Response of Soil-Fava System Irrigated with Urban Treated Wastewater to Nutrient-Enriched Biochar and Zeolite

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Abstract. With the global population rising, the demand for fertilisers to maintain soil fertility and boost crop productivity has surged. However, the excessive reliance on chemical fertilisers has raised serious concerns regarding economic and environmental sustainability. In response to this challenge, the utilisation of treated wastewater presents a promising opportunity for irrigation water and nutrient recovery. Among the tested materials, biochar and zeolite have emerged as highly effective in nutrient recovery from wastewater sources, particularly phosphate and ammonium, respectively. Indeed, when applied to the soil, these materials serve as soil amendments and function as slow-release fertilisers. This study aimed to investigate, through a plant-pot experiment, the utilisation of treated wastewater for irrigation purposes, coupled with the application of PO_4^{3-} enriched biochar and NH_4^+ enriched zeolite, as slow-release fertilisers, and natural biochar and zeolite as control. The results revealed that wastewater, rich in soluble salts, increased soil electrical conductivity and adversely impacted plant growth. However, the application of biochar and zeolite effectively mitigated these adverse effects. Enriched biochar and zeolite acted as slow-release fertilisers, leading to increased biomass in fava plants and enhancing the uptake of nitrogen (N) and phosphorus (P).

Keywords: Nutrient recovery · Treated Wastewater Irrigation · Enriched Biochar · Enriched Zeolite

1 Introduction

Due to the continuous growth of the world population, there is an increasing reliance on chemical fertilisers to improve soil fertility and increase crop yields. This overuse is not economically and environmentally sustainable. The growing demand for fertilisers increases costs, while their excessive presence in the environment poses significant

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risks to the ecological balance. Thus, it is imperative to shift towards more sustainable nutrient management. A key strategy for this change is the recovery and reuse of nutrients, aligning agricultural practices with the principles of the circular economy (Mannina et al. 2021a). An underutilized resource for nutrient recovery is wastewater from the secondary treatment process. Despite their low nutrient content, urban treated wastewater (TWW) can provide macro- and micronutrients essential for plant growth. Hence, treated wastewater represents an opportunity not only for irrigation but also for nutrient recovery. Several materials have been studied for their ability to adsorb these nutrients from wastewater, with biochar and zeolite standing out for their effectiveness in adsorbing PO_4^{3-} and NH_4^+, respectively (Wang et al. 2022; Muscarella et al. 2023a). Moreover, biochar and zeolite, organic and inorganic soil amendments, respectively, once applied to soil, have been shown to contribute to improving soil properties (e.g. Zhang et al. 2021; Girijaveni et al. 2018). Then, PO_4^{3-} enriched biochar and NH_4^+ enriched zeolites can be applied in agriculture to improve soil physical and chemical properties (Mannina et al. 2021b; Muscarella et al. 2023b) and as slow-release fertilisers within a circular economy perspective (Mannina et al. 2022a; Sengupta et al. 2015).

This work aimed to evaluate the impact of treated wastewater use for crop irrigation and the application of nutrient-enriched biochar and zeolite on soil fertility and plant growth. The focus is primarily on the dynamics of nitrogen (N) and phosphorus (P), microbial biomass carbon, and the biometric properties of fava beans as model crop. Furthermore, microbiota analysis was carried out to investigate the influence of the TWW on rhizosphere microbial community structure to infer metabolic process associated to plant growth. The findings of this research are expected to provide valuable insights into sustainable nutrient management practices, contributing significantly to the advancement of environmentally friendly agriculture.

2 Materials and Methods

2.1 Experimental Design

For the purpose of this study, a pot experiment was carried out in a greenhouse at the Department of Agricultural, Food and Forest Sciences of the University of Palermo (38°10′66.6″N, 13°35′03.9″E). The experimental design included eight treatments as summarised in Table 1. The experimental design included eight treatments, classified according to irrigation type and soil amendment: (i) three treatments irrigated with tap water, comprising unamended soil (TAP), soil amended with enriched biochar (TAP – EB) and soil amended with enriched zeolite (TAP – EZ); (ii) five treatments irrigated with treated wastewater, comprising unamended soil (TWW), soil amended with enriched biochar (TWW – EB), soil amended with enriched zeolite (TWW – EZ), soil amended with natural biochar (TWW – NB) and soil amended with natural zeolite (TWW – NZ). Each treatment consisted of 5 replicates.

