Research article

Plant Growth and Fruit Quality of Tomato (*Solanum lycopersicum*) Using Advanced Treated Water in Hydroponics

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Abstract Biologically Treated Water (BTW) and Chlorinated Disinfected Water (CDW) are byproducts of wastewater treatment. Both BTW and CDW contain significant amounts of nutrients that can be used in agricultural systems. Although the use of BTW has been investigated relative to nutrient recovery, filtering treatment, and social and economic development, more research is required to determine the applicability of using CDW and BTW in hydroponic systems. This study evaluated the growth and quality of Cindy Sweet tomatoes irrigated by BTW and CDW and demonstrated the effectiveness of low application of fertilizer in hydroponic systems. The results demonstrated that tomato plants irrigated with CDW tend to have higher fresh-weight than those irrigated with BTW. Statistical analysis of fruit quality showed that the fruits of plants grown in BTW were larger in diameter and weight, but further t-test analysis showed no significant differences between water types. This study also discovered that hydroponic irrigation with BTW and CDW resulted in larger fruit clusters without a corresponding increase in fruit density. The Index for Relative Chlorophyll content (IRC) showed no difference between BTW and CDW. In contrast, despite presenting lower levels of pH, the control performed best with twice the chlorophyll content in terms of IRC. These results show that even with low IRC of plants from BTW and CDW, there were no differences in fruit size and weight among the treatments. The study also suggests that plants irrigated with CDW have higher biomass accumulation, which can be useful for comparing yields in leafy vegetables.

Keywords hydroponic, tomato, wastewater, advanced treated water

INTRODUCTION

Environmental concerns, greenhouse gas emissions (GHG), geopolitical issues, and rising energy costs are some problems related to the accessibility of manufactured fertilizers (Maggio et al., 2012). A report of the OECD-FAO for Agricultural Outlook 2023-2032 (OECD and FAO, 2023) outlines that the direct contribution of synthetic fertilizer and resultant GHG emissions is among the four main contributors of GHG emissions ranked just after ruminant emissions and other livestock groups. Nitrogen is the most commonly used fertilizer worldwide with about 109 million tons applied per year, followed by phosphates accounting for 46 million tons (FAO, 2023). Therefore, alternatives such as nutrient recovery and recycling, sustainable practices, strict governmental policies and regulations, and improving manufacturing processes are targeted for better resource management with reduced environmental impact (Mahankale, 2024). Treated wastewater is reported to be an important source of nutrients for agriculture despite its treatment based on a standard procedure of three stages called primary, secondary, and tertiary treatments (Hussain et al., 2002).

Biologically treated water (BTW), also called secondary treated water has been tested in hydroponics with several crops to evaluate the removal of nutrients, organic pollutants, and pathogens (Magwaza et al., 2020; Ruan et al., 2016). However, most evidence is focused on using hydroponics with BTW as a filtering method; Rana et al. (2011) reported that tomato plants had a removal capacity of 72.25% and 78.03% of NO_3-N and PO_4-P, respectively from sources of treated wastewater.

Alternatively, a higher-quality resource called chlorinated disinfected water (CDW) has emerged from advanced wastewater treatment. The difference between BTW and CDW relies on the filtration and disinfection process that aims to reduce the microbiological load; therefore, chlorinated water offers more safety in terms of crop production compared to BTW. Traka-Mavrona et al. (1998) demonstrated that when BTW and CDW are not complemented with stock solutions, the reduction in marketable fruits can be up to 18% and 34%, respectively. In this study, we compared BTW and CDW's effects on tomatoes' growth and quality by directly applying advanced treated water in hydroponic systems with a low application of fertilizer.

OBJECTIVE

Since the direct application of advanced treated water alleviates water shortages along with nutrient recovery, the objective of this research is to compare the effects of BTW and CDW on the growth and development of tomatoes.

METHODOLOGY

The experiment was conducted in the Northern Second Water Reclamation Center facilities of Yokohama City, Japan, from April to July, 2023. Tomato (*Solanum lycopersicum*) seeds from the Cindy Sweet variety were watered with soaked paper towels until germination, installed in polystyrene sponges, and then transplanted to hydroponic benches with a nutrient film technique (NFT) after 5 days. The experiment had a plant density of 5 units/m^2 with no replicates. All three benches were installed inside an automated greenhouse in which environmental parameters such as temperature, solar radiation, CO_2 concentration, and relative humidity were automatically monitored and controlled using the Arsprout Platform ®. Additionally, the Arsprout System automatically adjusted pH, electrical conductivity (EC), and temperature levels within the mixing tank.

