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Study on rules of dynamic variation of nitrogen in soil after reclaimed water drip irrigation

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ABSTRACT

Reclaimed water belongs to one of makeup waters to be applied to agricultural production, which can not only reduce the quantity of wastewater effluent, but also reduce the quantity in demand of good-quality water, and is key element in utilization of limited water resources. Through field experimental method and taking drip irrigation, the regulation of reclaimed water drip irrigation on dynamic variation of nitrogen in soil was studied in this paper. The results indicate that compared to the contrast treatment, NH₄⁺ – N content in the surface layer increased sharply in the initial period after reclaimed water drip irrigation, and then decreased significantly in the fifth day, and down to the level before irrigation on the ninth day, which was uniform between soil layers. NO₃-N content under all the treatments presented the almost same trend in soil profile: NO₃-N content increased with the soil depth, indicating an obvious tendency of NO₃-N leaching down to lower layers. However, at the depth of 100–150 cm, NO₃-N content began to decrease. When reclaimed water drip irrigation was used for cucumber planting, NO₃-N content in different layers at the ending of the growing period increased by 38.20%, 44.67%, 34.94%, 30.88%, respectively, than that before planting.

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Introduction

Reclaimed water belongs to one of makeup waters to be applied to agricultural production, which can not only reduce the quantity of wastewater effluent, but also reduce the quantity demanded for good-quality water, and is key element in utilization of limited water resources with high efficiency. Yet, contaminating materials in the wastewater have not been fully removed as the result of economic and

technical difficulties. The N and P element, higher salt content, various toxic trace substances and pathogenic agent abounded in reclaimed water possibly become new pollution source which could bring about adverse impact to the quality of soil and crop [1,2].

Reclaimed water belongs to the water resource which is reclaimed from non-conventional water resources such as the effluent discharged from sewage disposal plant, industrial water drainage and domestic wastewater that could be recycled for specific utilization due to acceptable water quality

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after proper treatment [3–6]. Yet, the worldwide scarcity of water resources pushes on reuse of wastewater. It's estimated that water scarcity in China would reach $1.3 \times 10^{10} \text{ m}^3$ and the quantity in demand of reclaimed water would reach $7.67 \times 10^{10} \text{ m}^3$ in 2030. However, such countries as US, Australia, Israel, Japan and France etc. have already adopted reclaimed water as one of important solutions to alleviate the crisis of water resources. Furthermore, gross amount in demand of reclaimed water in Israel, Australia and Tunis etc. has respectively reached 25%, 11% and 10% total demand of water resources. Whereas reclaimed water is mainly applied to farming irrigation, the Werdbbee Farm in Australia began to apply reclaimed water to irrigation since 1897, and 42% reclaimed water has already been applied to farming irrigation in US, but the irrigation by reclaimed water now is at starting point in China, e.g. Beijing Municipality plans to establish 40,000 hm^2 reclaimed water irrigated area and utilize $3 \times 10^8 \text{ m}^3$ reclaimed water in 2010. Along with the increase of reclaimed water irrigation area for 30 years, the safety and environmental impact of which has attracted wide attention [7–13]. The trend of irrigation by reclaimed water is spread worldwide and such countries as US, Australia, India, Israel and former USSR etc. have abounded in successful experience in utilization of poor quality water. But for long time, research fellows have only been focusing on the study of water salinity of irrigation water quality instead of in-depth and systematic study of chemical composition of irrigation water and its impact against physicochemical property of soil. Therefore, many countries recently began to focus on the study of impact from reclaimed water irrigation against soil physicochemical property and reclaimed water utilization approach [14–17].

