



Residual Effects of Compost and Manure Fertilizers on Quinoa Production and Nutrient Uptake

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Abstract

Organic fertilizers have the potential to improve soil quality and quinoa (*Chenopodium quinoa* Willd.) yields, but their long-standing benefits are unknown. Therefore, a three-years field experiment (2019–2022) was conducted in Morocco to investigate the residual effects of organic fertilizers on the productivity and mineral status of quinoa. Compost and manure were applied during the first season at 5, 10, and 20 t ha⁻¹ and 10, 20, and 40 t ha⁻¹, respectively. Soil organic matter (SOM), plant growth, and quinoa yield were monitored during the year of organic fertilizer applications and two and three years after the applications. 40 t ha⁻¹ of manure produced the highest SOM, plant height, and chlorophyll content index. Compost at 20 t ha⁻¹ produced the highest grain yield (4.6 t ha⁻¹) during the first year, but the residual effect of 40 t ha⁻¹ of manure exceeded other treatments in the second and third years (3.4 t ha⁻¹ and 1.4 t ha⁻¹, respectively). Average quinoa grain yield over the three years was highest with 10 and 20 t ha⁻¹ of compost and 20 and 40 t ha⁻¹ of manure and average quinoa nutrient content was 1.8 kg N, 0.3 kg P, 4.1 kg K, 0.5 kg Ca, 0.6 kg Mg, 0.5 g Cu, 1.9 g Zn, 7.9 g Mn, and 7.9 g Fe per 100 kg of total biomass. A single application of manure at 20 t ha⁻¹ was optimal to increase quinoa productivity for three growing seasons, promoting agricultural sustainability in arid regions.

Keywords Quinoa · Organic fertilizer · Residual effect · Yield · Morocco

1 Introduction

In the context of climate change, quinoa (*Chenopodium quinoa* Willd.) represents a promising alternative crop to valorize the marginal soils in arid regions and contributes to food security and environmental sustainability (González et al. 2015). Quinoa is a seed-producing crop that has been

cultivated in the Andes for thousands of years (Ruiz et al. 2013). This crop has high tolerance to frost, drought, salinity, and nutrient-poor soils, and it produces gluten-free grains of high nutritional value and balanced proteins (Adolf et al. 2013; Jacobsen 2003; Razzaghi et al. 2015; Andreotti et al. 2022). Quinoa gained global interest during the last decades and its cultivation expanded to different regions of the world (Bazile et al. 2014, 2016), but little is known about its best management practices under dryland farming. The impact of quinoa boom using unsustainable production practices may lead to soil degradation and loss of productivity (Alandia et al. 2020).

Drylands are characterized by poor soils and low precipitations and face high risks of degradation and expansion (Scheffer et al. 2001; Huang et al. 2016). These drylands are experiencing increased temperatures leading to high rates of water loss to evaporation and transpiration (Davies et al. 2016). In addition to water scarcity, drylands are characterized by low organic matter and N content which increase the soil vulnerability to erosion, resulting in loss of soil fertility, reduced agricultural productivity, and environmental

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degradation (Jordaan et al. 2022). Thus, cultivating drought resilient crops such as quinoa as well as implementing soil conservation practices such as the application of organic fertilizers can improve soil health and increase agricultural productivity in these regions. The application of manure and compost also improved soil water holding capacity, soil organic matter (SOM), and soil microbial activity which affected positively quinoa growth and yield under saline stressed conditions (Ciarkowska et al. 2017; Gupta et al. 2016; Hirich et al. 2014). Organic matter improved soil nutrient content and availability, resulting in an increase of quinoa nutrient uptake and productivity (Hartley et al. 2010), mainly in low input farming systems. In this context, quinoa positively responded to the addition of goat manure up to 4 t ha^{-1} (González et al. 2023). Although some studies have reported the positive effect of soil organic fertilizers on quinoa productivity (Taaime et al. 2023), no research has addressed the residual effect of such fertilizers on quinoa productivity and nutrient uptake.

