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Impact of digestate-based biofertilisers on the agronomic performance of quinoa cultivation

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ABSTRACT

Due to drought and low soil fertility, Moroccan farmers have a limited choice of crops. In this context, quinoa (*Chenopodium quinoa*) is considered a promising alternative due to its adaptability to arid and semi-arid conditions. This study investigated the effect of fertilising quinoa with four digestates derived from the anaerobic co-digestion of olive mill wastewater (OMW), with fruits and vegetable waste (FVW), fish waste (FW), and cow dung (CD). In addition, the combined effects of these digestates with chemical fertiliser were evaluated. The experiment was conducted under greenhouse conditions to evaluate the effects on the agronomic, morphological, and physiological parameters of quinoa. The results showed that the highest grain yield (16 $q \cdot ha^{-1}$) was obtained with the treatment $[CD\text{-}Mx]_{R2:1}$-NPK, followed by $[CD\text{-}OMW]_{R3:1}$-NPK (14 $q \cdot ha^{-1}$), whereas both the negative and positive controls produced 13 $q \cdot ha^{-1}$. The effects on morphological and physiological parameters, such as plant height, number of leaves, leaf area, number of inflorescences, chlorophyll content, and the '1000 seed' weight, were quite disparate and significantly differed among all treatments.

Keywords: biofertiliser, digestate, olive mill wastewater, fruits and vegetable waste, fish waste.

INTRODUCTION

Quinoa (*Chenopodium quinoa* Willd.) is an annual, dicotyledonous plant classified as a pseudo-cereal within the Amaranthaceae family (Lallouch et al., 2025). Native to the Andes region, quinoa has been cultivated for approximately 7.000 years, valued for its rich nutritional profile and resilience to diverse climatic conditions (Lebonvallet, 2008). Originally centred in Bolivia, Peru, and Ecuador, quinoa production has successfully expanded to Asia, Africa, Australia, North America, and other Andean regions (Yacoub et al., 2023). Known for its relatively high protein content (14% to 15%), balanced amino acid content and considerable nutritional value (Valenzuela Zamudio et al., 2024; Gonzalez et al., 2012; Prado et al., 2014; Tang et al., 2015), quinoa can be considered a valuable alternative crop in the regions with severe climatic and soil conditions Fghire et al. (2021). Furthermore, the nutritional value of quinoa varies according to its genetic variability, cultivar, ecotype and farming practices, such as fertilisation, organic amendments, and irrigation (González et al., 2023).

Today, quinoa is cultivated in over 125 countries, including Morocco, which has shown growing interest in its production over the past two decades. Initially introduced in the Khénifra region in 1999/2000 (Morocco), quinoa has emerged as a promising crop to address Morocco's agricultural and food security challenges. It has been selected for its adaptability, high yield potential, disease resistance, and seed quality (Rafaralahinirina, 2023).

Several studies conducted in Morocco on quinoa cultivation have highlighted its adaptability to water and salinity stress conditions (Hirich et al., 2014a; Hirich et al., 2014b; Fghire et al., 2015). On the other hand, the use of organic soil amendments has been shown to enhance quinoa grain yield by increasing the plant's tolerance to salt stress, improving soil water retention capacity, and enhancing the availability of nutrients (Hirich et al., 2014b; El Mouttaqi et al., 2023).

The use of fertilisers, whether organic or mineral, remains limited in quinoa field fertilisation. However, recent research indicates that appropriate nitrogen inputs are linked to increased seed yield (Geren, 2015), estimated at 3.5 $t.ha^{-1}$ with 120 $kg.ha^{-1}$ of nitrogen, as well as an increase in protein content (Jacobsen et al., 1994). Similarly, phosphorus promotes seed formation and ripening, while a deficiency can cause leaves to turn purple or brown (Valarezo Ramos, 2023). However, excessive use of chemical fertilisers exacerbates soil salinity and acidity problems as well as causes intense mineralisation of the soil organic matter (Erraji et al., 2024a).

The most abundant wastes in Morocco suitable for digestate production include fermentable organic materials, such as fruit and vegetable waste and fish waste. Olive pomace is also available in considerable quantities. Inappropriate management of this waste can lead to harmful environmental pollution (Arabi et al., 2020; Galloni et al., 2022; El-Emam, 2023). The digestates used in this study are derived from the co-digestion of liquid olive mill wastewater with fruit and vegetable waste, fish waste, as well as cattle dung under mesophilic conditions (Erraji et al., 2025). To our knowledge, no study has investigated the fertilisation of quinoa (*Chenopodium quinoa*) using a digestate derived from the anaerobic co-digestion of olive mill wastewater.

