

CAN TREATED WASTEWATER BE USED FOR IRRIGATION WITHOUT COMPROMISING VEGETABLE QUALITY?

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Irrigation of plants in agriculture will become a problem in the future due to water shortages. One of the most appropriate solutions is to irrigate plants with treated wastewater from treatment plants. In our study, we irrigated pepper, carrot, and onion plants with fresh water, water treated by reverse osmosis, and water treated by ultrafiltration. We analysed the effect of each treatment on the content of individual vitamins in the edible parts of the plants. The results showed that irrigation with treated wastewater does not affect the content of individual vitamins in peppers and carrots. In onions, only the riboflavin (B2) content differed between treatments, with the highest content detected at treated wastewater. The study provided some promising results, as we did not detect any negative impact of irrigation with treated wastewater on the quality of the edible parts of peppers, carrots, and onions. In the future, it would be good to focus on testing other plant species, such as strawberries.

Keywords: Treatment plant, vitamins, reverse osmosis, ultrafiltration.

Introduction

Due to the growing world population, food production and consumption are also increasing, which is not possible without irrigation. Irrigation is required because of a lack of natural precipitation or its uneven temporal distribution (Atamaleki et al., 2021). In recent years, the world's supply of clean freshwater has been constantly decreasing, as the supply does not meet the growing demand. Irrigation in agriculture is one of the main consumers of clean freshwater globally, accounting for approximately 70%-80% of consumption (Ali et al., 2019; Hashem and Qi, 2025). Therefore, it is necessary to find an alternative solution to this problem, as it is expected that the consumption of fresh water in agriculture will increase even further in the future (Hashem and Qi, 2025). One of the fastest and most appropriate solutions is the reuse of wastewater (Cirelli et al., 2012). Wastewater contains higher levels of nutrients compared to fresh water and can therefore reduce the use of chemical fertilizers in agriculture. On the other hand, the presence of ions and heavy metals in such water can have a toxic effect on plants and thus a negative impact on human health (Demir and Sahin, 2017). Treated wastewater is defined as "water that has received at least secondary treatment and basic disinfection and is reused after flowing out of a domestic wastewater treatment facility" (Hashem and Qi, 2025). The safety of treated wastewater remains uncertain, so it is tested for various chemical compounds and microorganisms before reuse. The impact of irrigation with treated water on the quality of different vegetables and fruits is still poorly studied; therefore, the aim of our study was to analyse the effect of fresh water (control) and wastewater treated by two methods (reverse osmosis and ultrafiltration) on the vitamin content of pepper, carrot, and onion. This research was conducted as part of the Europe Horizon CircSyst project.

Research methodology

Research was conducted in the experimental field of the Agricultural Institute of Slovenia, Infrastructural Centre Ptuj (latitude: 46,407396, longitude: 15,879535, altitude: 224 m) on three vegetable species: pepper, carrot and onion. Each plant species was grown in its own greenhouse. Uniform young seedlings of pepper Enix F1 were grown from seed at the Centre and transplanted into the greenhouse on 19th of May 2025. Carrot (cv. Laguna F1) was direct seeded on 25 April 2025 into previously prepared raised beds in the greenhouse. Onion seedlings of the cultivar 'Ptujška rdeča' (a Slovenian autochthonous variety) were grown from seed and transplanted into the greenhouse on 15th of April 2025. All crop species were cultivated on raised beds in a single row system. For onion and pepper, the raised beds were covered with perforated strawberry growing PE foil, which allowed us to avoid herbicide use for weed management. Throughout the season, standard plant protection practices were applied to control diseases and pests. At the beginning of July, support structures were installed for the pepper plants. During the period of intensive growth, plant height was measured for all crop species. The experimental design followed a randomized complete block (RCB) method with four replicates, identical for all plant species.