Quinoa responded positively to nitrogen fertilization (Bahrami et al. 2022). Thus, using organic fertilizers constitutes a sustainable solution to improve soil fertility for a long period of time which has positive effect on the succeeding crops (Bhalshakar 2020). This residual effect differs according to organic fertilizer type, rate, timing of application, and soil temperature and moisture (Aguilera et al. 2012; Hood 2001). Studies conducted to evaluate the residual effect of organic fertilizers on soil characteristics indicated higher content of residual soil nutrients and increased SOM over a long period of time (Saha et al. 2008). Cultivating quinoa after leguminous crops resulted in yields 50% higher than quinoa monocropping and quinoa-fallow systems (INIAP 1992). This can be explained by the enriching effect of leguminous crops on soil N levels, thereby positively impacting quinoa yields in subsequent seasons. In Ecuador, quinoa yielded 20% higher when planted in plots fertilized the previous seasons (Nieto-Cabrera et al. 1997). However, studies addressing the response of quinoa to residual effect of organic fertilizers in quinoa monocropping systems are scarce. Investigating the residual effect of organic fertilizers on the productivity of other crops showed that vermicompost applied at 3 t ha^{-1} increased the dry matter, grain yield, and protein content of chickpea during the year of application and had a positive effect on dry fodder yield of the succeeding maize, essentially due to enhanced SOM, nutrient status, and microbial population (Jat and Ahlawat 2006). Similarly, Eghball et al. (2004) found that the residual effect of manure and compost on maize grain yield and nitrogen (N) uptake persisted for at least one growing season. Nnabude and Mbagwu (2001) also evaluated the residual effect of fresh and burnt rice-mill wastes as well as their combination with mineral fertilizers on maize crop.

The results of this study revealed that the most significant reduction in residual maize yield occurred in the mineral fertilizer treatment, followed by the combination of waste fertilizers with mineral fertilizers. In contrast, plots that received waste fertilizers alone experienced a lower reduction in residual yield, demonstrating the capacity of these waste materials to maintain productivity over time.

In the present study, we hypothesized that commercial compost will decompose faster than manure during the first year of application and enhance quinoa productivity while the residual effect of manure will last for a longer period. Identifying the optimal organic fertilizer type and rate is of high importance for maximizing quinoa productivity in drylands and promoting sustainable and environmentally friendly farming practices. This can empower farmers to make informed decisions that benefit both their agricultural systems and the long-term health of their fields. Thus, the objective of the present study was to study the residual effect of organic fertilizers on quinoa growth, productivity, and nutritional status, two and three years after their application.

2 Materials and Methods

2.1 Experimental Site

The experiment site is situated in an arid region. The field trials were conducted at the experimental farm of Mohammed VI Polytechnic University (UM6P) in Ben Guerir Morocco ($32^{\circ}13.08'' \text{ N}$, $7^{\circ}53.23' \text{ W}$) for three growing seasons 2019–2020, 2020–2021, and 2021–2022.

During the first season (2019–2020), the crop received 83 mm of rainwater, concentrated during quinoa sowing period and before the harvest (Fig. 1). The average temperature was 15.7°C and the absolute minimal and maximal temperatures were 0 and 39°C , recorded in January and May, respectively. During the second season (2020–2021), the total rainfall received was 117 mm of which 56 mm was recorded in February. The average temperature was estimated to 15°C , with an absolute minimal and maximal temperatures of -1 and 40°C , recorded in January and May, respectively. The last season recorded 90 mm of rainwater and an average temperature of 15.7°C . Quinoa was irrigated using a drip irrigation system and the applied water volumes (W) were calculated following the formula: $W = (K_c \cdot ET_0)/e$, where K_c represents the crop coefficient, with a value of 0.5 from the initial growth stages to branching, and a value of 1 from branching to seed filling (Garcia et al. 2003), ET_0 represents the reference evapotranspiration obtained from the weather station, and “e” is the irrigation system efficiency, being equal to 80%. Water volumes applied were measured using water flow meter and were estimated to 330, 322 and