The treatments differed only in water quality: the control treatment used tap water, the second treatment used BTW, and the third treatment used CDW. The EC of the original water sources was 0.10 mS/cm for tap water, 0.58 mS/cm for BTW, and 0.79 mS/cm for CDW. Each treatment was adjusted to 1.3 mS/cm, which is the minimum recommended electrical conductivity for tomato growth (Zhang et al., 2017). Physical and chemical parameters in the water such as pH, EC, temperature, and nutrient content in each treatment with and without stock solution were measured (Table 1). Water samples were collected weekly for analysis using an Ion Analyzer IA-300 (TOA-DKK) to determine the concentration of the main nutrients in water tanks, including Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, NO_3^-, PO_4^{3-}, and SO_4^{2-}.

Chlorophyll content, a key parameter used to measure the reaction of photosynthetic activity in plant tissues, is difficult to measure in the field, so the Index for Relative Chlorophyll (IRC) was measured using a SPAD-502 Plus Chlorophyll Meter. IRC (SPAD units) is directly correlated with total chlorophyll content and varies according to the stage (Jiang et al., 2017). IRC was measured weekly using an average of 10 leaves per plant, after 3 older leaves located at the lower part of each plant were discarded during the reproduction/harvest stage.

Fruits were harvested weekly from July 17th to August 7th. Only ripened fruits were included in the analysis. The number of fruits and their weight and diameter were recorded in situ after the experiment, and aerial biomass without fruits was weighed by trimming the stem in several pieces. Fruit clusters' lengths were also measured. Statistical analyses for the data collected were carried out using JASP 0.18.0.0 software, and descriptive graphs as well as the power trendline for uniformity correlation were generated in Excel (Eq. 1);

$$y = ax^b \tag{1}$$

where *y* is the diameter (mm), *x* is the weight (g), a and b are constant values.

RESULTS AND DISCUSSION

Water Quality of Treated Wastewater and Nutrient Concentration

In this experiment, the automation system for pH adjustment couldn't maintain optimum pH levels in the control treatment during the vegetative stage (May 1st - June 26th). The mean and standard deviation of pH values observed during the vegetative stage were 4.7±0.8, 6.3±0.7, and 6.4±0.5 for Control, BTW, and CDW, respectively. During the reproduction and harvesting stage (June 26th – August 7th), the values were 6.7±0.6, 6.4±0.5, and 6.6±0.5 for Control, BTW, and CDW respectively. Since this parameter plays a key role in nutrient uptake by the plants, the analysis of results focuses on the differences between BTW and CDW.

Upon balancing the EC to 1.3 mS/cm in all treatments, it was clear that the control plot was supplied with almost double the amount of nutrient solution compared to BTW and CDW. In Table 1, it can be observed that in the Control treatment, there were higher dissolved ions mainly of K^+, NO_3^-, and PO_4^{3-} while higher concentrations of Na^+ and Cl^- were found in BTW and CDW.

The levels of Na^+ and Cl^- in CDW are caused by the residual chlorine remaining from the addition of NaOCl (Chlorine Residual Testing Fact Sheet by CDC SWS Project). On the other hand, the same levels in BTW can be explained by the leaching of detergents from households into wastewater (Tjandraatmadja et al., 2010). The importance of Na^- and Cl^- in the nutrition of tomatoes is related to the salinity tolerance of this crop. Additionally, it has been reported that high concentrations of Na^+ in water used for tomato irrigation increased the sweetness of fruits when the K^+ is partially replaced by Na^+, leveling up soluble solids without altering the dry matter (Dorais et al., 2000). However, the nutrient content inside the fruits was not investigated.

