Research article

A Multispecies Growth and Yield Performance Comparison of Vegetables Cultivated Under Hydroponics Using Sewage Wastewater

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Abstract Reusing sewage wastewater for vegetable cultivation is becoming a solution to sustainable water utilization, particularly in water-scarce regions. Using two types of sewage wastewater, Biologically Treated Water (BTW) and Chlorine Disinfected Water (CDW), and tap water, this study aimed at making a comparison of and understanding the yield performance and chlorophyll content in three vegetables, *Phaseolus vulgaris* (common beans), *Brassica rapa* var. *perviridis* (komatsuna), and *Solanum lycopersicum* (tomato), grown under hydroponics. The experiment was carried out in the hydroponics greenhouse within the Yokohama Wastewater Reclamation Center, between May 2023 and August 2023. We used a Nutrient Film Technique (NFT) hydroponic system supplied with BTW, CDW, and tap water. The three water types served as our treatments. The plants were grown to maturity at a controlled water temperature. In comparing vegetable yield, an ANOVA test demonstrated significant differences among the treatments for common beans, komatsuna, and tomatoes. The Post hoc test showed significantly higher chlorophyll content for common beans and tomatoes grown in tap water, compared to BTW and CDW. Regarding yield, common beans performed best in the tap water hydroponic system, while tomato and komatsuna performed best in the BTW and CDW hydroponic systems. Results indicate a vegetable differential preference for the three water types used. These three vegetables can thus be cultivated concurrently. Research on the safety of vegetables grown in sewage wastewater and the economic feasibility of using treated sewage wastewater for vegetable production is urged before upscaling this technology.

Keywords hydroponics, sewage resources, vegetables, wastewater, advanced treated water

INTRODUCTION

Crop production using hydroponic systems has a long history (Caputo, 2022; Velazquez-Gonzalez et al., 2022). Vegetables are a critical crop in hydroponic systems (Sharma et al., 2018) and comprise a key crop group cultivated under such systems. Hydroponic vegetable production is known for its advantages over soil-based production systems, including all-year production, water, and space-saving benefits, avoidance of soilborne diseases, and high-quality and palatable vegetable products with greater market value (Swain et al., 2021). Hydroponic production, however, is faced with challenges including the risk of waterborne diseases, maintenance of electrical conductivity (EC) and pH at correct levels, and high initial costs (Sharma et al., 2018). More recently, hydroponic production has evolved towards the utilization of treated sewage wastewater resources as a potential water source (Cifuentes-Torres et al., 2021). Research on hydroponic crop performance using treated wastewater has found varied results. A study on *Hordeum vulgare L*, a fodder crop, reported different crop performance using treated wastewater, tap water, and a mix of both (Al-Karaki, 2011). Little research has been reported regarding the performance of common beans and komatsuna when using hydroponics with different water types. The use of sewage resources for tomato production under NFT is also limited. In an assessment of horticultural research in Japan, (Asao et al., 2014) the authors called upon modernizing and updating outdated hydroponic systems and facilities and using modern facilities, including using treated sewage wastewater resources as a water source. Yokohama's sewage treatment hydroponic infrastructure offers a unique opportunity to study how different vegetable crops can perform in different water types. Mixed vegetable production in hydroponics presents an efficient way to utilize hydroponic infrastructure. A multi-species comparison of vegetable growth and yield performance in hydroponic systems is an area that has received comparatively less attention (Maucieri et al., 2018).