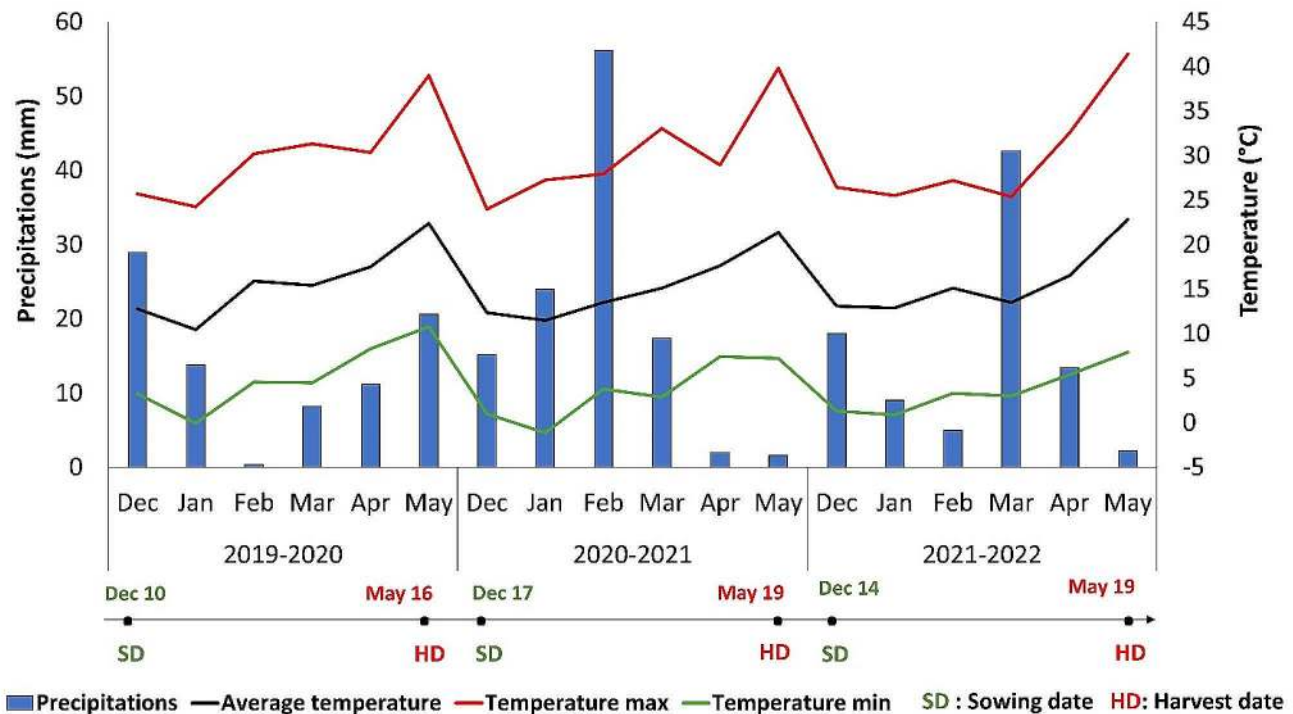


Fig. 1 Annual precipitations and temperature at the experimental site during 2019–2020, 2020–2021, and 2021–2022 seasons

325 mm during 2019–2020, 2020–2021, and 2021–2022 seasons, respectively.

Soil samples were collected in 2019, before the application of organic fertilizers, from the 20 cm topsoil and analyzes for chemical characteristics. The dried soil was crushed and sieved to 2 mm. The soil pH and electrical conductivity (EC) were measured following the 1:5 soil-to-water extract method, as described by NF ISO 11,265 (1997). Total N was determined using the Kjeldahl method (NF ISO 112,611,995). Available phosphorus was analyzed according to the Olsen method (Olsen et al. 1954), exchangeable potassium was extracted by ammonium acetate at pH=7 and determined by atomic absorption spectroscopy (Agilent Technologies. 200 Series AA), and calcium carbonate was measured using chlorohydric acid (Alison 1960). SOM was determined according to Walkley and Black (1934), using sulfochromic oxidation of carbon in a mixture of potassium dichromate ($K_2Cr_2O_7$) and sulfuric acid (H_2SO_4) at 135 °C.

For compost and manure analysis, total N was analyzed by the Kjeldahl method. Total P and total K were analyzed by inductively coupled plasma atomic emission spectroscopy (ICP-EOS) following mineralization with nitric acid and filtration. The organic matter content, also known as volatile solids, was determined through loss on ignition at 550 °C over a period of 4 h (Allison 1965).

The results showed that the soil has a sandy clay loam texture, a moderate content of organic matter and P, and

Table 1 Initial chemical characteristic of the experiment soil and the organic fertilizers

Chemical characteristics	Soil of the experiment	Compost	Manure
Total Nitrogen (%)	0.2	1.6	0.29
Phosphorus ($mg\ kg^{-1}\ P_2O_5$)	32	1.9	0.17
Potassium ($mg\ kg^{-1}\ K_2O$)	579	1.0	0.10
Organic Matter (%)	2.6	27.9	11.8
Total $CaCO_3$ (%)	0.2	-	-
Electrical Conductivity ($dS\ m^{-1}$)	0.11	-	-
pH	8.45	-	-
Total organic C (%)	1.5	16.2	6.9
C: N	7.5	10	24
Cation Exchange Capacity ($meq\ 100\ g^{-1}$)	23.5	-	-

high content of N and K. Other characteristics of the soil are presented in Table 1.

Quinoa cultivar ‘ICBA-Q5’ was used in this study because its high adaptation to Rehamna environmental conditions (Taaime et al. 2022a). Quinoa growing season was from December 10 to May 16 in 2019–2020, from December 17 to May 19 in 2020–2021, and from December 14 to May 19 in 2021–2022.

2.2 Experimental Set-Up

During the first season (2019–2020), manure and compost were incorporated in the soil 10 days before sowing at three different rates. Compost was applied at 5, 10, and 20 t ha⁻¹ and manure at 10, 20, and 40 t ha⁻¹. During the second and third seasons, no application of organic fertilizer was done, and quinoa was sowed two years consecutively in the plots previously amended and sowed with quinoa in 2019 to study their residual effect. The selection of organic fertilizer rates was based on the assessments of compost and manure rates commonly recommended for quinoa cultivation in international literature. The experimental units (80 m²) were arranged in a randomized complete block design with three replications. Each plot was 80 m² with crop row spacing of 50 cm.