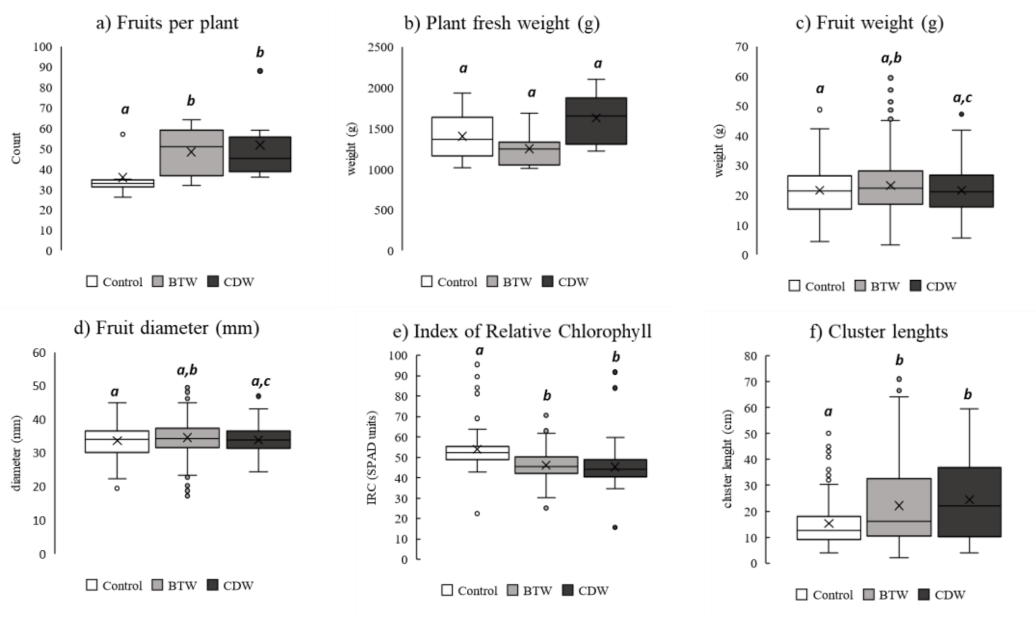
Fresh Weight, Dry Weight, and Yield per Plant

On average, yield per plant was measured at 757.3 g, 1023.1 g, and 1128.8 g. A total of 215, 339, and 310 fruits were collected from Control, BTW, and CDW respectively. The Kruskal-Wallis Test for non-homogenous samples with post hoc revealed that there was a significant difference in yields and fruits' number of Control to BTW and CDW (Fig. 2a). Meaning that the imbalances in pH affected the yield, which is explained by the limitation of important nutrients uptake like Ca^{2+}, Mg^{2+}, Mo^+ and K^+ (Arnon et al., 1942). Figure 2b referring to fresh weight appears to show greater biomass accumulation in plants irrigated by CDW, but no significant differences were found in the statistical analysis (p_{Tukey}=0.13).

Table 1 Characteristics of water and Ion concentration

		pH	EC (mS/cm)	Temp (ºC)	Cations				Anions			
					Na^+	K^+	Mg^{2+}	Ca^{2+}	Cl^-	NO_3^-	PO_4^{3-}	SO_4^{2-}
Control	Original	5.5±1.22	1.2±0.4	21.9±2.7	7±0.59	5±6.85	0±0.75	19±2.22	8±0.59	2±2.15	5±0.49	17±2.42
	+Fert				19±22.16	172±22.26	24±3.01	98±10.21	15±30.83	481±65.48	72±17.68	112±21.83
BTW	Original	6.3±0.67	1.3±0.0	20.3±1.1	115±33.87	34±6.04	4±1.51	73±10.98	78±15.17	14±2.35	9±1.29	31±2.89
	+Fert				100±34.3	104±30.74	24±2.59	78±12.92	118±46.62	308±57.55	47±18.41	138±22.27
CDW	Original	6.5±0.55	1.2±0.2	20.9±2.5	131±37.4	32±6.73	5±1.91	77±10.51	87±15.27	14±2.82	10±1.59	29±4.43
	+Fert				98±29.77	93±41.7	21±4.31	72±17.41	115±34.1	275±81.33	39±18.84	135±26.28

Data are mean ± standard deviation, determined in weekly samples with 3 replicates. Expressed in mg/L.



**Different letters indicate significant differences among the treatments (p<0.05).*

Fig. 2 Fruits per plant (a), fresh weight of aerial biomass (b), fruit weight (c), fruit diameter (d), IRC (e), and length of clusters per treatment (f)

Fruit's Weight and Diameter

The effects of the lack and toxicity of essential elements are reflected not only in the biomass of the plant but also in its fruit development. A wide range of fruit sizes was observed in treatment with BTW and ANOVA with a post-hoc test showed a significant difference of means in diameter and weight among the plants grown in BTW and CDW (p_{tukey}=0.02).

To corroborate the differences among these two treatments, a correlation between fruits' diameter and weight was performed. All treatments showed a strong correlation with uniformity coefficients above 0.9, meaning that despite the differences in ion concentration and pH levels in the control, there were no negative effects in terms of fruit size among them, revealing that differences in weight and diameter of fruits between BTW and CDW were caused by the wide range of sizes in BTW (Fig. 3).