On the one hand, reclaimed water irrigation can reduce serious non-point source pollution resulted from direct irrigation by wastewater, provide important nutrient to plant growth, promote plant growth and enhance crop yield [18–21]; on the other hand, superfluous nutrients, toxic chemicals and pathogenic agents will simultaneously enter environmental ecosystem along with the irrigation by reclaimed water, which would result in environmental pollution [22,23] and probably imperil human health. Moreover, the nitrogen also is one of key factors [23–25] in water body pollution and eutrophication even though it's one of important elements to make up biomass. Meanwhile, through excessive application of nitrogenous fertilizer and such human activities as unrestricted discharge of domestic sewage etc., massive nitrogen remains in soil after rejection by the crop and which would bring about latent and real environmental pollution [26–28] through volatilization, sprinkling or runoff etc. with composition pattern of $\text{NO}_3^- - \text{N}$ and $\text{NH}_4^+ - \text{N}$. Therefore, the study of nitrogen in soil, especially the dynamic variation of $\text{NO}_3^- - \text{N}$ and $\text{NH}_4^+ - \text{N}$ provides important theory and instruction to prediction and control of agricultural non-point source pollution.

Besides, with such characteristics as keeping watering duration, watering amount and soil moisture range in high control, drip irrigation can adjust soil moisture and nutrient according to soil physical property [29–33], distribution of crop root system and consumptive use of crop, and ensure crop yield with good quality and high yield while reducing agricultural non-point source pollution. The reuse of rural

domestic sewage through drip irrigation will enhance utilization efficiency of such nutrients as nitrogen and phosphorus etc. in reclaimed water, which saves fertilizer, water and increases crop yield while reducing redundant pollutant entering environmental ecosystem, meanwhile it's significant in relief of water resources crisis [34–36], prevention and treatment of agricultural non-point pollution as well as promotion of recycling economy. Under similar conditions, this experiment compares and researches the rules of dynamic variations of nitrogenous agent in soil after drip irrigations by reclaimed water and groundwater with different proportion.

Material & method

Overview of experimental field

The experimental field is entitled “Pilot Zone of Agricultural Non-point Source Pollution Control in Water Source Area at Centerline of South-to-North Diversion Project”, which is jointly established by Geographical Science & Resources Research Institute to Chinese Academy of Sciences and Policy & Engineering Research Center to South-to-North Diversion Project to State Council. The experimental field is located in mountainous area at south part of Maojian District, Shiyan City, Hubei Province, where belongs to subtropical monsoon climatic region with 4 distinctive seasons and enjoys such characteristics as longer wintertime and shorter summertime, faster temperature rise during springtime, continuous precipitation during autumn days, less sleet during wintertime, relatively higher temperature during wintertime with less bitter cold, annual solar radiation of 106.6 kcal/cm^2 , physical radiation of 50.4 kcal/cm^2 , annual average sunshine duration of 1925.8 h, mean annual temperature at 15.3°C , extreme minimum temperature at -14.9°C , extreme maximum temperature at 41°C , $\geq 10^\circ\text{C}$ annually accumulated temperature of 4936.5°C , annual frost-free period for 246 days, mean annual precipitation of 855 mm, great fluctuation in annual rainfall, rainfall during flood period (from May 1st to October 20th) accounted for 58%–62% annual rainfall, which is endowed with great intensity, short duration, limited infiltration and liability to scour and erode ground surface. In addition, the soil in experimental field belongs to yellow–brown soil with unit weight between 1.56 and 1.71 g/cm^3 .

Tentative layout

The experiment was conducted during growing period of cucumber in 2011 from September 20th to December 10th. Ridge planting is applied to the cucumber cultivation with 60 cm-wide ridge shoulder, 15 cm-high ridge height, 140 cm spacing between centerlines of two ridges, 2-row planting in the ridge and 40 cm-wide plant spacing. Diammonium phosphate compound fertilizer is applied to the field with proportion of 20kg/mu before cucumber planting, and composition of irrigated water is classified with 3 marks as T1 (fully irrigated by reclaimed water), T2 (irrigation by water combined with 50% reclaimed water and 50% groundwater) and C (fully irrigated by groundwater), which is detailed in Table 1 below. The 3-classification experiment shall be

Table 1 – Experimental drip irrigation by reclaimed water.