The purpose of this study was to assess the effect of biofertilising on quinoa (*Chenopodium quinoa*) grown in pots in a greenhouse, using the digestate derived from olive mill wastewater, fruit and vegetable waste, fish waste and cattle dung. The specific aim of this study was to determine the most appropriate treatment for quinoa cultivation by comparing the effect of digestate alone and in combination with chemical fertilisers, through the assessment of agronomic parameters (growth and yield) and physiological parameters (photosynthetic efficiency and chlorophyll content).

MATERIALS AND METHODS

Field experiment and plant material

In order to evaluate the effect of fertilisation by using a biofertiliser derived from the co-digestion of the olive mill wastewater (OMW), with fruits and vegetable waste (FVW), fish waste (FW), and cow dung (CD) on quinoa cultivation. The trial was conducted at the experimental research station of the Faculty of Science in Oujda, in a climate-controlled greenhouse set at 25 °C (34°39′8.19″ N and 1°53′58.06″ W), at an altitude of 621 meters. The experiment was conducted using one variety of quinoa (*Chenopodium quinoa*), namely Q5.

Digestates and characterisation

The digestates used as biofertilisers in this study were obtained from a previous study by (Erraji et al., 2025), conducted in the laboratory of the Institute for Training in Renewable Energy and Energy Efficiency (IFMEREE). These digestates were obtained from the anaerobic co-digestion of a mixture of OMW, with FVW, and FW, referred to as Mx, with each waste representing 33% of the mixture. The co-digestion process was carried out using two inoculum-to-substrate (I/S) ratios of 2:1 and 3:1, based on the volatile solids (VS) content of the inoculum: CD and the waste mixture (Table 1).

The physicochemical characterization of the digestates was performed to evaluate their qualities and properties as biofertilisers. These analyses will be used to determine the concentrations of major nutrients, such as nitrogen (N), phosphate (PO_4^{3-}) and potassium (K), as well as pH and electrical conductivity (EC). These parameters are crucial for determining the appropriate application rates of digestates and optimising their use as agricultural fertilisers.

NPK nutrient content was determined using Laboratory-Cuvette-Kit test (LCK) with a HACH-DR1900 spectrophotometer on liquid samples of the digestate after centrifugation. The pH and EC of the liquid digestates were determined directly using liquid samples and a METTLER-TOLEDO pH meter and a sensIONtm (HACH) conductivity meter. A phytotoxicity test was also conducted to assess the potential inhibitory effect of the digestates on plant growth, following the method described by (Erraji et al., 2023). The characteristics of digestates are presented in Table 2.

Seed germination and application of treatments

The quinoa seeds used in this study were sown in December 2023 in a seedling tray using unamended peat as the substrate. In January 2024, the plants were transplanted into 25 cm diameter pots filled with unamended peat. Two plants were transplanted into each pot, spaced 10 cm apart to promote optimal growth. The plants were maintained in a climate-controlled glass greenhouse. Fertilisation of quinoa plants was carried out during the crop cycle using digestates and/or chemical fertilizer (NPK), as outlined in Table 3.

The study included ten treatments, each replicated three times in three blocks, resulting in a total of 30 pots (i.e., 60 plants). Each pot contained two quinoa plants grown under similar conditions and selected for morphological uniformity. The experimental design followed a randomised complete block design (Figure 1).

Measured parameters

To assess the effect of fertilisation with an OMW-based biofertiliser on quinoa cultivation, several key parameters were monitored. Morphological parameters included plant height, stem diameter, and leaf area. Physiological parameters comprised photosynthetic activity and chlorophyll content. Finally, agronomic performance was evaluated based on yield and the weight of 1000 seeds.

Statistical analysis

The results were subjected to descriptive statistical analysis and analysis of variance (ANOVA) using IBM-SPSS Statistics version 25.0 software. Mean comparisons were performed using Tukey's test, and differences were considered statistically significant at $P<0.05$.

RESULTS AND DISCUSSION

To evaluate the effect of applying digestate derived from the anaerobic co-digestion of OMW on quinoa growth and yield, morphological, physiological, and agronomic parameters were measured and compared across treatments.

Effect of digestate on morphological parameters of quinoa

Height

Over the three measurement timepoints, significant variation in quinoa plant height was observed among the treatments. At the first measurement, heights ranged from 80 to 110 cm. Treatment T4 recorded the highest value (90.75 cm), followed by T6 and T7. Treatments C– (negative control), T1, T2 and T8 showed similar heights around 80 cm, while T5 showed the lowest height (77 cm), representing a reduction of 8.34% compared to the negative control and 3.35% compared to the positive control (Figure 2).

At the third measurement, which was taken at the fruiting stage, plant heights ranged from 130 to 145 cm. Remarkably, the positive control (C+) showed the lowest height at this stage. In contrast, treatment T3 $[CD\text{-}Mx]_{R3:1}$ achieved the greatest stem length, demonstrating the most favourable growth response.