Index for Relative Chlorophyll Content (IRC) in Leaves

Considering the pH changes in the control plot, separate analyses for IRC values were carried out in each stage of this treatment, but no inter-stage variations were observed, probably caused by the variance in the measured leaves along the plant. On the other hand, the comparison of BTW and

CDW versus the control plot resulted in a p_{tukey} <0.001 with the highest values in the control, whereas no significant difference between BTW and CDW was observed (p_{tukey}=0.926). IRC mean values were 53.9, 46.1, and 45.3 for Control, BTW, and CDW, respectively. These results are consistent with previous studies where NaCl reduced chlorophyll content in tomato leaves with increased salinity (Azarmi et al., 2010; Taffouo et al., 2010).

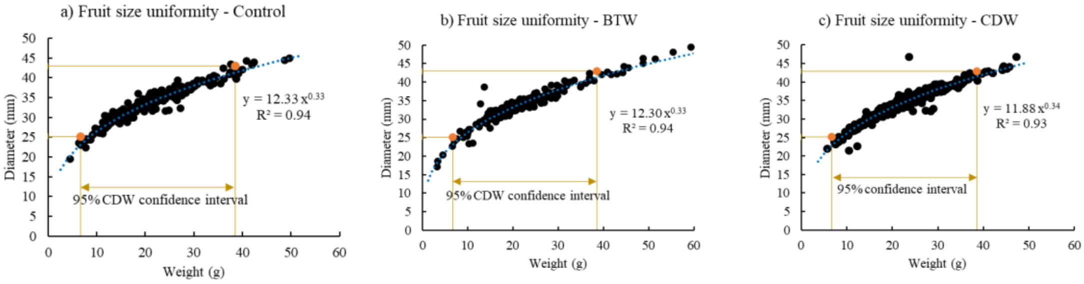


Fig. 3 Correlation between fruit weight and fruit diameter on all treatments

The uniformity of fruits is presented with a trendline of the power equation.

Clusters Per Plant

The highest number of plants with shorter cluster lengths was observed in the control plot. In contrast, larger clusters appeared on BTW and CDW (Fig. 2f) without affecting fruit density per cluster (data not presented). Despite observing significant differences among the treatments in ANOVA, a post hoc test revealed that the uniformity of clusters is consistent only in the control due to the strong differences between Control to BTW (p_{tukey}<0.001) and Control to CDW (p_{tukey}=<0.001). Plant growth regulators that control meristem and apical growth do not vary within the same plant species nevertheless, synthetic compounds may be present in treated wastewater and act as natural plant hormones, consequently inducing the elongation of clusters (Gaspar et al., 1996).

CONCLUSION

Reusing advanced treated wastewater in hydroponics is crucial for resource-saving and water purification since it minimizes the use of potable water and fertilizers in agriculture. In this research, similar levels of Na^+ and Cl^- ions in BTW and CDW were found, and there was no evidence of significant differences between the fresh and dry weights of the plants irrigated with these water types, yet the greater means in the plants grown with CDW shows a better tendency for biomass accumulation. Since fruit quality can be improved by using NaCl content in BTW and CDW, it is essential to consider that this can reduce chlorophyll activity in tissues. Although CDW presented higher Na^+ and Cl^- levels as part of residual chlorine, the size and weight of fruit were not affected and the differences between means were caused by the wider range of sizes in BTW. The advantage of applying a chlorination process to CDW reduces the risk of pathogen contamination in crops, rather than using only BTW. The tendency to reuse treated wastewater is gaining further attention, therefore, this research must be complemented with other analyses regarding nutrient content in fruits, as well as the translocation of heavy metals, which are of great importance for the safe consumption of vegetables. Additionally, the presence of volatile organic and pharmaceutical compounds in water must be evaluated since recent studies indicate that those are the main hazards for wastewater reuse in agriculture.

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REFERENCES

Arnon, D.I., Fratzke, W.E. and Johnson, C.M. 1942. Hydrogen ion concentration in relation to absorption of inorganic nutrients by higher plants. Plant Physiology, 17 (4), 515-524, Retrieved from DOI https://doi.org/10.1104/pp.17.4.515

Azarmi, R., Taleshmikail, R.D. and Gikloo, A. 2010. Effects of salinity on morphological and physiological changes and yield of tomato in hydroponics system. Journal of Food, Agriculture and Environment, 8 (2), 573-576, Retrieved from DOI https://doi.org/10.1234/4.2010.1762

Dorais, M., Dorval, R., Demers, D., Micevic, D., Turcotte, G., Hao, X., Papadopoulos, A.P., Ehret, D.L. and Gosselin, A. 2000. Improving tomato fruit quality by increasing salinity, Effects on ion uptake, growth and yield. In XXV international horticultural congress, Part 1, Culture techniques with special emphasis on environmental implications, Nutrient management, Acta Horticulturae, 511, 185-196, Retrieved from DOI https://doi.org/10.17660/actahortic.2000.511.21