Plants were irrigated (drop irrigation) with fresh water, treated wastewater by reverse osmosis and treated wastewater by ultrafiltration. Irrigation was supplied using T tape drip lines with emitters spaced 10 cm apart and a discharge rate of 0.57 L h⁻¹ per emitter. Irrigation of all crop species began two days prior to transplanting

or sowing, depending on the species. Irrigation doses were determined separately for each species, based on the growth stage and soil moisture measurements. Soil moisture was monitored using high precision sensors placed at 10 cm intervals down to a depth of 60 cm. For all species, irrigation initially consisted of 10 minutes per day, split into two irrigation events. During the period of maximum crop water demand, the total daily irrigation duration was increased to 30 minutes, divided into five events. Irrigation in each greenhouse was controlled by a programmable timer, which operated according to the measured parameters and the growth stage of the plants. Irrigation of carrot was terminated on 10th of August. In onion, irrigation doses were reduced during the maturation stage and completely stopped on 6th of July. Pepper plants were irrigated until the final harvest on 1st of October 2025.

As part of the CIRCSYST research and development project, a pilot plant for tertiary treatment of treated effluent was established and commissioned at the Ptuj Wastewater Treatment Plant. Its purpose is to produce Class A water in accordance with Regulation (EU) 2020/741 on minimum requirements for water reuse. The system, designated TEHNO MF/UF RO CP OXY/ZON, is officially named the Pilot Plant for the Preparation and Distribution of UF Filtrate and RO Permeate for Irrigation Purposes. It was custom built according to our specifications and leased from the Slovenian company Tehnobiuro, which integrates equipment from various manufacturers.

The plant produces two water qualities – ultrafiltrated water (UF filtrate) and reverse osmosis water (RO permeate) – used for irrigating selected greenhouse crops (carrots, peppers, onions, and strawberries) and for evaluating their suitability for agricultural use.

The ultrafiltration unit consists of an equalization tank, submerged UF membrane modules, and the associated instrumentation. Treated wastewater is pumped into the tank, where the UF modules operate under negative pressure. Particles larger than 0.08 µm (suspended solids, colloids, microorganisms) are retained on the membrane surface, while the filtrate passes through. After each filtration cycle, an automatic backwash with UF filtrate restores membrane permeability. Key parameters such as turbidity, temperature, flow, and pressure are continuously monitored. The process is supported by oxygenation and ozonation (TEHNO OXY/ZON) in the equalization tank to enhance filtration efficiency, to provide higher oxygen concentration in the water, to ensure sterile conditions and reduce fouling. A disinfection dosing unit adds peroxide at the beginning of the process to ensure compliance with Class A water standards. The UF filtrate is stored in a dedicated tank and is used directly for irrigation of the crops.

In the second stage, the UF filtrate passes through the reverse osmosis module, where dissolved salts, micropollutants, organic compounds, and remaining microbiological contaminants are removed (if there are any left). The remaining concentrate is removed into a separate reservoir. The RO permeate is stored in a dedicated tank and is used directly for irrigation of the crops.

Water quality is assessed according to the limits set by Regulation (EU) 2020/741:

- E. coli: <10 mpn/100 mL
- Turbidity: <5 NTU
- BOD₅: ≤10 mg/L
- Suspended solids: ≤10 mg/Ultrafiltration

For the analysis of individual vitamins in peppers, carrots and onions, the following methods were used: For riboflavin (B2), pyridoxine (B6) and folic acid (B9), a method described in Zia et al. (2023), for vitamins A and E, a method described in Zamljen et al. (2025) and for vitamin C, a method described in Zamljen et al. (2021). For each vitamin, analysis was made in 4 replicates. Values were expressed in mg 100 g⁻¹ of fresh weight.

Statistical analysis was performed in statistical programme R commander (R 4.5.2). Statistically significant differences between treatments were determined by one-way analysis of variance (ANOVA). Significant differences between treatments are represented by different letters.