These findings were supported by statistical analyses, which confirmed significant differences among the treatments. The results are consistent with previous studies reporting the

Table 1. Composition of digestates used in this study (Erraji et al., 2025)

Biofertilizer code	Composition (fresh weight based)	I/S *(ratio)*
$[CD\text{-}Mx_{]R2:}1$	33% olive mill wastewater + 33% fruits and vegetable waste + 33% fish waste + cow dung	2:1
$[CD\text{-}OMW]_{R2:1}$	Olive mill wastewater + cow dung	2:1
$[CD\text{-}Mx]_{R3:1}$	33% olive mill wastewater + 33% fruits and vegetable waste + 33% fish waste + cow dung	3:1
$[CD\text{-}OMW]_{R3:1}$	Olive mill wastewater + cow dung	3:1

Table 2. Physico-chemical characteristics of digestates used in this study

Parameters	[CD-Mx]$_{R2:1}$	[CD-OMW]$_{R2:1}$	[CD-Mx]$_{R3:1}$	[CD-OMW]$_{R3:1}$
Hydrogen potential “pH”	6.27	7.46	7.68	7.47
Electrical conductivity “EC” ($\mu S\cdot cm^{-1}$)	5.24	4.92	5.11	5.54
Total Kjeldahl nitrogen “TKN” ($g\cdot l^{-1}$)	0.74	1.16	0.92	2.27
Total phosphorus “P” ($g\cdot l^{-1}$)	1.60	0.65	0.48	1.76
Total potassium “K” ($g\cdot l^{-1}$)	3.96	1.83	1.40	4.49
Germination index “GI” %	11.30	65.57	3.04	46.46

Table 3. Amounts of biofertilisers and nitrogen applied to quinoa cultivation

Treatment	Code	Amount of biofertilizer applied (ml)	NPK fertilization rate ($kg\cdot ha^{-1}$)
T1	[CD-Mx]$_{R2:1}$	764.84	100-100-200
T5	[CD-Mx]$_{R2:1}$-NPK	764.84	
T2	[CD-OMW]$_{R2:1}$	283.34	
T6	[CD-OMW]$_{R2:1}$-NPK	283.34	
T3	[CD-Mx] $_{R3:1}$	350.00	
T7	[CD-Mx]$_{R3:1}$-NPK	350.00	
T4	[CD-OMW]$_{R3:1}$	433.33	
T8	[CD-OMW]$_{R3:1}$-NPK	433.33	
Positive control (C+)	NPK (C+)	NA	
Negative control (C–)	C (C–)	NA	0

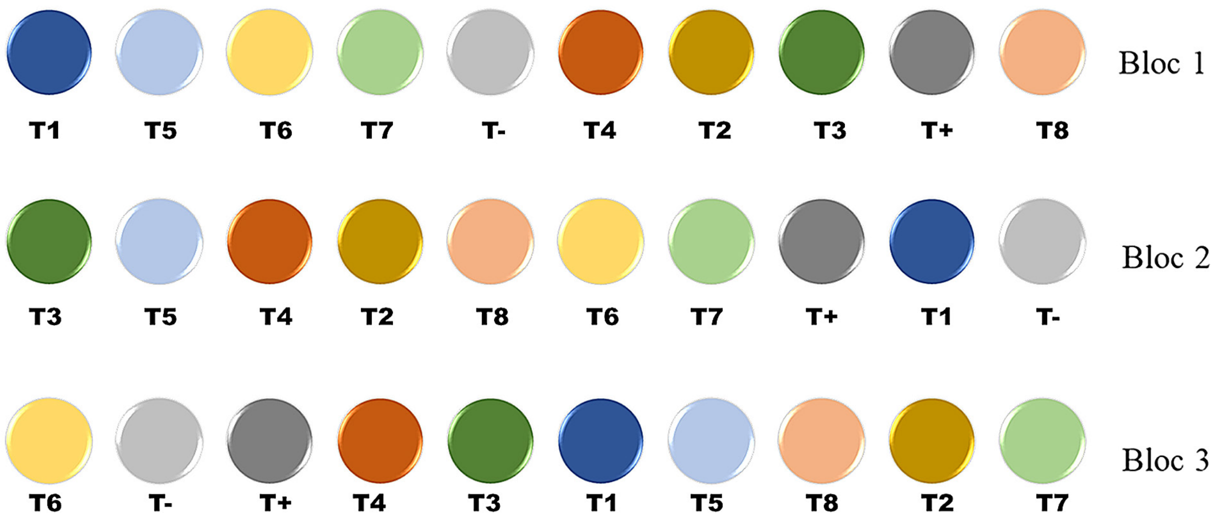

Figure 1. Schematic diagram of the experimental design

positive effects of digestate on various crops (Kalambura et al., 2016). In particular, the increase in plant height observed in the conducted experiment aligns with the findings from other studies, which demonstrated that digestate application tends to produce taller plants compared to those grown without fertilisation (Nikiema et al., 2024).