OBJECTIVE

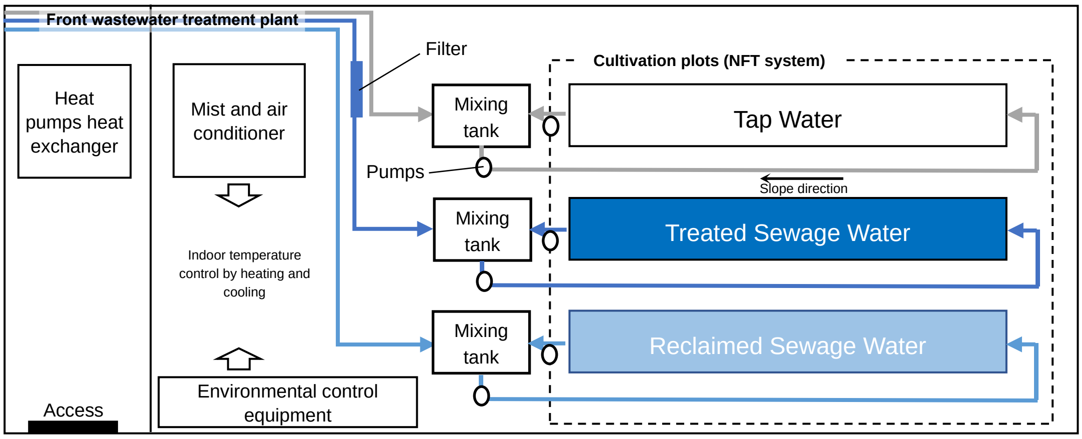
This study sought to investigate the performance of common beans (*Phaseolus vulgaris*), Komatsuna (*Brassica rapa* var. *perviridis*), and Tomato (*Solanum lycopersicum*), in three water types in hydroponic systems. Specifically, we will assess and compare chlorophyll dynamics and yield performance.

MATERIALS AND METHODS

Study Site

Seeds for common beans were obtained from Malawi. Komatsuna seeds and tomato seeds were purchased in Japan. For common bean seeds, pretreatment involved soaking the seeds in water for 24 hours. The seeds were then planted in peat moss for germination. Seedlings were transplanted onto cultivation benches a week after germination at the two-leaf stage. Before seedlings were transferred, the roots were washed clean of germination media. For tomato seeds, the seeds were placed on tap water-soaked paper towels for 4-5 days until germination. The germinated tomato seeds were then transferred onto planting sponges and placed on germination benches. The komatsuna seeds were treated similarly to tomato seeds, except the komatsuna seeds were germinated in tap water without using paper towels before being transferred onto cultivation benches. In the study greenhouse, the NFT comprised three autonomous systems with three types of water: tap water (Treatment 1), Biologically Treated Water (BTW) (treatment 2), and Chlorine Disinfected Water (CDW) (Treatment 3). Figure 1 shows the water supply and associated infrastructure to the three cultivation benches.

The main difference between BTW and CDW is that both undergo routine primary and secondary treatment, while CDW undergoes further advanced treatment such as filtration and chlorination. Table 1 shows the chemical composition of the three water types used in the experiments. The system used wastewater from a Wastewater Reclamation Center in Yokohama, Japan. Each system has a mixing tank with sensors for EC, pH, temperature, and water level.



Notes: Dark blue is BTW, and light blue is CDW.

Fig. 1 Yokohama hydroponics greenhouse setup and water supply layout showing individualized mixing tanks and cultivation benches.

Table 1 Chemical composition of the hydroponic water types used in the experiments

Hydroponic water	Essential elements (mg/L)										Heavy metals (ppm)					
	TN	TP	Na	K	Mg	Ca	Cl-	NO_3-	PO_4-	SO_4-	Cu	As	Fe	Pb	Zn	Ni
TW+F	144.52	36.45	14.77	170.59	24.17	97.66	7.83	476.03	70.60	109.88	0.04	0	0.3	0	0.53	<0.00
TW	1.57	0.03	7.82	1.52	4.78	17.18	6.71	3.84	0.02	19.17	-	-	-	-	-	-
BTW+F	107.32	25.82	94.38	96.94	23.78	76.59	109.92	302.02	43.33	135.84	-	-	-	-	-	-
BTW	12.38	2.34	76.43	13.93	9.16	30.55	109.45	32.97	3.41	72.48	<0.01	<0.00	<0.01	<0.00	0.01	<0.02
CDW+F	93.35	22.01	93.81	74.97	20.86	69.06	110.41	259.45	34.39	132.21	-	-	-	-	-	-
CDW	11.77	2.50	85.94	14.24	9.80	28.33	125.35	31.38	4.28	75.80	<0.01	<0.00	<0.02	<0.00	0.04	<0.00

Notes: Cr, Cd, and Se (heavy metals) were below detection limits. Geomean values: essential elements in water were analyzed weekly, and heavy metals were analyzed in 3 samples during the experimental period. Analysis carried out in the laboratories of hydro-structure engineering and Laboratory of soil fertility and fertilizers, Tokyo University of Agriculture.

