxicity of the irrigated water samples was evaluated according to Bakopoulou et al. (2011), where the microbiotest measures the root growth rate of lettuce and pak choi periodically. Specifically, 10 seeds of each plant were placed at equal distances near the middle ridge of the test plates on black filter paper placed on reference soil which was hydrated with secondary, tertiary, and SAT effluents. Another series of plates (containing reference soil) was hydrated with tap water as a control. Three replicates were used for each plant species. The plates were placed vertically in a holder and incubated for 3 days at 25 °C in the dark. Pictures of the test plates at the end of the exposure period were taken by a digital camera and the length of the root of each plant was measured using the Image Tool 3.0 software (UTHSCSA, USA). The percent inhibition of root growth was calculated according to Bakopoulou et al. (2011).

Fresh weight (wt weight) of the vegetables and leaves was recorded immediately after 40 days’ growth. Specifically, the collected vegetables and leaves were first washed with tap water, then rinsed with distilled water and dried in an oven at 80 °C for 72 h, finally ground in a stainless steel mill and retained for further analysis (Singh & Bhati 2005).

Accumulation of heavy metals in the crops after irrigation

The crops cucumber, cabbage, and maize used for the irrigation study were planted in spring and harvested in autumn, and irrigated in the same condition (irrigation was performed once 3–5 d, 2 L water/strain). For comparison, the secondary effluent, tertiary effluent, and SAT effluent (0.5, 1.0, and 1.5 m) were selected as the irrigation water samples. Once the crops were harvested, each of the samples was immediately collected and homogeneously mixed and then stored in plastic bags for further analysis.

Chemical analysis

All the collected water samples were filtrated using 0.45 µm cellulose nitrate membrane filter and stored at 4 °C prior to analysis. Parameters, namely, pH, water content, organic matter, COD, soluble COD (SCOD), total nitrogen (TN), NH₄⁺-N, NO₃⁻N, and total phosphorus (TP) of the dewatered sludge were analyzed according to Standard Methods (APHA 2005). Samples for the analyses of heavy metals within the vegetables were pre-treated by wet-clear up-method (HNO₃: HClO₄ = 4:1), the concentration of heavy metals in the extracts was then determined using inductively coupled plasma atomic emission spectroscopy (ICP-AES, Optima 5300DV, Perkin Elmer, USA). Before the trihalomethane formation potential analysis, all the water samples were diluted to produce a DOC concentration of 1 mg/L. The concentration of DOC
and UV-254 was analyzed using Shimadzu TOC-5000 total organic carbon analyzer and Shimadzu UV-2550 ultraviolet-visible spectrophotometer (Shimadzu, Japan).

RESULTS AND DISCUSSION

Pollutants’ removal during the artificial SAT system operation

As shown in Table 1, more than 70% of NH$_4^+$-N, TP, biochemical oxygen demand (BOD$_5$), Cr, Cd, As, Zn, Ni, and Mn in the secondary effluent was efficiently removed during the laboratory-scale 1.5 m depth SAT operation, ascribing to the efficient filtration, adsorption, and biodegradation within the vadose ozone and aquifer zone of the SAT system (Dillon et al. 2006; Alidina et al. 2014). The artificial SAT system also exhibited an efficient removal of the organic matter in secondary effluent, with a removal efficiency of 51.3% for COD and 58.7% for TOC. The majority of those removed organics were non-aromatic components, as evident by a relatively lower reduction of 35.7% for UV-254. For comparison, a relatively lower removal efficiency of 19.4% for NO$_3^-$-N, 30.0% for SO$_4^{2-}$, and 32.1% for Cl$^-$ was observed when the SAT operation progressed. The hardness of the SAT effluent increased 55.3% as compared to the secondary effluent, ascribing to the desorption and cation exchange of the sediments within the packed soil (Candela et al. 2007; Long et al. 2011; Qiu et al. 2016). As the bulk removal efficiency of pollutants for the artificial 1.5 m SAT column is much lower than the actual groundwater recharging systems, the reusing of SAT effluent for agricultural irrigation water is meaningful in practice. In addition, the top layer of the SAT system played a key role in pollutants’ reduction during the secondary effluent recharging process, evidenced by the predominant removal of most pollutants within the top 0.5 m depth soil, noted in Table 1.