Results and discussion

Vegetables are an important part of human diet, since they are a rich source of different chemical compounds, such as dietary fiber, phytochemicals, minerals and vitamins. Among vitamins, peppers, carrots and onions contain vitamins B (B2, B6, B9), vitamin A, vitamin E and vitamin C (Dias, 2022). These vitamins were also found during the analysis in our fruit samples, with the exception of vitamin E that was not found in onions (Figures 1–3). Significant differences between different irrigation regimes were detected only in vitamin B2 (riboflavin) content in onions, where the highest values contained onions irrigated with treated wastewater. It is believed that nutrients, such as nitrogen, phosphorus and potassium remain in the wastewater after the treatment and act as additional nutrient that could affect plant metabolism and therefore vitamins synthesis (Al-Ansari et al., 2013; Sibanda et al., 2025). However, the exact mechanisms remain unclear. Therefore, these results should be interpreted cautiously and the lack of data on nutrient uptake and metabolic

changes represents a limitation of this study. Regarding other analyzed vitamins, no significant differences in their contents in all three selected vegetables were found. This can be considered a positive result, as growers want to irrigate their plants optimally, even with treated wastewater, without any negative impact on the plants, yield, and its quality.

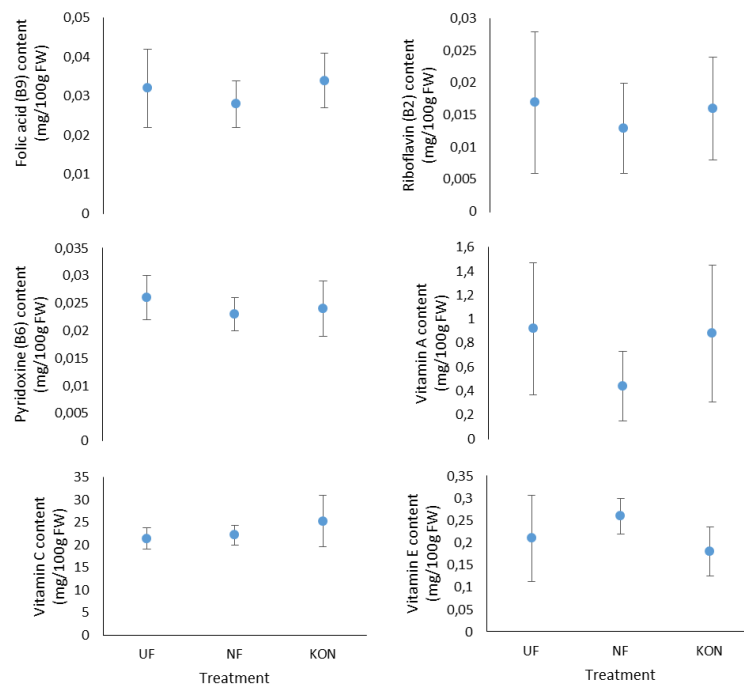


Fig. 1 The contents of folic acid (B9), riboflavin (B2), pyridoxine (B6), vitamin A, vitamin C and vitamin E (mg 100 g⁻¹) in peppers at individual treatment

Data are presented as the mean ± standard error calculated from four replicates per treatment. Differences between the treatments were determined using Tukey's test and were found to be significant at $\alpha < 0.05$.