During the cultivation period, bench water temperatures averaged 21.91ºC, 20.31ºC, and 20.97ºC for tap water, BTW, and CDW water, respectively. Relative humidity across the shared cultivation plots averaged 75%, while the average pH was 5.53 for tap water, 6.33 in BTW, and 6.5 in CDW. Fluctuations in water pH were regulated by adding alkaline and acidic pH adjusters when the pH went down or up, respectively. Fertilized water was irrigated on each cultivation bench using a submersible pump at a flow rate of 19 L/min. The hydroponic fertilizer used was OAT house fertilizers No.1 and No.2 manufactured by OAT Agrio Co. Ltd., a Japanese company. During cultivation, fertilizer was added to all three treatments. The fertilizer stock solution was prepared using the manufacturer's recommendations. The stock comprised both macronutrients and micronutrients. Data collection for multiple variables was continuously performed from planting to harvest including measurement of the number of leaves, plant height, and chlorophyll content. At harvest, yield data was collected for all three vegetables across all three water treatments. For common beans, yield data included pods per plant and seeds per pod. For komatsuna, yield data comprised the number of leaves and fresh weight. For tomatoes, yield data included the number of fruits per plant and fresh weight. Data was analyzed through an analysis variance (ANOVA) and the difference between treatment means, computed at $P < 0.05$ according to the post hoc Tukey HSD test where data satisfied equal variance condition for ANOVA. A Welch ANOVA was done where the equal variance condition was violated, followed by a Games-Howell post-hoc test. Data were statistically analyzed using analysis of variance using the statistical package JASP 0.17.3 (Love et al., 2019) and XLSTAT statistical software.

RESULTS AND DISCUSSION

A one-way ANOVA was computed using yield data to investigate the performance of the three vegetables over the three treatments. Table 2 summarizes key ANOVA statistics for common beans, komatsuna, and tomatoes. All data satisfied ANOVA assumptions, particularly the equality of variance (as shown by Levene's test p-value).

Table 2 ANOVA primary model results for analyzed variation for the three vegetables across the three water treatments

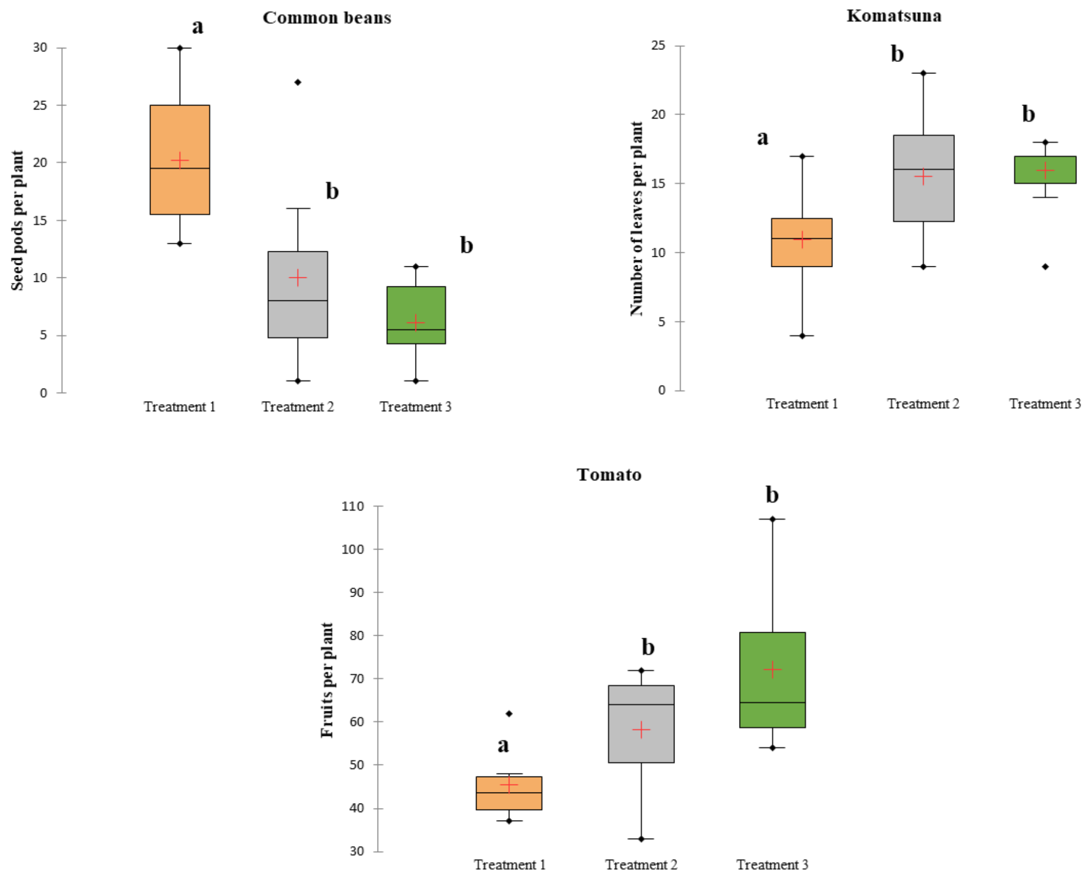
	df	Between-group means	F	*p*-value	η^2_p	Levene's test *p*-value
Common beans yield	2	25	13.88	<0.001	0.53	0.178
Komatsuna yield	2	42	10.29	<0.001	0.33	0.069
Tomato yield	2	16	4.67	<0.025	0.37	0.136