2.2 The Soil-Fava Growth System

The soil used for the experiment was amended with 10% of mature manure. The main characteristics of soil after manure amendment were clay-loam texture, 7.9 and 0.34

dS m^{-1} of pH and electrical conductivity (1:2.5, w/v, in water), respectively, 31 g kg^{-1} of TOC, 1.4 g kg^{-1} of TN and 129 mg kg^{-1} of available P, and 7.98 $cmol_+$ kg^{-1} of cation exchange capacity. To avoid soil compaction, 10% of perlite in volume was added. The treated wastewater used to irrigate the plants was obtained from the University of Palermo's water resource recovery plant (Mannina et al. 2021a). A pilot plant with an advanced membrane bioreactor produced treated wastewater (TWW) (Mofatto et al. 2024; Mannina et al. 2022b). The biochar and zeolite used in the experimental test were enriched with PO_4^{3-} and NH_4^+, using a full-scale column pilot plant at the urban wastewater treatment plant in Marineo, Sicily (Mannina et al. 2022a). The main characteristics of water biochar, and zeolite, enriched or not, were reported in Tables 1 and 2, respectively.

Table 1. The main characteristics of the water used for fava plant irrigation are as follows: Tap water (TAP), Treated Wastewater (TWW)

Parameters	pH	EC	NH_4^+	NO_3^-	Total P	Fe	Mn	Ca	K	Mg	Na
u.m.		dS m^{-1}	mg L^{-1}								
TAP	7.5	0.1	0.1	0.1	0.02	0.10	0.001	14.0	1.0	2.1	3.0
TWW	8.4	0.9	10.1	0.9	4.95	0.12	0.006	127.5	17.5	11.9	87.8

Table 2. Main characteristics of biochar natural and enriched (NB and EB, respectively) and zeolite natural and enriched (NZ and EZ, respectively)

Parameters	Ca^{2+}	K^+	Na^+	Mg^{2+}	Total P	Available P	Total N
u.m.	(exchangable cations) mEq 100 g^{-1}				mg g^{-1}	mg g^{-1}	mg g^{-1}
NB	19.0 ± 0.9	7.0 ± 1.3	5.0 ± 0.6	4.3 ± 0.3	1.2 ± 0.1	66.0 ± 1.5	n.d
EB	42.7 ± 0.3	36.2 ± 1.0	16.8 ± 0.3	4.0 ± 1.1	2.7 ± 0.3	72.9 ± 1.2	2.0 ± 0.1
NZ	53.0 ± 3.1	38.1 ± 2.9	8.7 ± 0.1	0.4 ± 0.1	1.0 ± 0.1	82.3 ± 2.9	n.d.
EZ	23.0 ± 1.0	20.9 ± 1.2	7.1 ± 1.9	5.3 ± 0.3	0.3 ± 0.1	23.9 ± 2.3	13.1 ± 0.1

Biochar and zeolite, natural or enriched, were mixed with soil at a concentration of 10 g kg^{-1} each, corresponding to 25 t ha^{-1}. Each pot was filled with 1.4 kg of soil, and two beans were sown for each pot. Plants were irrigated twice weekly with tap water (TAP) and treated wastewater (TWW) according to the experimental design to maintain the soil at 50% of the field water capacity.

2.3 Soil and Plants Analysis

After 92 days from sowing, the fava plants were harvested and analysed to assess their biometrical and chemical properties. Soils, sieved at 2 mm, were analysed to determine nutrient availability, biological and microbiological characteristics. In particular, the analysis of microbiota structure of three replicates of rhizosphere was performed by metataxonomics based on Next Generation Sequencing (NGS) analysis of 16S rRNA gene using an Illumina Miseq platform. The number of ASVs and the percentages of relative abundances of species, orders, classes, and families were determined for each sample.

3 Results and Discussion

Enriched biochar and zeolite positively affected the fresh and dry weight of plants grown in soil irrigated with tap water (Fig. 1). Such a positive effect also occurred when TWW was used for crop irrigation. Conversely, plants were adversely affected in soil irrigated with TWW and not amended or amended with natural zeolite. Tested experimental factors affected in the same manner plant total nitrogen and phosphorus (Fig. 1). Such results suggested that 1) enriched biochar and zeolite can meet the nutrient demand of plants, 2) TWW adversely affect plant growth and 3) the adverse effect of TWW may be counteracted by supplying enriched zeolite or enriched or not biochar. On the other hand, not enriched zeolite cannot counteract the negative effect of TWW on plants. Considering the main characteristics of TWW, the negative effect on plants may be ascribed to the high electrical conductivity and soluble Na^+ concentration. Such an hypothesis was confirmed by soil electrical conductivity, which showed significantly higher values in soil irrigated with TWW than those irrigated with tap water and by the increase of exchangeable Na^+ (Table 3) (Fig. 2).