The commercial compost and local cow manure characteristics are presented in Table 1. The compost used in our study was derived from agricultural and livestock waste.

2.3 Crop Management

Chisel plow followed by disc harrow were used for seed-bed preparation. Quinoa was sown mechanically at 8 kg ha⁻¹ seeding rate using a seed drill and then thinned at the ramification stage to 20–25 plants per m². Weeding was done manually one month after sowing and mildew was controlled applying 500 g ha⁻¹ of fungicide based on metaxyl-M and mancozeb. Daily weather data (Rainfall and temperature) were obtained from the Agricultural Innovation and Technology Transfer Center (AITTC) weather station 100 m nearby the experiment site.

2.4 Plant and Soil Measurements

At the end of each season, composite soil samples, with 7 subsamples collected from the 20 cm topsoil from each plot, were analyzed for the organic matter content. Before harvest, ten plants were randomly selected from each experimental unit and the plant height was measured from the ground level to the top of quinoa panicle of the mean stem. Ten quinoa plants were randomly sampled from each experimental unit before the flowering stage and the CCI was measured for the two youngest fully expanded leaves using a chlorophyllometer (Opti-Sciences, CCM-200). For each experimental unit, three squares of 1 m² each were harvested manually at about 10 cm above the soil. Total plant biomass was measured after natural drying of the harvest in the field and quinoa plants were threshed for grain yield measurements. Thousand seed weight (TSW) was measured in three samples from each experimental unit.

Nutrient uptake was determined on ten sampled plants per plot at the crop physiological maturity. Total plant biomass was dried, grinded, and sieved to 225 µm. Total N was determined colorimetrically on a Skalar San⁺⁺ after digestion using salicylic acid. For P, K, Cu, Zn, Fe, and Mn analysis, the ground samples were digested with nitric acid and analyzed using ICP-AES (Inductively Coupled Plasma - Atomic Emission Spectrometry).

2.5 Statistical Analysis

One-way analysis of variance (ANOVA 1) was used to test the effect of ‘organic fertilizers’ on quinoa plant height, CCI, total biomass, grain yield, TSW, and nutrient uptake. Student-Newman-Keuls test was used to reveal homogeneous groups between organic fertilizers within each year. Significant differences between the treatments were assessed at 5% probability level ($\alpha \leq 0.05$) using the SPSS program (Version 20, IBM SPSS Inc., Chicago IL).

3 Results

3.1 Soil Organic Matter

Soil organic matter in the control treatment declined by 11% over the three years (Fig. 2). Manure increased SOM in the first year at all three rates compared to the control, but SOM after three years was only significantly higher than the control at 40 t ha⁻¹. Compost did not increase SOM in any year but remained stable over the 3 years. The average of three years showed that manure at 20 and 40 t ha⁻¹ were significantly higher than the control whereas no significant difference was recorded between the other treatments and the control.

3.2 Plant Growth Parameters

The lowest plant heights, 54.1 and 39.9 cm, were recorded in the control treatment plots during 2020–2021 and 2021–2022 seasons, respectively (Fig. 3, A). Manure at 40 t ha⁻¹ resulted in the highest plant height during 2020–2021 and 2021–2022 seasons, with 78.3 cm and 74.2 cm, respectively. Likewise, the average of plant height over the two experimental years showed that 40 t ha⁻¹ resulted in the highest plant height.

Similarly, the control recorded the lowest CCI during both seasons (2020–2021 and 2021–2022) whereas the highest values of CCI, 24.2 and 22.6, were recorded with 40 t ha⁻¹ of manure during 2020–2021 and 2021–2022, respectively (Fig. 3, B). Across the two experimental years, the average plant CCI was highest at 40 t ha⁻¹ of manure.