Mark	Composition of irrigated water
T1	Reclaimed water
T2	50% reclaimed water in total amount
C	Groundwater

conducted in 3 experimental plots, and every experimental plot enjoys 4 m × 4 m area and includes 3 ridges with 4 m-long length. The gravity drip irrigation shall be applied to the experiment with one drip irrigation hose embedded along centerline of every ridge, 20 cm dripper spacing equal to plant spacing, dripper discharge of 2.7 L/h, i.e. One dripper for one cucumber root. Each 3-category experiment (including 3 experimental plots) shall be equipped with 1 water tank (volumetric capacity of 240 L) which is positioned some 1.2 m away from the ground for water supply. In the second experimental plot, one set of negative pressure gauge shall be embedded 20 cm deep beneath the dripper, when the gauge indicates that soil water potential is lower than −25 kPa, drip irrigation shall be initiated with the amount of 5mm/time and totally 7 times with gross amount of 35 mm during growing period of cucumber.

Besides, reclaimed water to be applied to this experiment is rural domestic wastewater filtrated through multi-layer soil percolation system [7,37,38], and water quality of groundwater, domestic wastewater and reclaimed water is shown in Table 2, with which it can be seen that treatment effect of domestic wastewater through the simple multi-layer soil percolation system is not as good as expected, there are many indicators of reclaimed water still slightly exceeding national standard values.

Measurement & method

The test shall be conducted during a watering duration within the cucumber growing period. Whereas drip irrigation for cucumber planting initiates on October 7th, it's required to carry out soil sampling in the second day, 5th day and 9th day after the irrigation with sampling depth 0–10 cm, 10–20 cm, 20–40 cm, 40–60 cm, 60–90 cm and 90–100 cm. 1 mol/L KCl lixiviation

process – flow analyzer shall be applied to the measurement of soil $\text{NO}_3^- \text{N}$, and 2% K_2SO_4 lixiviation process – flow analyzer shall be applied to the measurement of soil $\text{NH}_4^+ - \text{N}$.

Analysis of results

Dynamic variation of ammonium nitrogen in soil after drip irrigation with reclaimed water

Fig. 1 indicates dynamic variation of $\text{NH}_4^+ - \text{N}$ content in soil within a watering duration through different treatments. It can be seen from the Figure that the variation of $\text{NH}_4^+ - \text{N}$ in soil is mainly influenced by drip irrigation. The content of $\text{NH}_4^+ - \text{N}$ in topsoil has been keeping in relatively high level 3 days before drip irrigation, but the content of $\text{NH}_4^+ - \text{N}$ in soil began to increase after drip irrigation T1 and T2, and which remarkably lowered 5 days after drip irrigation, and even lowered to the level before watering on 9th day after drip irrigation, showing uniform distribution in all soil layers. Due to extremely low content of $\text{NH}_4^+ - \text{N}$ in groundwater, the content of $\text{NH}_4^+ - \text{N}$ in soil profile varies little after drip irrigation with groundwater, and topsoil only shows a small amount of accumulation of $\text{NH}_4^+ - \text{N}$ content, the major cause probably is that the increase of soil water content varies mineralization rate of nitrogen in soil and nitrification rate of $\text{NH}_4^+ - \text{N}$ in soil, i.e. relatively great soil moisture provides favorable condition to mineralization of nitrogen in soil while inhibiting nitrification of $\text{NH}_4^+ - \text{N}$ after drip irrigation, and short-time accumulation of $\text{NH}_4^+ - \text{N}$ takes place due to that mineralization rate probably is obviously faster than nitrification rate of $\text{NH}_4^+ - \text{N}$ in the meantime.

Dynamic variation of nitrate nitrogen in soil after drip irrigation with reclaimed water

Fig. 2 indicates dynamic variation of $\text{NO}_3^- \text{N}$ content after drip irrigation with different treatments. It can be seen from the Figure that $\text{NO}_3^- \text{N}$ content shows consistent variation along soil profile, i.e. gradually increasing from topsoil down to bottom layer. On the second day after drip irrigation, the content of $\text{NO}_3^- \text{N}$ increases obviously in bottom layer of soil, but begins to decline since 5th day after drip irrigation, and

Table 2 – Comparison between water quality index, measuring method & national relevant standards.