Table 3. Exchangeable cations in soils subjected to different irrigation treatments (TAP and TWW) and different amendments (NB, EB, NZ and EZ)

	Ca^{2+}	K^+	Mg^{2+}	Na^+
	mEq 100 g^{-1}			
TAP	36.3 ± 2.6	1.1 ± 0.1	3.8 ± 0.3	1.6 ± 0.2
TAP – EB	34.3 ± 0.9	1.1 ± 0.1	3.6 ± 0.3	1.6 ± 0.0
TAP – EZ	34.7 ± 2.1	1.3 ± 0.2	3.2 ± 0.4	1.7 ± 0.3
TWW	36.1 ± 1.3	1.3 ± 0.1	3.5 ± 0.2	2.2 ± 0.1
TWW – EB	35.5 ± 0.8	1.1 ± 0.0	3.4 ± 0.1	2.0 ± 0.2
TWW – EZ	40.2 ± 0.9	1.5 ± 0.1	3.8 ± 0.1	2.3 ± 0.1
TWW – NB	35.4 ± 0.4	1.0 ± 0.1	3.2 ± 0.1	1.9 ± 0.3
TWW – NZ	34.0 ± 2.3	1.2 ± 0.1	3.0 ± 0.2	1.9 ± 0.2

Soil nutrient availability was significantly affected by tested factors. Total nitrogen showed the lowest value in soil amended with enriched zeolite and irrigated with tap water, as well as in soli irrigated with TWW and amended with enriched biochar. Such results may be ascribed to a more excellent absorption of such elements by plants as

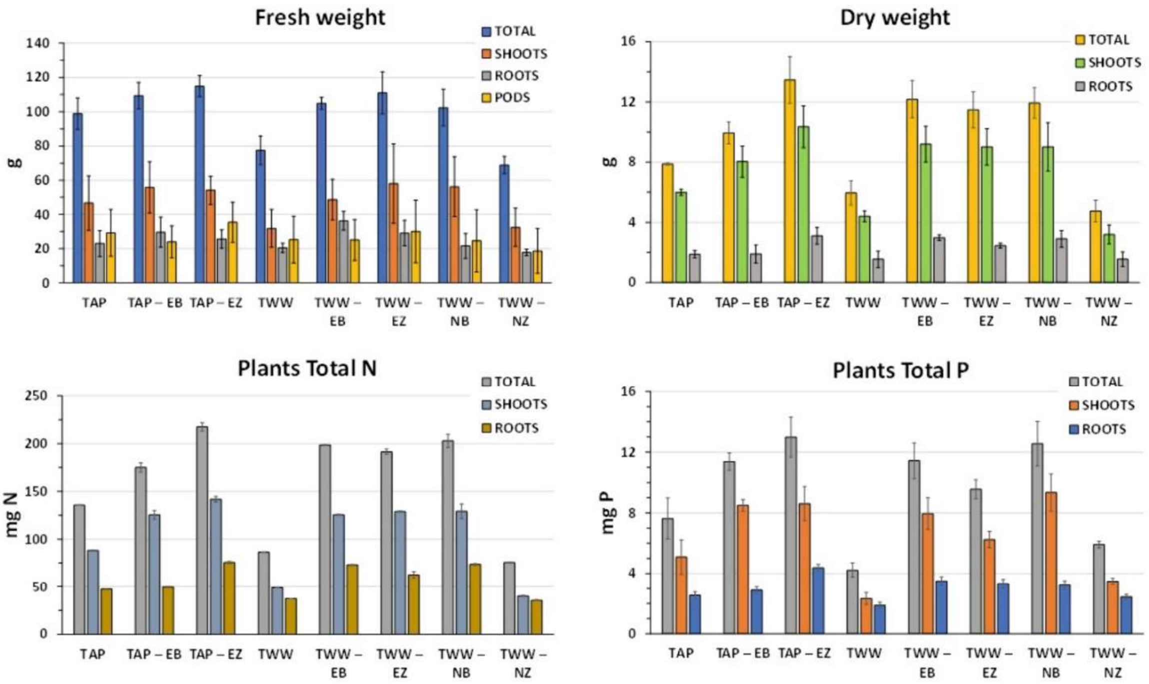

Fig. 1. Fresh and dry weight, total N and P of plants subjected to different irrigation treatments (TAP and TWW) and different amendments (NB, EB, NZ and EZ).