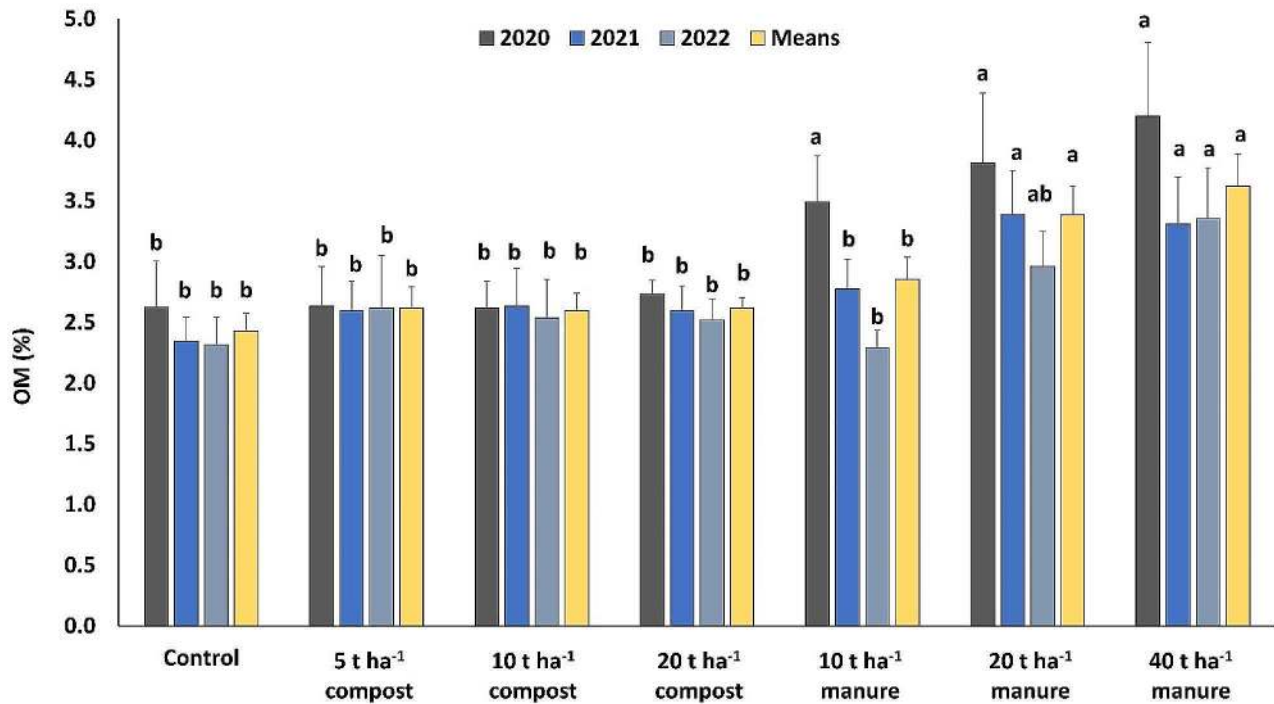


Fig. 2 Effect of organic fertilizer on soil organic matter content. For each year, means followed by small letters are not significantly different at $p \leq 0.05$