Generally, the tertiary treatment of coagulation/filtration showed a relatively lower removal rate of the organic contaminants, NH$_4^+$-N, Cl$^-$ and majority heavy metal ions, leading to an average removal efficiency of 17.1% for COD, 53.8% for BOD$_5$, 35.7% for TOC, 32.1% for NH$_4^+$-N, and 10.3% for Cl$^-$, respectively. For

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Secondary effluent</th>
<th>Tertiary effluent</th>
<th>SAT effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD (mg/L)</td>
<td>45.1 (29.4)</td>
<td>0.5 m (23.8)</td>
<td>1.0 m (22.1)</td>
</tr>
<tr>
<td>BOD$_5$ (mg/L)</td>
<td>24.6 (11.4)</td>
<td>0.5 m (7.3)</td>
<td>1.0 m (4.9)</td>
</tr>
<tr>
<td>TOC (mg/L)</td>
<td>17.4 (11.4)</td>
<td>0.5 m (4.9)</td>
<td>1.0 m (3.3)</td>
</tr>
<tr>
<td>SS (mg/L)</td>
<td>13.9 (5.4)</td>
<td>0.5 m (3.3)</td>
<td>1.0 m (2.2)</td>
</tr>
<tr>
<td>UV$_{254}$ (mg/L)</td>
<td>0.14 (0.01)</td>
<td>0.5 m (0.01)</td>
<td>1.0 m (0.01)</td>
</tr>
<tr>
<td>Turbidity (NTU)</td>
<td>6.2 (2.2)</td>
<td>0.5 m (1.1)</td>
<td>1.0 m (0.7)</td>
</tr>
<tr>
<td>Hardness (mg CaCO$_3$/L)</td>
<td>57.6 (47.2)</td>
<td>0.5 m (40.0)</td>
<td>1.0 m (34.0)</td>
</tr>
<tr>
<td>pH</td>
<td>7.2 (7.1)</td>
<td>0.5 m (7.2)</td>
<td>1.0 m (7.1)</td>
</tr>
<tr>
<td>mg CaCO$_3$/L</td>
<td>157.2 (121.7)</td>
<td>0.5 m (10.1)</td>
<td>1.0 m (5.1)</td>
</tr>
<tr>
<td>mg CaCO$_3$/L</td>
<td>45.1 (29.4)</td>
<td>0.5 m (23.8)</td>
<td>1.0 m (22.1)</td>
</tr>
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</tr>
<tr>
<td>mg CaCO$_3$/L</td>
<td>0.14 (0.01)</td>
<td>0.5 m (0.01)</td>
<td>1.0 m (0.01)</td>
</tr>
<tr>
<td>mg CaCO$_3$/L</td>
<td>6.2 (2.2)</td>
<td>0.5 m (1.1)</td>
<td>1.0 m (0.7)</td>
</tr>
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<td>1.0 m (7.1)</td>
</tr>
</tbody>
</table>
In comparison, a relatively higher removal rate of 29.0% for NO\textsubscript{3}\,-N, 42.9% for UV-254, and 92.3% for Pb was also observed. Previous study demonstrated that the existence of non-biodegradable organic, phytotoxic metals like Cr, Pb, Cu, Mn, and Zn in secondary effluent markedly enhanced the phytotoxicity of the target crops (Ellouze et al. 2009; Ma et al. 2015), thus, the efficient removal of these pollutants during SAT operation might guarantee a safe agricultural reusing of secondary effluent.