Food and Agriculture Organization (FAO). 2023. Inorganic fertilizers 2000-2021. FAOSTAT Analytical Brief 68, FAOSTAT, Rome, Italy, Retrieved from DOI https://doi.org/10.4060/cc6823en

Gaspar, T., Kevers, C., Penel, C., Greppin, H., Reid, D.M. and Thorpe, T.A. 1996. Plant hormones and plant growth regulators in plant tissue culture. In Vitro Cellular and Developmental Biology. Plant, 32 (4), 272-289, Retrieved from DOI http://www.jstor.org/stable/20064922

Hussain, I., Raschid, L., Hanjra, M.A., Marikar, F. and van Der Hoek, W. 2002. Wastewater use in agriculture, Review of impacts and methodological issues in valuing impacts. Working Paper 37, International Water Management Institute (IWMI).

Jiang, C., Johkan, M., Hohjo, M., Tsukagoshi, S. and Maruo, T. 2017. A correlation analysis on chlorophyll content and SPAD value in tomato leaves. HortResearch, 71, 37-42, Retrieved from DOI https://doi.org/10.20776/S18808824-71-P37

Maggio, A., Malingreau, J. and Eva, H. 2012. NPK, Will there be enough plant nutrients to feed a world of 9 billion in 2050? EUR 25327 EN, Publications Office of the European Union, Luxembourg, Retrieved from DOI https://dx.doi.org/10.2788/26586

Magwaza, S.T., Magwaza, L.S., Odindo, A.O. and Mditshwa, A. 2020. Hydroponic technology as decentralized system for domestic wastewater treatment and vegetable production in urban agriculture, A review. Science of The Total Environment, 698, 134154, Retrieved from DOI https://doi.org/10.1016/j.scitotenv.2019.134154

Mahankale, N.R. 2024. Global influence of synthetic fertilizers on climate change. Applied Geomatics, 16, 317, Retrieved from DOI https://doi.org/10.1007/s12518-023-00511-0

Organization for Economic Co-operation and Development (OECD) and the Food and Agriculture Organization (FAO). 2023. OECD-FAO agricultural outlook 2023-2032. OECD Publishing, Paris, Italy, Retrieved from DOI https://doi.org/10.1787/08801ab7-en

Rana, S., Bag, S., Golder, D., Mukherjee, S., Pradhan, C. and Jana, B.B. 2011. Reclamation of municipal domestic wastewater by aquaponics of tomato plants. Ecological Engineering, 37 (6), 981-988, Retrieved from DOI https://doi.org/10.1016/j.ecoleng.2011.01.009

Ruan, X., Yang, E.W., Zuo, J., Chen, H., Wang, L., Qiana, G.R. and Frost, R.L. 2016. Hydroponic removal of organic contaminants from water by using ryegrass and organobentonites simultaneously. Applied Clay Science, 119 (2), 333-337, Retrieved from DOI https://doi.org/10.1016/j.clay.2015.10.036

Taffouo, V.D., Nouck, A.H., Dibong, S.D. and Amougou, A. 2010. Effects of salinity stress on seedlings growth, mineral nutrients, and total chlorophyll of some tomato (*Lycopersicum esculentum* L.) cultivars. African Journal of Biotechnology, 9 (33), 5366-5372, Retrieved from URL https://academicjournals.org/journal/AJB/article-abstract/A85093931808

Tjandraatmadja, G., Pollard, C., Sheedy, C. and Gozukara, Y. 2010. Sources of contaminants in domestic wastewater, Nutrients and additional elements from household products. Water for a Healthy Country National Research Flagship, CSIRO, Retrieved from URL https://docs.niwa.co.nz/library/public/Tjandraatmadja2010.pdf

Traka-Mavrona, E., Maloupa, E., Papadopoulos, F. and Papadopoulos, A. 1998. Response of greenhouse tomatoes to wastewater fertigation in soilless cultivation. In International symposium on water quality and quantity-greenhouse, Acta Horticulturae, 458, 411-416, Retrieved from DOI https://doi.org/10.17660/actahortic.1998.458.54

Zhang, P., Senge, M., Yoshiyama, K., Ito, K., Dai, Y. and Zhang, F. 2017. Effects of low salinity stress on growth, yield and water use efficiency of tomato under soilless cultivation. Transactions of The Japanese Society of Irrigation, Drainage and Rural Engineering, 85 (1), Retrieved from DOI https://doi.org/10.11408/jsidre.85.i_15