Item	Groundwater	Domestic wastewater	Reclaimed water	Analysis method	Irrigation water quality standard (GB5084-2005)-vegetable [11]
COD_{Cr} (mg L ⁻¹)	3.21–5.83	450–730	68–112	Dichromate process	100
$\text{NH}_3\text{-N}$ (mg L ⁻¹)	0.08–0.17	73–108	14–29	Nessler's reagent colorimetric method	–
Turbidity	0.4–2	20–113	21–98	Turbidity meter	–
SS (mg L ⁻¹)	2–10	60–190	30–60	Gravimetric method	60
Temperature	10–20	14–38	14–38	Thermometer	–
pH	7–8	6–9	6–9	Glass electrode method	6–9
BOD_5 (mg L ⁻¹)	1.2–2.33	179–271	28–47	Dilution inoculation method	40
DO (mg L ⁻¹)	0.21–0.14	2.9–5.7	2.0–4.8	Portable dissolution measuring apparatus	≥0.5
TN (mg L ⁻¹)	0.99–2.03	53–79	17–37	Ultraviolet spectrophotometry	≤30
TP (mg L ⁻¹)	0.08–0.22	4.9–10.4	4.1–9.3	aluminic acid Spectrophotometric method	≤30

Fig. 1 – Variation of NH_4^+ – N content in soil after different treatments.

Fig. 2 – Variation of NO_3^- – N content in soil after different treatments.

nearly matches with the content of NO_3^- N on 9th day after drip irrigation. Whereas the content of NO_3^- N in soil begins to gradually rise along with the increase of depth, hence we select T1 approach and compare the variation of NO_3^- N content in soil layer with depth between 0 and 200 cm before watering at the beginning of growing period and after watering at the end of growing period, this 2-process measurement is conducted once every 50 cm deep as shown in Fig. 3. It's measured out that the content of NO_3^- N in soil increases 38.20%, 44.67%, 34.94% and 30.88% respectively at soil layers (0–50 cm, 50–100 cm, 100–150 cm and 150–200 cm) before watering. But which begins to decline at the depth of 1.5 m.

Conclusion

The influence on soil dispersion rate and saturated hydraulic conductivity which is resulted from reclaimed water irrigation is correlated with the frequency of continuous irrigation with reclaimed water. This article concluded as follows:

The content of NH_4^+ – N in topsoil sharply increases after drip irrigation with reclaimed water, but obviously declines on 5th day after drip irrigation and lower to original level on 9th day after drip irrigation. The content of NO_3^- N in soil after different treatments shows consistent variation, i.e. gradually increasing from topsoil down to bottom layer, which shows obvious process of downward spread of NO_3^- N content. But NO_3^- N content begins to decline at the depth between 100 and

150 cm, which indicates that the content of NO_3^- N averagely increases 38.20%, 44.67%, 34.94% and 30.88% respectively at the depths (0–50 cm, 50–100 cm, 100–150 cm and 150–200 cm) when drip irrigation with reclaimed water is suspended at the end of cucumber growing period.

Fig. 3 – Variation of NO_3^- – N content in different soil layers.

Due to there is enrichment of pollutant in soil to a certain degree under the condition of drip irrigation with reclaimed water, there must be some contaminants entering ground-water system when contaminant concentration in reclaimed water reaches great degree [39,40], and which might bring about adverse impact to soil environment, plant growth and crop yield.

At present, ecological risk of new-type contaminant in utilization of irrigation with reclaimed water is attracting widespread attention from the research fellows. However, it's appropriate to enhance relevant scientific research and subsequently provide scientific references to risk control in spite of various categories, complexity in transformation of soil ecosystem, lack of relevant environmental standards and difficulty in effectively evaluating environment risk with existing data.