Yield Performance Across Treatments

It is well-documented that different species of cultivars have distinct cultivation requirements. In the case of common beans, a higher yield was realized in tap water (Treatment 1). For Komatsuna, a leafy crop with higher nitrogen demands, BTW and CDW met the optimal conditions for superior growth. Likewise, when examining tomato yields, CDW displayed more fruits per plant than other treatments. ANOVA analysis demonstrated no significant differences among treatments using sewage wastewater BTW and CDW sources. Fig. 3 comprises univariate plots showing yield performance for the three vegetables in the different treatments. Tukey's HSD Test for multiple comparisons shows that the mean yield for common beans was significantly higher in Treatment 1 (tap water) than in Treatment 2 (p=0.004) and Treatment 3 (CDW) (p=0.001). For Komatsuna, treatment 2 (BTW) and treatment 3 (CDW) showed no difference (p= 0.933) but were significantly different from treatment 1 (p=0.002, 0.001 respectively). For tomato, there was no significant difference between treatment 1 (tap water) and treatment 2 (BTW) (p=0.316) and between treatments 2 (BTW) and 3 (CDW) (p=0.248), while there was a significant difference between treatment 1 (tap water) and treatment 3 CDW (p=0.020), as demonstrated in Figure 2.

The three species investigated produced more vegetation in treated sewage wastewater, BTW, and CDW, compared to tap water. Yield is measured using different attributes in vegetables. Based on the research objective, fresh weight, biomass, number of leaves, and number of fruits are some commonly used attributes. In this study, yield assessment used fruits per plant in common beans and tomatoes, whereas several representative leaves were used for measurement in Komatsuna. Common beans did better in terms of both chlorophyll composition and yield in tap water than in BTW or CDW. While BTW and CDW produced excessive vegetative growth compared to tap water, yield, assessed as the number of pods per plant, was significantly lower in these two treatments. This observation can partially be explained by fertilization. Excessive nitrogen (N) and phosphorus (P) have been suspected of yield reduction in vegetables (Wang and Li, 2004). In the case of our experiments, BTW and CDW had inherently higher levels of N and P. The additional fertilization led to excesses in these key elements. It is hypothesized that this excessive N and P led to excessive vegetative growth at the expense of fruit production. During excessive growth, vegetative and reproductive meristems compete as sinks for photosynthates (Huett, 1996), leading to fewer carbohydrates sinking in the reproductive parts of the common beans. Komatsuna yielded a higher number of leaves in BTW and CDW, with no significant differences between the two media, compared with tap water treatment. This is unsurprising at a vegetative growth level, as all three taxa performed highly in BTW and CDW. Earlier studies on this species show mixed results. There are few studies regarding the usage of sewage wastewater on komatsuna growth and yield. Notable studies include Kohda et al. (2017) who showed the potential for use with smaller amounts of Biodiesel fuel (BDF) wastewater in the hydroponic production of komatsuna. For tomatoes, while chlorophyll was significantly greater in tap water than in BTW and CDW, yield was higher in BTW and CDW. The comparatively low yield for tomatoes in tap water could partially be explained as being due to insufficient fertilizer addition. It is known that the addition of fertilizer to wastewater enhanced tomato yield more than when fertilizer or wastewater was used alone (Magwaza et al., 2020).

This implies that while fertilizer was added to tap water in treatment 1 (tap water media), the fertilizer was insufficient to surpass the yield of where wastewater was boosted with fertilizer.