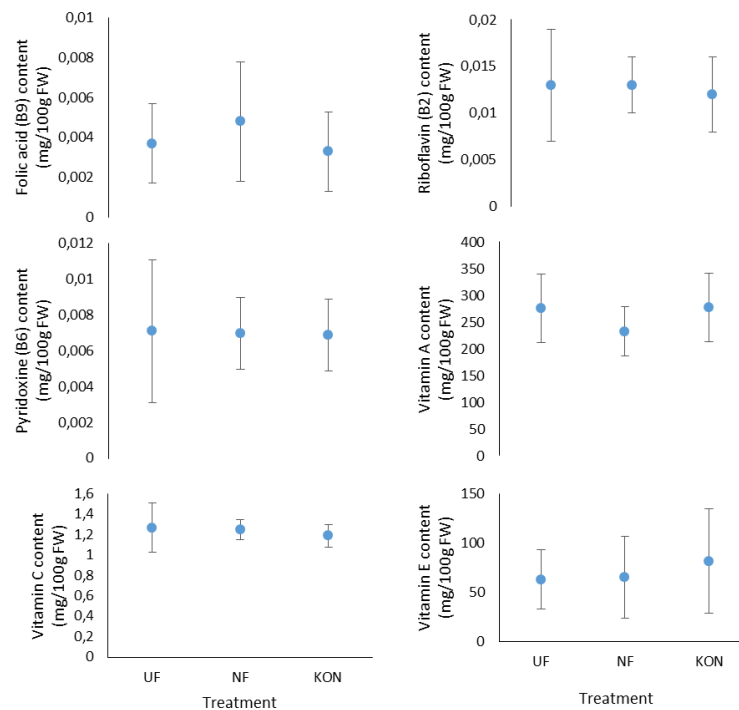


Fig. 2. The contents of folic acid (B9), riboflavin (B2), pyridoxine (B6), vitamin A, vitamin C and vitamin E (mg 100 g⁻¹) in carrots at individual treatment

Data are presented as the mean ± standard error calculated from four replicates per treatment. Differences between the treatments were determined using Tukey's test and were found to be significant at $\alpha < 0.05$.

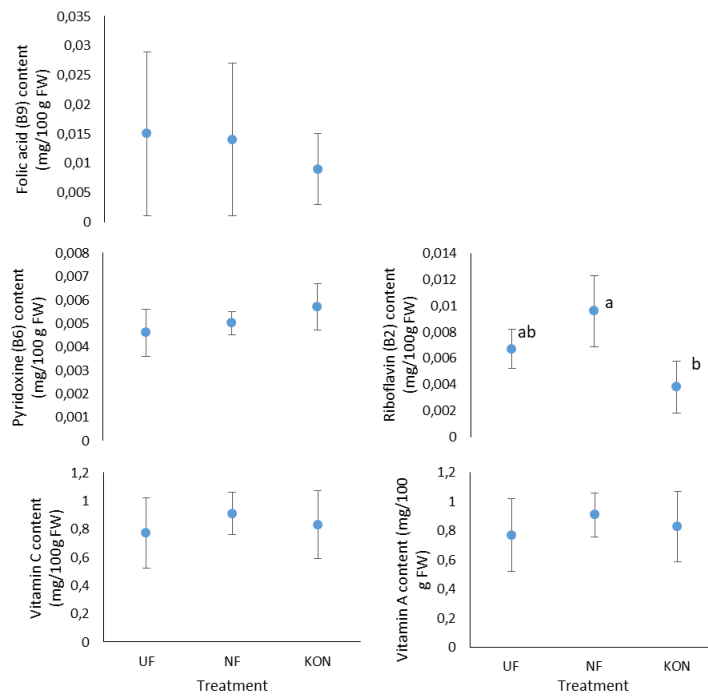


Fig. 3. The contents of folic acid (B9), riboflavin (B2), pyridoxine (B6), vitamin A and vitamin C ($\text{mg } 100 \text{ g}^{-1}$) in onions at individual treatment

Data are presented as the mean \pm standard error calculated from four replicates per treatment. Differences between the treatments (a-b) were determined using Tukey's test and were found to be significant at $\alpha < 0.05$.

Conclusions

In our research, irrigation of three different vegetables, pepper, carrot and onion with fresh water and wastewater treated with reverse osmosis and ultrafiltration and its impact individual vitamin content was evaluated. The results showed that irrigation with treated wastewater did not have any negative impact on the quality of the edible parts of peppers, carrots, and onions. From our results, we can conclude that this method of irrigation is suitable for use in agronomy, as it would save fresh water and at the same time preserve the content of the analysed vitamins in vegetables at their original level. For the future research it would be appropriate to evaluate the impact of irrigation with such water on other vegetables or fruit species, such as strawberries.

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