Number of leaves

As for the effect of digestate on the number of quinoa leaves, during the first counting, treatment T8 ([CD-OMW]$_{R3:1}$+ fertiliser NPK) recorded the highest number of leaves (250 leaves), representing an increase of 32.3% compared to the positive control. In contrast, T7 and the negative control (C–) had the

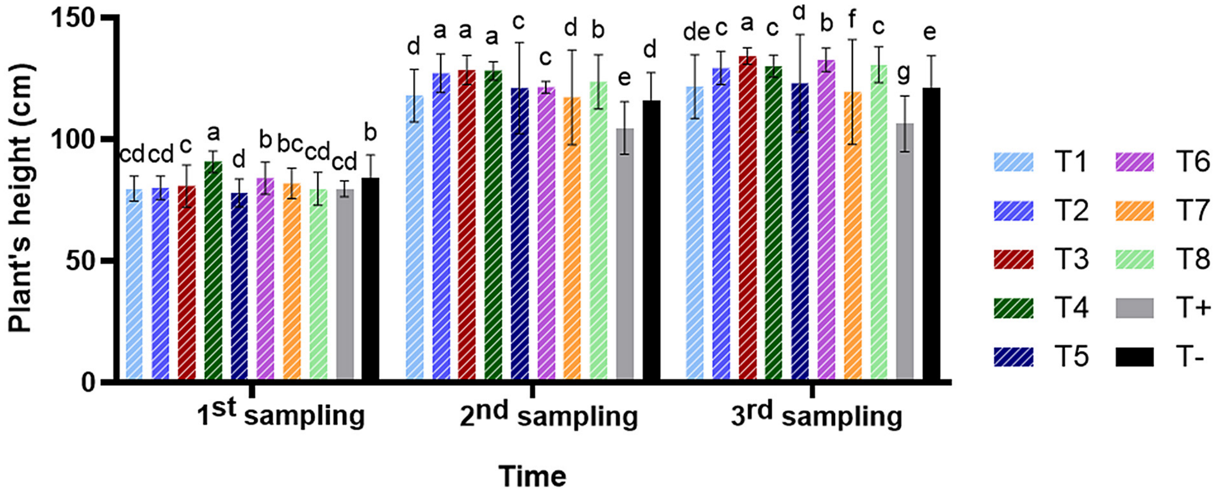

Figure 2. Effect of different digestate treatments (T1 to T8, C+, C−) on quinoa height at three measurement timepoints. Error bars represent standard deviation (n=3); C+ = positive control; C− = negative control. The different letters (a, b, c, etc.) indicate significant differences at the $p<0.05$ level

lowest values, with approximately 150 leaves. At the second counting, T8 maintained its superior performance, while C– continued to record the lowest number (120 leaves). These results underscore the significant impact of the treatments, with T8 promoting optimal leaf development, whereas C– was the least effective (Figure 3).

Similarly, other studies (Kalambura et al., 2016; Nikiema et al., 2024) reported that the application of digestate significantly increased the number of leaves in amaranth, with the highest values observed in fertilised plants compared to the control.

Leaf area

The analysis of leaf area revealed significant variations among treatments across the three measurement periods. At the first measurement, leaf areas ranged from approximately 24 cm² to over 50 cm², with treatments T3, T2, T4, T1 and T8 exhibiting the highest values, while the negative control (C–) recorded the lowest (Figure 4).

A general decrease in leaf area was observed over time, yet treatments T8, T3, and T4 consistently maintained relatively higher surface areas compared to the negative control (review this, C– actually maintained higher value with time).