**Inhibition/promotion of irrigation on vegetable growth and yields**

The growth conditions of vegetable after irrigation with different water samples could be reflected by the root growth inhibition rate, and the results of the lettuce and pak choi after the irrigation are shown in Figure 1. Regarding toxicity of different effluents on lettuce, secondary effluent collected from the WWTP exhibited a higher growth inhibition than that of tertiary effluent and SAT effluent, and a significant root growth inhibition rate of 21.3% was observed. Correspondingly, the irrigation with tertiary and SAT effluents enhanced the growth of lettuce, as evidenced by a negative root growth inhibition rate of −15.7% for tertiary and −11.6% for SAT effluents. For comparison, all three irrigated water samples (secondary, tertiary, and SAT effluents) improved the growth of pak choi during the laboratory-built irrigation systems operation, and the corresponding growth inhibition rate noted in Figure 1 exhibited a decreasing trend of secondary effluent (−5.9%) > tertiary effluent (−21.6%) > SAT effluent (−23.2%). This might be because some essential nutrients which are beneficial for crop growth were being supplied by the irrigated secondary/tertiary and SAT effluents (Kalkan et al. 2011; Norton-Brandão et al. 2013), in addition to some other hazardous heavy metals, pesticides, and pathogens that might jeopardize sustainable irrigation (Chan et al. 2014). Overall, the toxicities of the SAT effluent were collectively the lowest for pak choi, while tertiary effluent was for lettuce.

In comparison to the tap water, the irrigation with secondary, tertiary, and SAT effluents increased the productivity of lettuce and pak choi slightly. For example, the average leaf area of the pak choi was 10.7 cm\textsuperscript{2} for secondary effluent irrigated samples and 9.4 cm\textsuperscript{2} for SAT effluent; this is much higher than that of the tap water irrigated samples (7.8 cm\textsuperscript{2}). As shown in Figure 2, the wet weight of lettuce averaged 0.51 g after 40 days’ irrigation with secondary effluent, 0.43 g for tertiary effluent, and 0.44 g for SAT effluent, respectively, with that of the tap water being the lowest (0.37 g). In comparison, the wet weight of the pak choi after 40 days of irrigation decreased in the sequence of secondary effluent (0.33 g) > tertiary effluent (0.29 g) > SAT effluent (0.27 g) > tap water (0.19 g). Obviously, total productivity of the lettuce and pak choi were increased significantly after the irrigation with secondary effluent and advanced treated effluent, and was similar to the observation of Al-Lahhama et al. (2003), who reported that the diameter and weight of tomatoes from wastewater irrigated plants was much higher than those with potable water.
Accumulation of heavy metals in vegetables during agricultural irrigation

Heavy metals in irrigated water samples can accumulate in the soil, and can further be taken up by crops during long-term irrigation (Gupta et al. 2012; Khan et al. 2013). Generally, the uptake and accumulation of non-biodegradable heavy metals in crops during different irrigation regimes is dependent on the concentrations/solubility of the metal ions in the irrigated water samples and soils, as well as the plant species growing in these soils (Gebrekidan et al. 2013; Ma et al. 2015). As shown in Figure 3, the accumulation of the six typical heavy metals (Cr, Pb, Cd, Cu, Zn, Ni) in crops differed widely during the irrigation with secondary, tertiary, SAT effluents, and tap water. Generally, Zn was the element which easily accumulated in maize, and the other five elements which exhibited a decreasing trend of Cu > Ni > Pb > Cr > Cd, are similar to the observations of Weldegebriel et al. (2012). In addition, the concentration of Zn and Pb in cucumber, cabbage, and maize after irrigation decreased in the trends of tap water < SAT effluent < tertiary effluent < secondary effluent, implying a potential linear relationship between the accumulation of heavy metals and their concentration in the irrigated water.

As shown in Figure 3, the concentration of Cr in the SAT effluent irrigated maize accounted for 34.9% and 40.5% of the bulk accumulation of Cr in the secondary and tertiary effluents irrigated samples, respectively, and was 50.8% and 76.2% for cucumber and 58.1% and 46.4% for cabbage for comparison. Similarly, the concentration of Pb in the SAT effluent irrigated cucumber, maize, and cabbage decreased 61.1%, 43.8%, and 27.3% in comparison with the secondary effluent irrigated crops, respectively. Concentration distribution of element Cd exhibited a similar trend after the irrigation with SAT effluent and secondary effluent. Thus, a general conclusion that can be drawn from the above is that the reuse of SAT effluent would decrease the accumulation of heavy metals of Cr, Pb, and Cd in vegetables as compared with that of secondary and tertiary effluents. Conversely, the concentration of Cu, Zn, and Ni in the SAT effluent irrigated crops only decreased 9.3 ~ 2.9% for cucumber, 11.4 ~ 9.1% for cabbage, and 11.3 ~ 3.2% for maize in comparison with the corresponding crops irrigated with tap water and tertiary/secondary effluents. Generally, the accumulated Cr, Pb, Cd, Ni in cucumber was significantly decreased for SAT effluent irrigation, and Cr, Pb, Cu for cabbage, and Cr, Pb, Cd and Cu for maize. This demonstrates that SAT pre-treatment was efficient and useful for heavy metal pollution control during secondary effluent irrigation.