Different letters mean statistically significant differences in the ANOVA Tukey post hoc test (HSD) for alpha 0.05.

Fig. 2 Box plot for vegetable yield for common beans, komatsuna, and tomato in three treatments

Use of Sewage Wastewater for Common Beans, Komatsuna, and Tomato Production, Where To?

The findings of our study show no significant differences between BTW and CDW in terms of yield (Fig. 3) for common beans, komatsuna, and tomatoes. However, there were specific differences between tap water and the other two types of water meaning that even with the application of fertilizer at a lower limit than the recommended it can efficiently produce higher yields on vegetative crops.

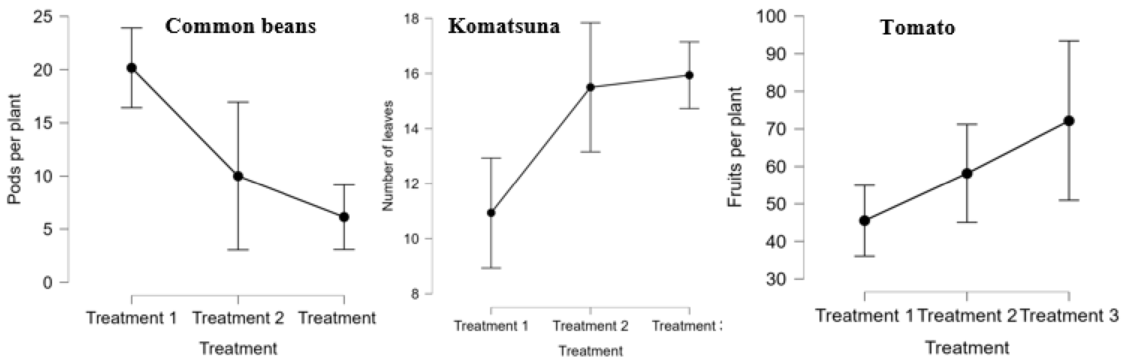


Fig. 3 ANOVA descriptive plots showing a lack of difference between Treatments 1, 2, and 3 in terms of yield

Results from this study point to the feasibility of using any of the three types of water in the production of these vegetables. However, it has been found that wider wastewater use has been hampered by public distrust related to potential human health risks (Truchado et al., 2021) as was noted in Europe. Specific to Japan (Takeuchi and Tanaka, 2020), several authors argue that the establishment of quality standards for the reuse of treated wastewater must include the removal of harmful and toxic chemicals which would help ensure wider public acceptance. Literature on the safety of common beans and komatsuna and tomatoes grown in hydroponics with wastewater remains inadequate, particularly for common beans and komatsuna. In the case of tomatoes, where wastewater has been used for irrigation, no health risks from heavy metal and microbial contamination on tomatoes irrigated with two types of treated wastewater (Christou et al., 2014) were found. Further, Osman et al., (2021) found no health risk in ten different vegetables (including tomato) irrigated with wastewater except for Cadmium (Cd) metal. In hydroponic systems, treated wastewater was found to have no health risk in lettuce (Lee et al., 2021).

However, the uptake and accumulation of wastewater contaminants varies depending on crop species (Liu et al., 2020) and the source of wastewater. For the vegetables in our study, a safety assessment would add value to the broader vision of using treated sewage resources safely.

CONCLUSION

Different vegetable species perform better in different growing media but with insignificant differences for BTW and CDW. Generally, these results indicate a potential for producing tomatoes and komatsuna using treated wastewater from sewage resources in hydroponics. Several issues need to be determined to ascertain the feasibility of sustainable vegetable production under sewage wastewater hydroponics like this one. These issues include the determination of the economic feasibility of multi-vegetable species production in such hydroponic systems and the assessment of the accumulation of chemical contaminants and associated safety issues. Due to their erect bush growth habit, common beans require relatively more space and may not be recommended for inclusion in smaller greenhouse hydroponics. Applying an optimal amount of fertilizer to treated wastewater is an indispensable part of hydroponics when using treated sewage wastewater. Wastewater used singly was found insufficient as a nutrient source for tomatoes (Magwaza et al., 2020). However, the optimum fertilizer dose must be determined partly depending on the amount of nutrients in wastewater. Uniform fertilization is not ideal for different crops across the three treatments.

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