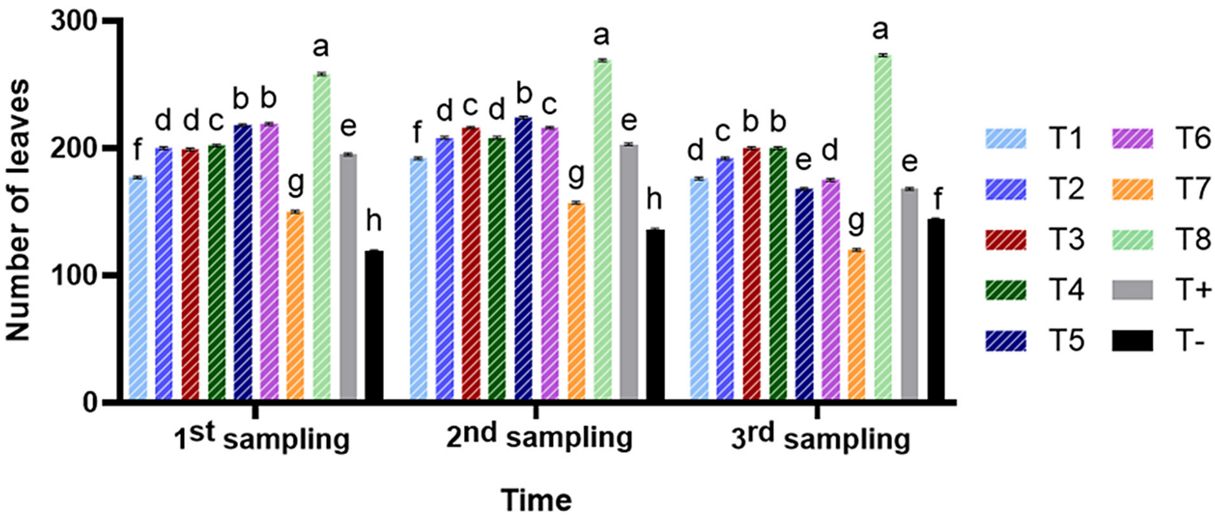

Figure 3. Effect of digestate on the number of quinoa leaves. The different letters (a, b, c, etc.) indicate significant differences at the $p < 0.05$ level

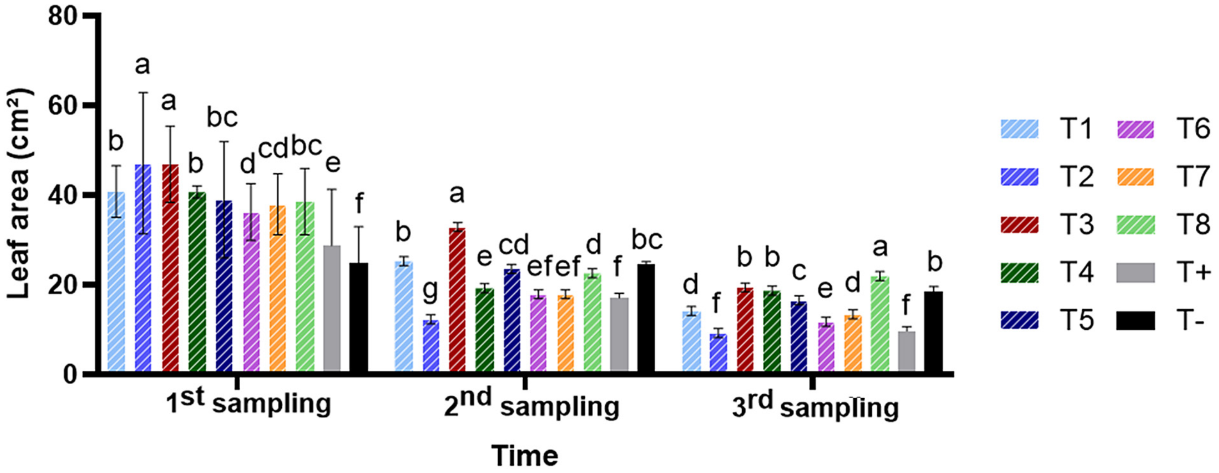

Figure 4. Effect of different treatments on leaf area. The different letters (a, b, c, etc.) indicate significant differences at the p < 0.05 level

Number of inflorescences

The assessment of the number of inflorescences showed a significant variation across treatments (P<0.001). As illustrated in (Figure 5), values during the first count ranged from 19 to 56 spikes.

A significant increase was recorded during the second count, with values between 30 and 57 spikes, indicating an active reproductive growth phase. Treatments T8 and Control + consistently showed the highest numbers of inflorescences during the second and third counts. In contrast, treatment T3, which included the digestate [CD-Mx] at a ratio of 3:1, recorded the lowest number of inflorescences throughout the cycle, showing a 43.53% reduction compared with C+. These results highlight the higher performance of digestate application in combination with chemical fertiliser, as demonstrated by the higher inflorescence number under treatment T8.

This can be attributed to the presence of essential nutrients such as nitrogen and phosphorus in these fertilisers, which play a key role in plant growth and development. Hence, the biofertiliser particularly promoted the formation of flowers, fruits, as well as both aerial and root biomass, compared to the control plants (Qi et al., 2018; Scaglia et al. 2017).