Carcinogenic risk of heavy metals during irrigation with different effluents

The risk effect of heavy metals and other contaminants during the different effluents’ irrigation, which consisted
of carcinogenic and non-carcinogenic risks, were assessed and the results are shown in Tables 2 and 3. Specifically, the elements Cd, Cr, and Pb were selected as the chemical carcinogenic heavy metals, while Cu, Ni, Zn, Mn, Hg, dimethylbenzene, and ethylbenzene were chosen as the non-carcinogenic elements. For the health risk of the non-carcinogenic components, a maximum acceptable level of 5.0 × 10⁻⁴/yr is recommended by the International Commission on Radiological Protection (ICRP), which can be calculated from a statistical model as follows (Niu et al. 2014; Cui & Zhou 2015):

\[ P_i = \frac{(d_i \times 10^{-6})}{RfD_i} \]  

(1)

where \( P_i \) is the lifetime risk caused by chemical non-carcinogen \( i \); \( d_i \) (mg/kg-d) represents the mean exposure dosage per weight per day; \( RfD_i \) (mg/kg-d) is the reference dosage related to the chemical non-carcinogen \( i \), thus 0.001 for Cd, 0.005 for Cr, 0.0014 for Pb, 0.02 for Ni, 0.037 for Cu, and 0.3 for Zn, respectively (Zhang et al. 2014).

Parameter of exposure dosage \( d_i \) can be expressed in linear form in Equation (2) as:

\[ d_i = CW \times IR \times EF \times ED / (BW \times AT) \]  

(2)

where \( CW \) (mg/L) is the concentration of the chemical carcinogen in reclaimed water; \( IR \) refers to the exposure dosage of the reclaimed water, averaged 2 L/d during the agricultural irrigation; \( EF \) represents the exposure frequency (365 d/yr); \( ED \) is the exposure time, averaged 70 years for Chinese individuals; \( BW \) denotes the averaged body weight of the worker for irrigation (averaged 70 kg in China), and \( AT \) means the regional averaged life span.

The risk to health caused by chemical carcinogens can be estimated by Xu et al. (2014) as:

\[ P_i = [1 - \exp(-d_i f_i)] \]  

(3)

where \( P_i \) is the lifetime risk caused by chemical carcinogen \( i \); \( d_i \) (mg/kg-d) is the mean exposure dosage per weight per day; \( f_i \) (kg-d/mg) is the carcinogenic intensity coefficient,

Table 2  | Health risk of the non-carcinogenic chemicals of the secondary, tertiary, and SAT effluents’ irrigation