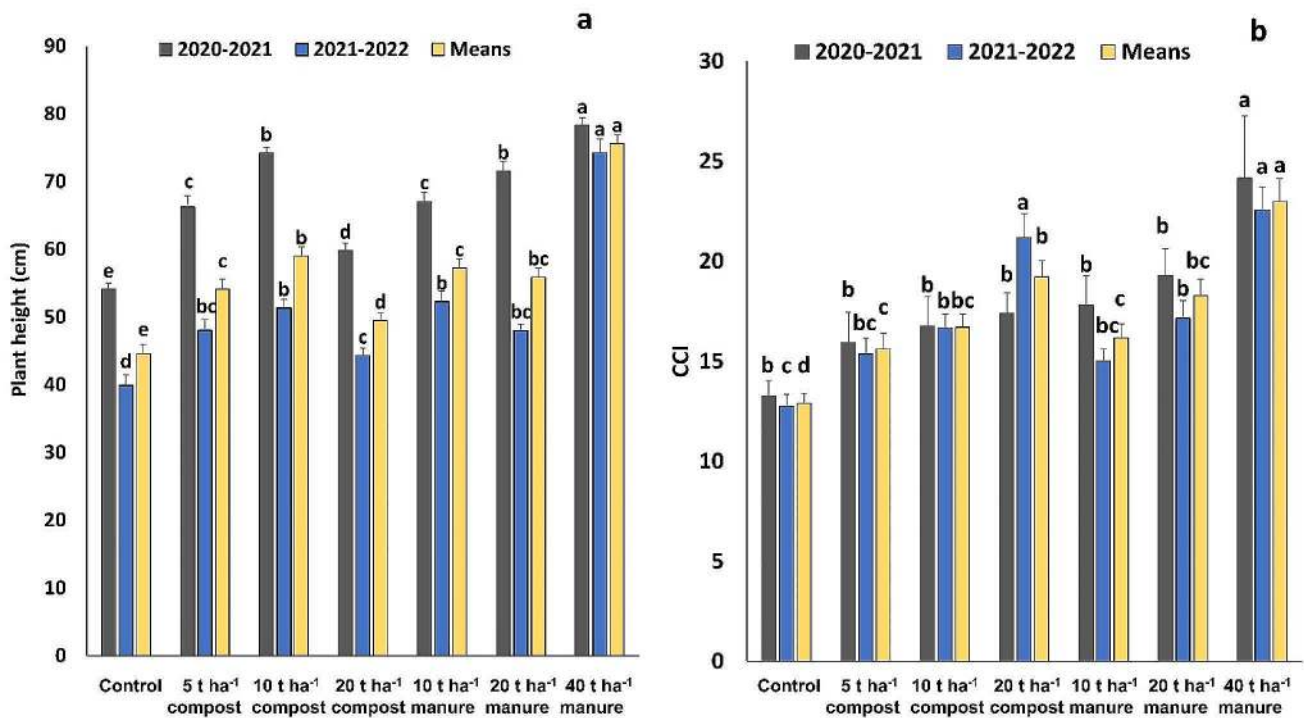


Fig. 3 Plant height (a) and CCI (b) as affected by organic fertilizer treatments. For each growing season, means followed by small letters are not significantly different at $p \leq 0.05$

3.3 Yield and its Components

During the first season, the highest grain yield, 4.6 t ha^{-1} , was recorded with 20 t ha^{-1} of compost (Fig. 4, a). All manure and compost treatments enhanced quinoa grain whereas the lowest value was recorded with the control (1 t ha^{-1}). During the second season, the highest grain yield (3.3 t ha^{-1}) was recorded with 40 t ha^{-1} of manure. However, compost at 10 and 20 t ha^{-1} and all manure rates had significantly enhanced grain yield. 5 t ha^{-1} of compost had no residual effect on grain yield two years after its application. During the third season, the highest and lowest grain yields, 1.4 kg ha^{-1} and 0.7 t ha^{-1} , were recorded with 40 t ha^{-1} of manure and the control, respectively. Compost at 5 and 10 t ha^{-1} had no residual effect on grain yield and were not significantly different from the control. Over the three years, application of compost at 10 and 20 t ha^{-1} and manure at 20 and 40 t ha^{-1} were not significantly different and resulted in the highest grain yields.

Similar results were observed for quinoa total biomass (Fig. 4, b). The highest value (12.4 t ha^{-1}) was recorded during the first season with 20 t ha^{-1} of compost. However, all the organic fertilizer treatments were significantly higher than the control. During the second season, the highest value, 5.1 t ha^{-1} was observed with 40 t ha^{-1} of manure. During the third season, the residual effect of organic fertilizers was recorded only with manure at 40 t ha^{-1} , being 70% higher than the control. The analysis of average total biomass over the three years showed that only 40 t ha^{-1} of manure was significantly higher than the control.

The highest TSW, 2.76 and 2.56 g , were recorded with 40 t ha^{-1} of manure during 2020–2021 and 2021–2022 seasons, respectively (Fig. 4, c). Results were similar when analyzing the average of the two growing seasons and 40 t ha^{-1} resulted in the highest TSW (2.66 g).

3.4 Nutrient Uptake

Two and three years after the applications, 40 t ha^{-1} manure treatments recorded the highest N, P, and K uptake, with an average of 76.2, 13.4, and 177.2 kg ha^{-1} , respectively (Fig. 5, a and b). Quinoa's uptake of other nutrients (Na, Ca, and Mg) was not significantly affected by organic fertilizers. Two years after the application, the highest Cu, Zn, and Mn uptake, 13.7 and 70.4 and 552 g ha^{-1} , and respectively, were recorded with manure at 40 t ha^{-1} (Fig. 5, c). No residual effect of these micronutrients was significant three years after the application of organic fertilizers (2021–2022) (Fig. 5, d). For iron uptake, the residual effect of organic fertilizer was significant only three years after the application and the highest Fe uptake, 410 g ha^{-1} , was recorded with manure at 40 t ha^{-1} .

4 Discussion

Quinoa yields under arid conditions are low, with a maximum grain yield of 0.8 t ha^{-1} (Taaime et al. 2022). This situation is attributed to the limited knowledge on best cropping practices, mainly water availability, soil fertility, and fertilization management using mineral and organic sources. The present study is focusing on the use of organic fertilizers. Our results showed that direct application of organic fertilizers, as well as their residual effect two and three years after their applications, enhanced the quinoa growth and yield. One application of compost at 20 t ha^{-1} gave the highest grain yield during the first growing season (4.6 t ha^{-1}). The compost had higher nitrogen content and stimulated the photosynthesis and nutrient uptake, which enhanced plant development and yield (Benaffari et al. 2022). Similar results were found by Antošovský et al. (2021) where the highest average yields of winter wheat and potato tubers were obtained with digestate and compost, which had several times N content compared to fermented urine and manure. Studying the direct effect of organic fertilizers revealed that compost at 10 and 20 t ha^{-1} as well as manure at 20 and 40 t ha^{-1} were optimal to increase quinoa biomass and yield during the first growing season. Similar results were found in Greece when comparing the impact of manure and compost on the yield and biomass quality of quinoa (Papastylianou et al. 2014). The result of this study revealed that fertilization with compost at 20 t ha^{-1} showed higher values in plant height and dry and fresh biomass. In an arid region of Morocco, Hirich et al. (2014) found that compost applied at higher rate (10 t ha^{-1}) attenuated the effect of water stress and increased quinoa yield by 18%. In our experiment, commercial compost may have been decomposed faster than cow manure. This is because compost went through a controlled process that breaks down organic materials into a stable, nutrient-rich, and humus-like substance.