Effect of digestate on chlorophyll content

Chlorophyll is a vital pigment for photosynthesis and key indicator for plant physiological status, particularly under stress conditions. As illustrated in (Figure 6), the chlorophyll content

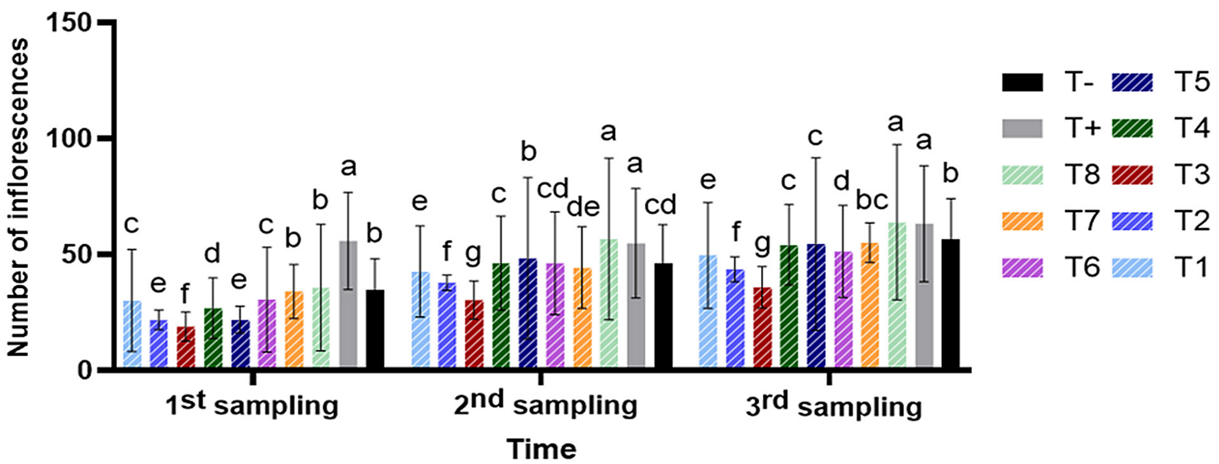

Figure 5. Effect of digestate application on the number of inflorescences. The different letters (a, b, c, etc.) indicate significant differences at the p < 0.05 level

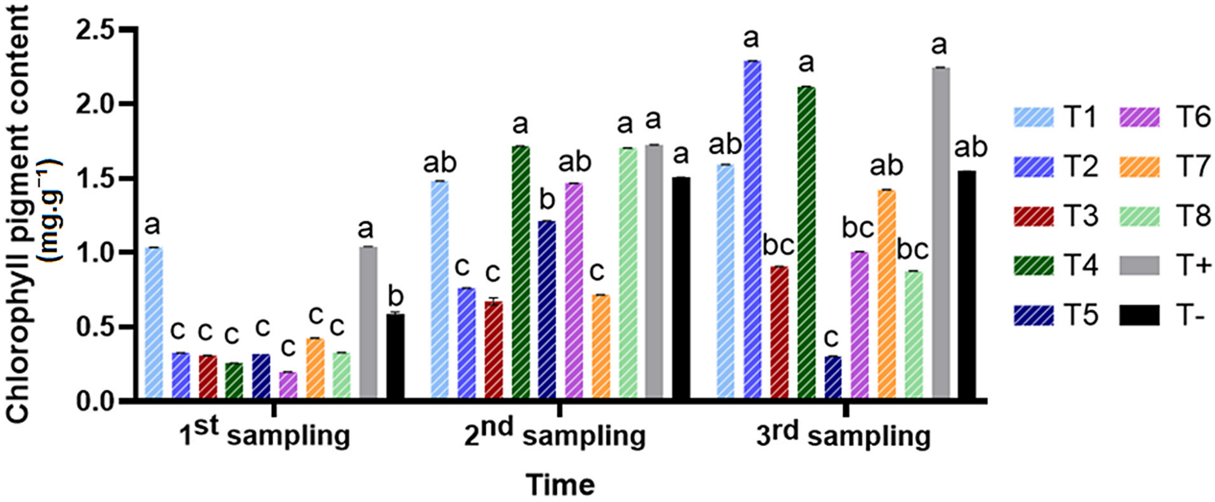

Figure 6. Effect of digestate treatments on chlorophyll content (mg.g^{-1}) in Quinoa leaves. The different letters (a, b, c, etc.) indicate significant differences at the p < 0.05 level

in quinoa plant leaves varied noticeably across treatments and sampling periods.

During the first sampling, T1 and the positive control (C+) showed the highest chlorophyll pigment levels (1.05 mg.g^{-1} and 1.04 mg.g^{-1}, respectively), while the remaining treatments recorded relatively low values. In the second sampling, an overall increase in chlorophyll content was observed. The highest values (up to 1.7 mg.g^{-1}) were recorded in treatments T4, T8, C+ indicating improved photosynthetic potential.

To a lesser extent, the treatments T1, T6 and negative control (C–) also showed elevated chlorophyll content, although values remained below 1.5 mg.g^{-1} By the third sampling, the highest chlorophyll contents were observed in T2 (2.30 mg.g^{-1}), C+ (2.25 mg.g^{-1}) and T4 (and 2.12 mg.g^{-1}), whereas T5 recorded the lowest value (0.30 mg.g^{-1}).