<table>
<thead>
<tr>
<th>Secondary effluent</th>
<th>Tertiary effluent</th>
<th>0.5 m SAT effluent</th>
<th>1.5 m SAT effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lifetime risk ( P )</td>
<td>Annual risk ( P_a )</td>
<td>Lifetime risk ( P )</td>
</tr>
<tr>
<td>Cd</td>
<td>2.86 × 10⁻¹⁰</td>
<td>4.08 × 10⁻¹²</td>
<td>1.43 × 10⁻¹⁰</td>
</tr>
<tr>
<td>Cr</td>
<td>2.62 × 10⁻¹⁰</td>
<td>3.74 × 10⁻¹²</td>
<td>2.38 × 10⁻¹⁰</td>
</tr>
<tr>
<td>Pb</td>
<td>2.04 × 10⁻¹⁰</td>
<td>2.92 × 10⁻¹²</td>
<td>1.02 × 10⁻¹⁰</td>
</tr>
<tr>
<td>Ni</td>
<td>3.57 × 10⁻¹¹</td>
<td>5.10 × 10⁻¹³</td>
<td>2.86 × 10⁻¹¹</td>
</tr>
<tr>
<td>Cu</td>
<td>2.32 × 10⁻¹¹</td>
<td>3.31 × 10⁻¹³</td>
<td>1.74 × 10⁻¹¹</td>
</tr>
<tr>
<td>Zn</td>
<td>1.19 × 10⁻¹¹</td>
<td>1.70 × 10⁻¹³</td>
<td>6.67 × 10⁻¹²</td>
</tr>
<tr>
<td>( \sum P_i / \sum P_{ai} )</td>
<td>8.23 × 10⁻¹⁰</td>
<td>1.18 × 10⁻¹¹</td>
<td>5.36 × 10⁻¹⁰</td>
</tr>
</tbody>
</table>

Table 3  | Carcinogenic risk of the secondary, tertiary, and SAT effluents in agricultural irrigation

<table>
<thead>
<tr>
<th>Secondary effluent</th>
<th>Tertiary effluent</th>
<th>0.5 m SAT effluent</th>
<th>1.5 m SAT effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lifetime risk ( P )</td>
<td>Annual risk ( P_a )</td>
<td>Lifetime risk ( P )</td>
</tr>
<tr>
<td>Cd</td>
<td>1.74 × 10⁻⁶</td>
<td>2.49 × 10⁻⁸</td>
<td>8.14 × 10⁻⁷</td>
</tr>
<tr>
<td>Cr</td>
<td>3.81 × 10⁻⁵</td>
<td>5.44 × 10⁻⁷</td>
<td>2.93 × 10⁻⁵</td>
</tr>
<tr>
<td>Pb</td>
<td>2.43 × 10⁻⁹</td>
<td>3.47 × 10⁻¹¹</td>
<td>1.21 × 10⁻⁹</td>
</tr>
<tr>
<td>( \sum P_i / \sum P_{ai} )</td>
<td>3.98 × 10⁻⁵</td>
<td>5.69 × 10⁻⁷</td>
<td>3.01 × 10⁻⁵</td>
</tr>
</tbody>
</table>
and is 6.1, 41, and 0.0085 for Cd, Cr, and Pb, respectively (Ni et al. 2009):

\[ d_i = y_i \times C_i / 70 \]  \hspace{1cm} (4)

where \( C_i \) (mg/kg) denotes contents of pollutants; 70 (kg) refers to the mean weight of human body; and \( y_i \) means the ingestion quantity of the chemical carcinogen.

The health risk of the different effluent irrigations via the food chain can be calculated based on the hypothesis that the exposure frequency is once per day, with an exposure dosage of 10 mL. As shown in Table 2, the calculated annual risk of the chemical non-carcinogens during the secondary effluent irrigation was \( 1.18 \times 10^{-11} \), and decreased to \( 7.62 \times 10^{-12} \) for tertiary effluent, and further declined to \( 3.64 \times 10^{-12} \) for the 1.5 m depth SAT effluent. It is obvious that irrigation using the SAT effluent would significantly decrease the health risk of chemical non-carcinogens to farmers, and is meaningful for agricultural irrigation purposes.

As shown in Table 3, the carcinogenic risk caused by inhalation during the secondary, tertiary, 0.5 m depth SAT and 1.5 m depth SAT effluents’ irrigations were \( 5.69 \times 10^{-7} \), \( 4.31 \times 10^{-7} \), \( 3.50 \times 10^{-7} \), and \( 4.58 \times 10^{-8} \), respectively, and are much lower than the threshold value \( (5.0 \times 10^{-5}/yr) \) recommended by ICRP. Overall, the carcinogenic risk of the chemical carcinogens during the SAT effluent irrigation was approximately an order of magnitude lower than the irrigation with secondary effluent. Moreover, element Cr contributed as much as 80% of the bulk carcinogenic risk during the SAT effluent irrigation, and was the predominant precursor of the chemical carcinogens within the SAT effluent.