Manure treatments enhanced SOM during all seasons whereas no residual effect was observed with compost treatments. The efficacy of organic fertilizers depends on their initial composition and decomposition rate (Widowati et al. 2020). Compared to manure, the compost tested in the present study had low C: N ratio equal to 10, which characterizes rapid mineralization and release of available N for plant assimilation (Gerald 2019). We assume that most of the compost applied during the first growing season was mineralized, more nutrients were available to quinoa crop which resulted in high grain yield during the first growing season. Manure C: N ratio was 24 and induced an equilibrium state between mineralization and immobilization (Gerald 2019). Thus, its residual effect on soil organic matter was persistent two and three years after the application. Livestock farming

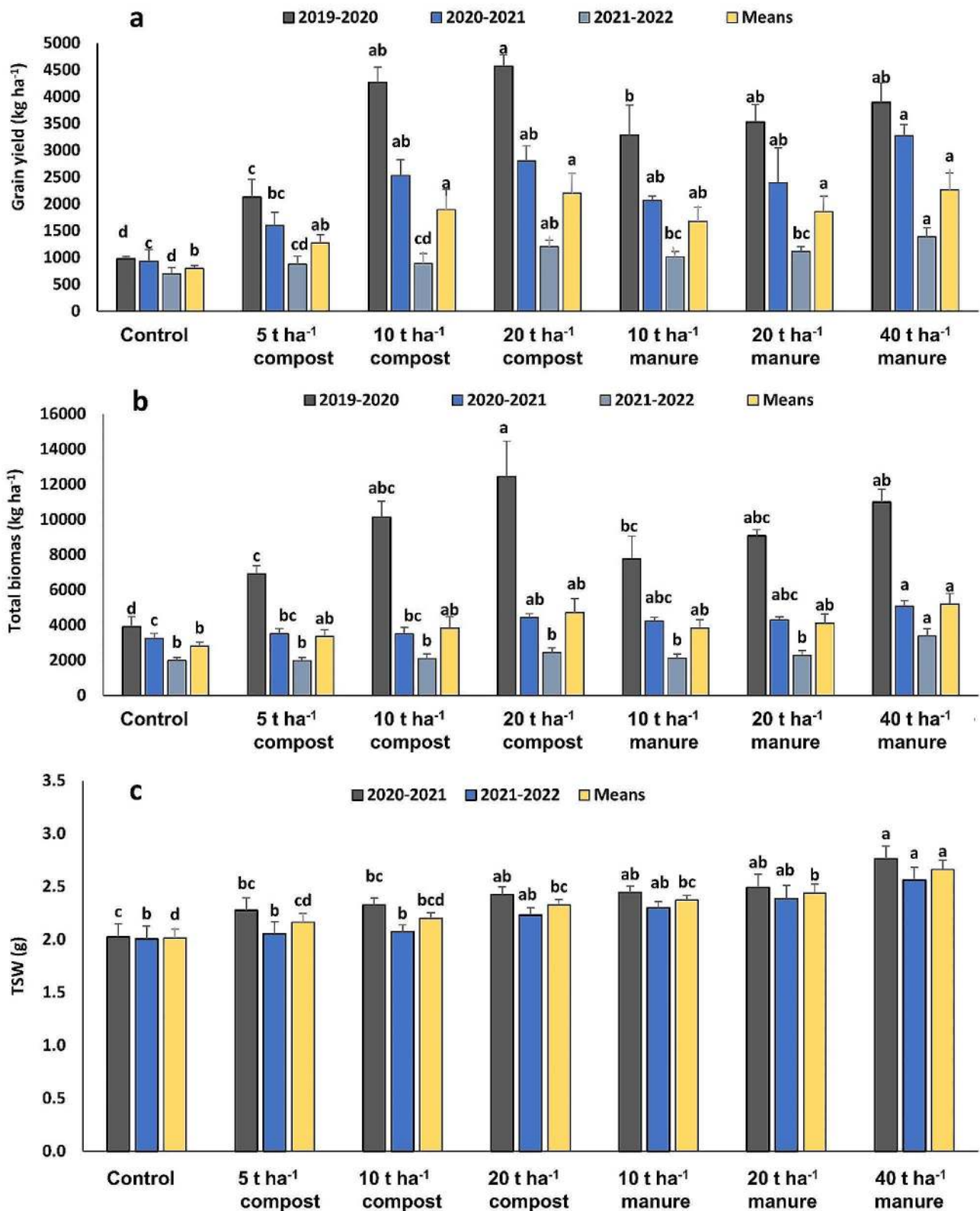


Fig. 4 Quinoa grain yield (**a**), total biomass (**b**), and TSW (**c**) as affected by organic fertilizer treatments. For each growing season, means followed by small letters are not significantly different at $p \leq 0.05$