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REFERENCES

- [1] Irénikatché Akponikpè PB, Wima Koffi, Yacouba Hamma, Mermoud Andre. A reuse of domestic wastewater treated in macrophyte ponds to irrigate tomato and eggplant in semi-arid West-Africa: benefits and risks. *Agric Water Manag* 2011;98:834–40.
- [2] Jang Taeil, Lee Sae-Bom, Sung Choung-Hyun, Lee Han-Phil, Park Seung-Woo. Safe application of reclaimed water reuse for agriculture in Korea. *Paddy Water Environ* 2010;8:227–33.
- [3] Jang TI, Kim HK, Seong CH, Lee EJ, Park SW. Assessing nutrient losses of reclaimed wastewater irrigation in paddy fields for sustainable agriculture. *Agric Water Manag* 2012;104:235–43.
- [4] Joo JH, Lee SB. Effects of several Silicate fertilizer on Potato-grown field. *J Agric Life Environ Sci* 2011;23:29–33.
- [5] Jung KW, Yoon CG, Jang JH, Jeon JH. Characteristics of indicator microorganisms in paddy rice plots after reclaimed water irrigation. *Water Sci Technol* 2007;55:267–73.
- [6] Kang MS, Kim SM, Park SW, Lee JJ, Yoo KH. Assessment of reclaimed wastewater irrigation impacts on water quality, soil, and rice cultivation in paddy fields. *J Environ Sci Health A* 2007;42:439–45.
- [7] Lu Shibao, Pei Liang, Bai Xiao. Study on method of domestic wastewater treatment through new-type multi-layer artificial wetland. *Int J Hydrogen Energy* 2015;40(34):11207–14.
- [8] Pereira BFF, He ZL, Stoffella PJ, Melfi AJ. Reclaimed wastewater: effects on citrus nutrition. *Agric Water Manag* 2011;98:1828–33.
- [9] Antonopoulos Vassilis Z. Modelling of water and nitrogen balances in the ponded water and soil profile of rice fields in Northern Greece. *Agric Water Manag* 2010;98:321–30.
- [10] Xu J, Peng S, Yang S, Wang W. Ammonia volatilization losses from a rice paddy with different irrigation and nitrogen managements. *Agric Water Manag* 2012;104:184–92.
- [11] Singh PK, Deshbhratar PB, Ramteke DS. Effects of sewage wastewater irrigation on soil properties, crop yield and environment. *Agric Water Manag* 2012;103:100–4.
- [12] Lu S, Wang J, Pei L. Study on the effects of irrigation with reclaimed water on the content and distribution of heavy metals in soil. *Int J Environ Res Public Health* 2016;13:298.
- [13] Abdelrahman AH, Al Yafie BA, Goosen MFA. Evaluation of environmental factors and equipment configuration on efficiency of a solar soil water collector. *Int J Environ Technol Manag* 2009;10:260–74.
- [14] Ahmad K, Ejaz A, Azam M, Khan ZI, Ashraf M. Cadmium and chromium contents of canola irrigated with sewage water. *Pak J Bot* 2011;43:1403–10.
- [15] Alade GA, Ojoawo SO. Purification of domestic sewage by water- hyacinth (*Eichhornia crassipes*). *Int J Environ Technol Manag* 2009;10:286–94.
- [16] Carr G, Potter RB, Nortcliff S. Water reuse for irrigation in Jordan: perceptions of water quality among farmers. *Agric Water Manag* 2011;98:847–54.
- [17] Da Fonseca AF, Melfia AJ, Montes CR. Maize growth and changes in soil fertility after irrigation with treated sewage effluent. II. Soil acidity, exchangeable cations, and sulfur, boron, and heavy metals availability. *Commun Soil Sci Plant Anal* 2005;36:1983–2003.
- [18] Evanylo G, Ervin E, Zhang X. Reclaimed water for turfgrass irrigation. *Water* 2010;2:685–701.
- [19] Galavi M, Jalali A, Ramroodi M, Mousavi SR, Galavi H. Effects of treated municipal wastewater on soil chemical properties and heavy metal uptake by sorghum (*Sorghum Bicolor L.*). *J Agric Sci* 2010;2:235–41.
- [20] Carli C, Yuldashev F, Khalikov D, Condori B, Mares V, Monneveux P. Effect of different irrigation regimes on yield, water use efficiency and quality of potato (*Solanum tuberosum L.*) in the lowlands of Tashkent, Uzbekistan: a field and modeling perspective. *Field Crops Res* 2014;163:90–9.
- [21] Subash N, Ram Mohan HS. Evaluation of the impact of climatic trends and variability in rice–wheat system productivity using Cropping System Model DSSAT over the Indo-Gangetic Plains of India. *Agric For Meteorol* 2012;164:71–81.
- [22] Bdour Ahmed N, Hamdi Moshrik R, Tarawneh Zeyad. Perspectives on sustainable wastewater treatment technologies and reuse options in the urban areas of the Mediterranean region. *Desalination* 2009;237:162–74.
- [23] Wang Jun, Wang Dejian. Nitrogen and phosphorus leaching losses from intensively managed paddy fields with straw retention. *Agric Water Manag* 2014;141:66–73.
- [24] Wu C, Spongberg AL, Witter JD, Fang M, Czajkowski KP. Uptake of pharmaceutical and personal care products by soybean plants from soils applied with biosolids and irrigated with contaminated water. *Environ Sci Technol* 2010;44:6157–61.
- [25] Deblonde T, Cossu-Leguille C, Hartemann P. Emerging pollutants in wastewater: a review of the literature. *Int J Hyg Environ Health* 2011;214:442–8.
- [26] Kim SD, Cho J, Kim IS, Vanderford BJ, Snyder SA. Occurrence and removal of pharmaceuticals and endocrine disruptors in South Korean surface, drinking, and waste waters. *Water Res* 2007;41:1013–21.
- [27] Sui Q, Huang J, Deng SB, Yu G, Fan Q. Occurrence and removal of pharmaceuticals, caffeine and DEET in wastewater treatment plants of Beijing, China. *Water Res* 2010;44:417–26.
- [28] Pisarenko AN, Stanford BD, Yan D, Gerrity D, Snyder SA. Effects of ozone and ozone/peroxide on trace organic contaminants and NDMA in drinking water and water reuse applications. *Water Res* 2012;46:316–26.