Statistical analysis revealed a highly significant effect of treatment on chlorophyll content ($P < 0.001$), confirming the influence of digestate composition and application on the physiological status of the plants.

A study on onion production found that neither organic nor inorganic fertilisers (NPK 15-15-15) alone significantly affected chlorophyll content. In contrast, their interaction had a significant effect (Mounirou, 2022). However, in the conducted study, the best chlorophyll performance across the three samplings was obtained with NPK alone (C+), followed by T4 ([CD-OMW]$_{R3:1}$), T1 ([CD-Mx]$_{R2:1}$), and T2 ([CD-OMW]$_{R2:1}$). Statistical analysis revealed a highly significant difference ($P < 0.001$) among treatments.

Effect of digestate on agronomic parameters

Grain yield

Grain yield values varied significantly among treatments, ranging from 10 to 16 q·ha^{-1} (Figure 7). The highest grain yield was recorded under T5 ([CD-Mx]$_{R2:1}$-NPK), followed by T7 and T1. In contrast, the lowest yield was obtained with T8, at around 10 q·ha^{-1}. These findings suggest that the combined application of mineral fertiliser with [CD-Mx]$_{R2:1}$ digestate (T5) was the most effective treatment in enhancing quinoa grain productivity.

To the best of authors' knowledge, no studies have directly addressed the effect of digestate application on quinoa, but comparisons can be made with other cereals. For instance, Salcedo-Serrano et al. (2022) showed that the application of anaerobic digestate from organic fraction of the municipal solid wastes significantly improved winter triticale yield (12.54 t.ha^{-1}), exceeding both inorganic fertiliser (11.16 t.ha^{-1}) and the unfertilised control. In the context of traditional organic amendments applied to quinoa, several studies have demonstrated the effectiveness of manure as an organic amendment for improving quinoa production. For example, the application of 20 t·ha^{-1} of farmyard manure significantly increased quinoa seed yield, reaching up to six times higher compared to the untreated control (Abdrabou et al., 2022). In another study investigating the agromorphological and biochemical responses of quinoa to various organic amendments under different salinity conditions, sheep manure performed the highest of values for dry biomass

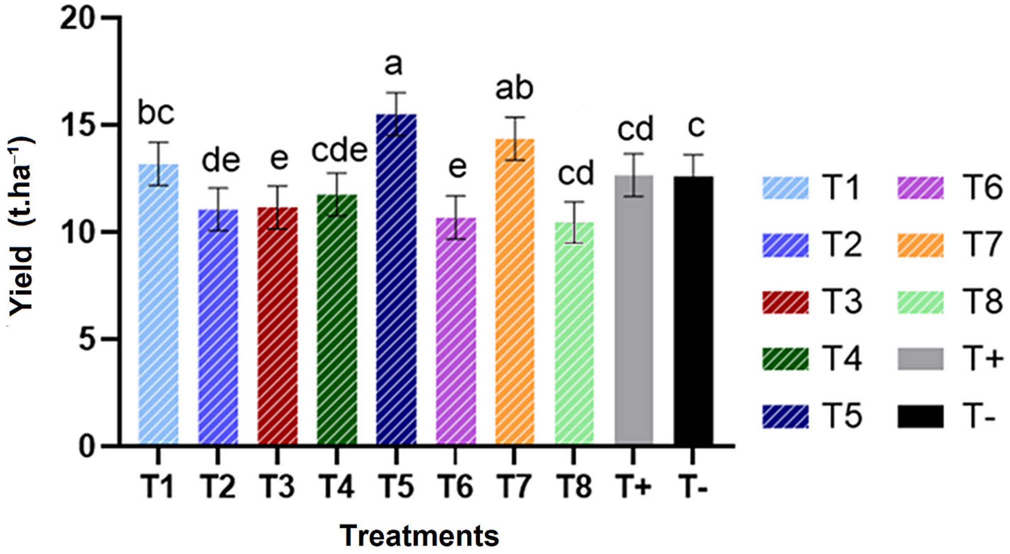

Figure 7. Effect of treatments applied on crop yields. The different letters (a, b, c, etc.) indicate significant differences at the $p < 0.05$ level

(1.91 t·ha⁻¹), seed yield (1.42 t·ha⁻¹) under conditions of high salinity (20 dS.m⁻¹) (El Mouttaqi et al., 2023). This improvement in yield can be explained by the nutrient content of the amendments, their rate and speed of mineralisation, and their ability to improve the water retention capacity of soil as well as stimulate biological activity (El Mouttaqi et al., 2023).

The "1000 seeds" weight

The treatments applied influenced the apparent vigour and size of quinoa seeds. In particular, T2 (the digestate from olive pomace + cattle dung with, 2:1) produced more vigorous seeds than the other treatments (Figure 8).