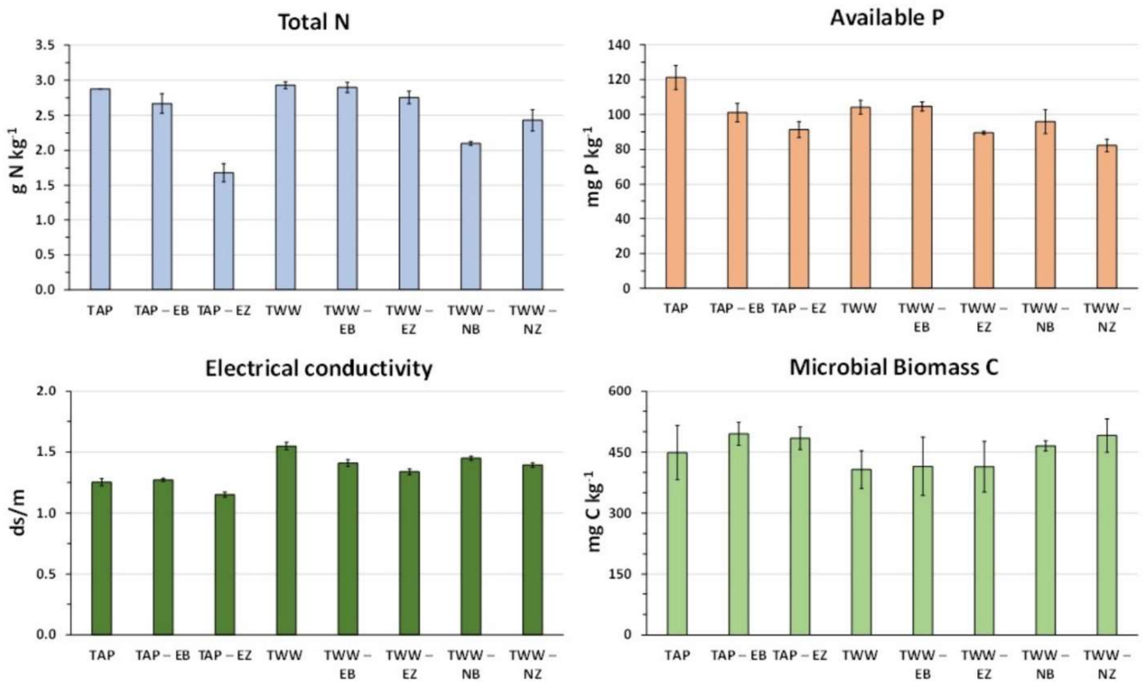

Fig. 2. Total N, available P, electrical conductivity and microbial biomass carbon (MBC) in soils subjected to different irrigation treatments (TAP and TWW) and different amendments (NB, EB, NZ and EZ)

confirmed by the dry and fresh weights and their total amount in plants. However, the available P decrease, especially in soil irrigated with TWW, could also be ascribed to a reduction in availability due to immobilisation. Indeed, TWW had a sub-alkaline reaction that is well-known to cause P immobilisation. Microbial biomass C did not show significantly different values among treatments, also in soil irrigated with TWW. This is probably because the soil used was sampled in a semiarid environment where soil microorganisms are adapted to harsh environments. Amplification of a DNA fragment of the expected size was obtained in the samples, confirming the presence of bacteria in the analysed soils. Bioinformatic analysis revealed the number of ASVs and the percentages of relative abundances of species, orders, classes, and families. Eventually, the soil core microbiota was elucidated and bacteria putatively playing a helpful role for plant growth were highlighted.

4 Conclusions

In conclusion, this study highlights the potential of treated wastewater (TWW) as a valuable resource for sustainable nutrient management in agriculture. Enriched biochar and zeolite have been demonstrated to serve as effective slow-release fertilisers, enhancing plant growth and nutrient uptake compared to conventional tap water irrigation. At the same time, TWW alone exhibited negative impacts on plant growth and increased soil electrical conductivity due to soluble salt content. However, applying both enriched and natural soil amendments successfully mitigated the negative effects of TWW. Overall, by utilising waste resources such as TWW and optimising their integration with soil amendments, it is possible to promote sustainable agriculture while addressing the challenges of soil fertility and nutrient sustainability in a growing world population.

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