**Virus risk assessment during irrigation with different effluents**

The pathogenic bacteria found in the irrigated water samples were mainly intestinal virus (e.g., Coxsackie, rotavirus and hepatitis A virus), and the probability of infection of these viruses can be calculated based on the beta-Poisson model as:

\[ P_i = 1 - [\frac{d}{N_{50}}(2^{\alpha} - 1)]^{-\alpha} \]  \hspace{1cm} (5)

where \( P_i \) is the probability of infection; \( d \) is the mean dose of pathogenic bacteria ingested into the human body; \( N_{50} \) refers to the median effective dose, representing the number of pathogenic bacteria that can infect 50% exposure crowd, the corresponding \( N_{50} \) of rotavirus, hepatitis A virus and Coxsackie were 5.6, 30, and 1,004.6, respectively. In addition, \( \alpha \) is the slope parameter describing the host–pathogen interaction (the ratio of \( N_{50} \) to \( P_i \)), and the value of \( \alpha \) was 0.265 for rotavirus, 0.2 for hepatitis A virus and 0.374 for Coxsackie (Fattal et al. 2004).

Assuming that the annual exposure frequency of the irrigated water to a farmer was 40 times per year, with an exposure dosage of 1 mL every time, the corresponding infection probability of the secondary, tertiary, 0.5 m depth SAT and 1.5 m depth SAT effluents were calculated and the results are listed in Table 4.

As shown in Table 4, the annual risk of rotavirus to the farmer was \( 6.72 \times 10^{-4} \) for the secondary effluent irrigation, which exceeded the maximum acceptable value of EPA \( (10^{-4}/yr) \) for individual risks. For comparison, the calculated annual risk of the tertiary effluent irrigation
declined to $5.28 \times 10^{-6}$, and further to $1.83 \times 10^{-7}$ for the 1.5 m SAT effluent. Similarly, the annual risk of the hepatitis A virus to farmers during the secondary effluent irrigation also exceeded the EPA benchmark, indicating that the typical virus in the secondary effluent should be of a high concern for its potential human health risk. As expected, the health risk of hepatitis A virus during the tertiary and SAT effluents’ irrigation was much lower, and both can meet the requirement of the criteria of EPA. Generally, the annual risk of a typical virus during the SAT effluent irrigation was three to four orders of magnitude lower than that of the secondary effluent irrigation, clearly demonstrating that the control of health risks during the secondary effluent irrigation would benefit from the pre-treatment of SAT.

CONCLUSION

The following conclusions are drawn based on the presented experimental results:

1. SAT system exhibited a relative higher removal efficiency of most pollutants within the secondary effluent as compared to the tertiary treatment, especially for the reduction of $\text{NH}_4^+$, TP, BOD$_5$, Cr, Cd, As, Zn, Ni, and Mn.

2. Irrigation with secondary, tertiary, and SAT effluents enhanced the growth of pak choi, with a root growth inhibition rate of −5.9% for secondary, −21.6% for tertiary, and −23.2% for SAT effluents, respectively. The noticeable toxicity of secondary effluent was observed for the growth of lettuce with a positive root growth inhibition rate of 21.3%, while the irrigation with the tertiary and SAT effluents enhanced the growth of lettuce. Moreover, irrigation with secondary, tertiary, and SAT effluents led to slight increases in the productivity both for lettuce and pak choi.

3. SAT pre-treatment was efficient for heavy metal pollution control during secondary effluent irrigation. Specifically, accumulation of Cr, Pb, Cd, Ni in cucumber during the SAT effluent irrigation significantly declined as compared to the irrigation with tap water, tertiary/secondary effluents, and Cr, Pb, Cu for cabbage, and Cr, Pb, Cd, and Cu for maize.

4. The carcinogenic risk of the chemical carcinogens during the 1.5 m SAT effluent irrigation was approximately an order of magnitude lower than that of secondary effluent irrigation, and the corresponding annual risk of Cox sackie, rotavirus and hepatitis A virus declined three to four orders of magnitude.

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REFERENCES


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