As it was shown in Figure 8, the "1000 seed" weight of quinoa ranged between 2.42 and 4.13 g. Although treatments T1, T2 and T3 showed slightly higher values than the other treatments, the differences were not statistically significant. For instance, T2 showed a 61% increase compared with the mineral fertiliser control (C+).

However, analysis of variance (ANOVA) confirmed the absence of significant differences between treatments (P>0.05), indicating that, despite the observed variability, none of treatments exerted a measurable effect on this parameter.

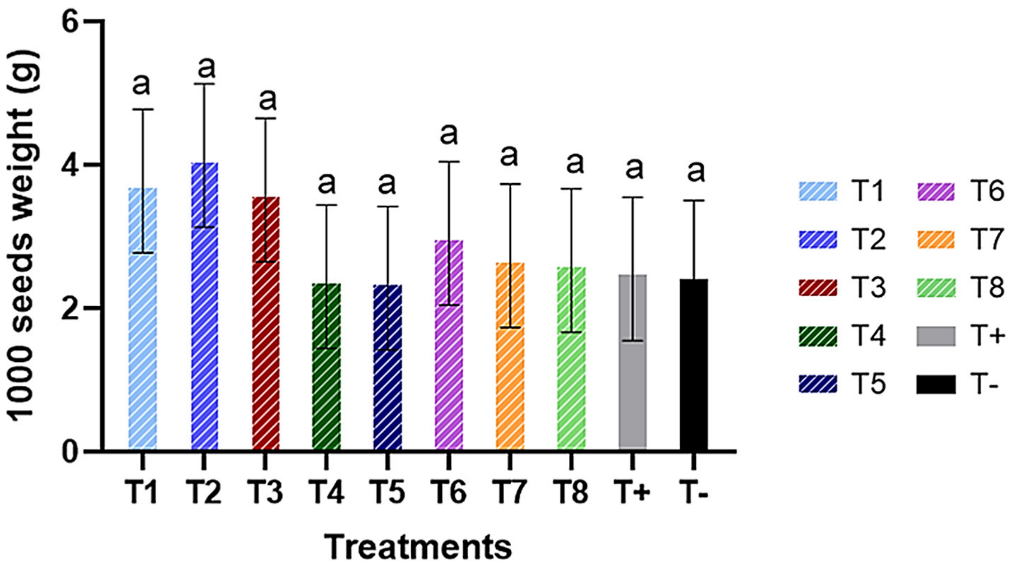

Figure 8. Effect of different treatments on 1000 seed weight

CONCLUSIONS

In this study, four digestates obtained from the co-digestion of olive mill wastewater with fruits and vegetable waste, fish waste, and cow dung under mesophilic conditions at two different inoculum-to substrate ratios (I/S ratio of 2:1 and 3:1) were evaluated for their fertilising effect on quinoa grown under greenhouse conditions. The digestates were tested either alone or in combination with chemical fertiliser (NPK).

The results obtained in the context of this work revealed a clear variability in the effects of different digestate based biofertilisers on the agronomic performance of quinoa, depending on the growth and yield parameters investigated. Among the treatments, $[CD\text{-}Mx]_{R3:1}$ had the greatest effect on plant height, while $[CD\text{-}OMW]_{R3:1}$-NPK enhanced leaf number and sustained larger leaf surface areas along with $[CD\text{-}Mx]_{R3:1}$ and $[CD\text{-}OMW]_{R3:1}$. The combined application of digestate and chemical fertilisers further improved crop performance, as evidenced by the higher number of inflorescences under $[CD\text{-}OMW]_{R3:1}$-NPK. Chlorophyll content varied significantly across treatments, with the highest levels observed under $[CD\text{-}OMW]_{R2:1}$, NPK (positive control) and $[CD\text{-}OMW]_{R3:1}$, whereas $[CD\text{-}Mx]_{R\ 2:1}$-NPK showed the lowest. The highest grain yield was obtained under $[CD\text{-}Mx]_{R2:1}$-NPK, followed by $[CD\text{-}Mx]_{R3:1}$-NPK and $[CD\text{-}Mx]_{R\ 2:1}$.

Thousand seeds weight were also impacted, with $[CD\text{-}OMW]_{R2:1}$ exhibiting more vigorous seeds, despite the lack of significant differences among treatments in seed weight. In conclusion, these suggest that digestate-based biofertilisers from the anaerobic digestion of agricultural residues, such as olive mill wastewater, fruit, and vegetable waste, can enhance quinoa growth and yield. Their combination with chemical fertilisers further improved physiological traits and productivity.

This approach provides a sustainable option to reduce reliance on chemical fertilisers while recycling organic waste, aligning with strategic national recommendations to strengthen biofertilisation and reduce the use of agrochemical inputs (Arabi et al., 2024). However, open field trials and the determination of the optimal application dose of digestate for quinoa are still required to ensure consistent yield improvement.

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