- [29] Wang J, Gardinali P. Analysis of selected pharmaceuticals in fish and the fresh water bodies directly affected by reclaimed water using liquid chromatography-tandem mass spectrometry. *Anal Bioanal Chem* 2012;404:2711–20.
- [30] Beverly SR. Bisphenol A: an endocrine disruptor with widespread exposure and multiple effects. *J Steroid Biochem Mol Biol* 2011;127:27–34.
- [31] Aronson D, , et al Howard PH. Environmental release, environmental concentrations, and ecological risk of N, N-diethyl-m-toluamide (DEET). *Integr Environ Assess Manage* 2012;8:135–66.
- [32] Kirwan Matthew L. Tidal wetland stability in the face of human impacts and sea-level rise. *Nature* 2013;504:53–60.
- [33] Syvitski JP, Kettner J, Overeem I, Hutton WH, Hannon T, Brakenridge GR, et al. Sinking deltas due to human activities. *Nat Geosci* 2009;2:681–6.
- [34] Törnqvist Torbjörn E, Wallace Davin J, Storms Joep EA, Wallinga Jakob, van Dam Remke L, Blaauw Martijn. Mississippi Delta subsidence primarily caused by compaction of Holocene strata. *Nat Geosci* 2008;1:173–6.
- [35] He Qiang. Economic development and coastal ecosystem change in China. *Sci Rep* 2014;8:189–201.
- [36] Dai ZJ, Liu JT. A thirteen-year record of bathymetric changes in the North Passage, Changjiang (Yangtze) estuary. *Geomorphology* 2013;187:101–7.
- [37] Zhou Chuncai. The environmental geochemistry of trace elements and naturally radionuclides in a coal gangue brick-making plant. *Sci Rep* 2014;28:280–91.
- [38] Williamson CE, et al. Lakes and reservoirs as sentinels, integrators, and regulators of climate change. *Limnol Oceanogr* 2009;54:2273–82.
- [39] Smith SV, Renwick WH, Bartley JD, Buddemeier RW. Distribution and significance of small, artificial water bodies across the United States landscape. *Sci Total Environ* 2002;299:21–36.
- [40] Nilsson C, Reidy CA, Dynesius M, Revenga C. Fragmentation and flow regulation of the world's large river systems. *Science* 2005;308:405–8.