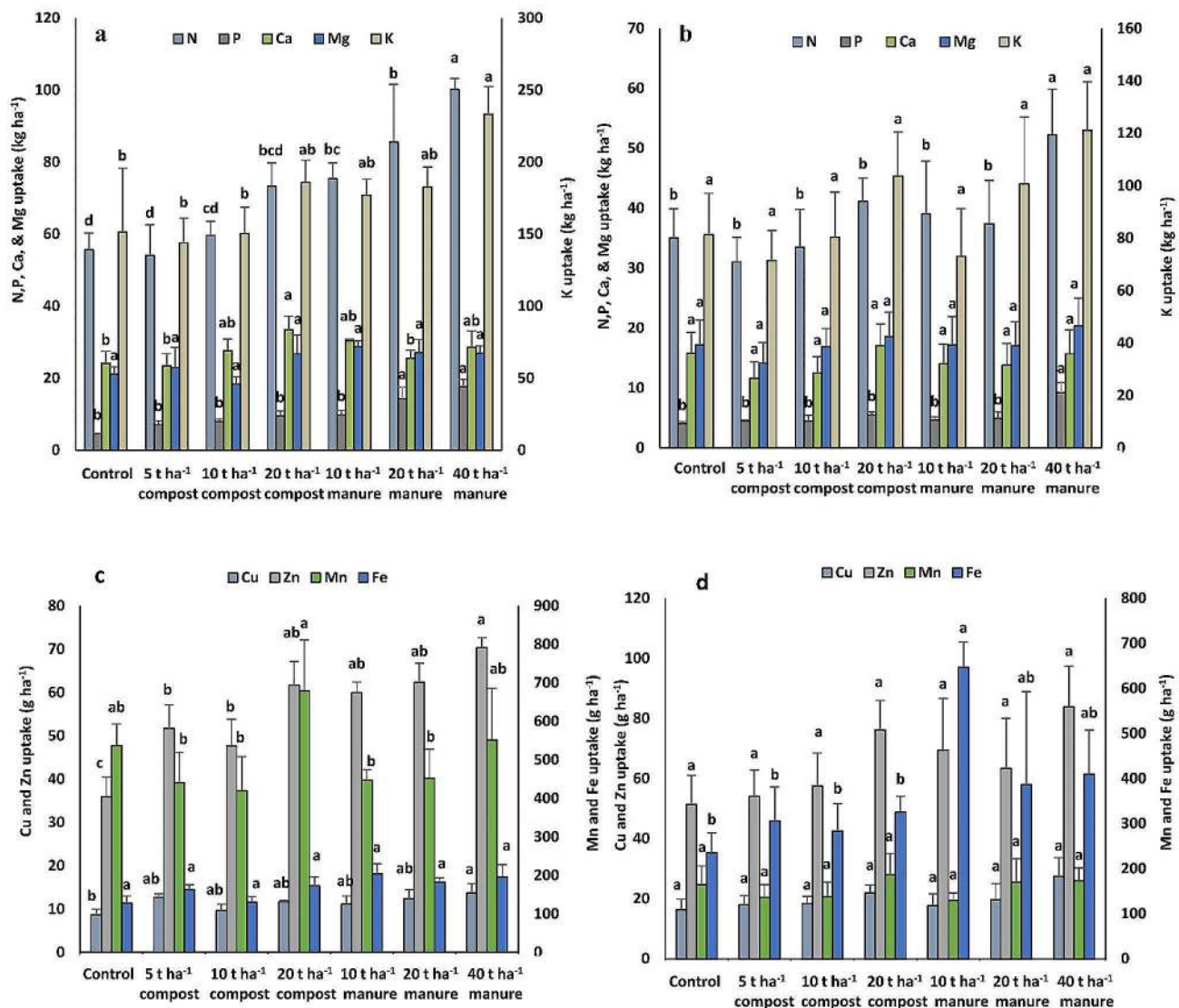


Fig. 5 Nutrient uptake as affected by organic fertilizers. **(a)** and **(c)** represent 2020–2021 growing season and **(b)** and **(d)** represent 2021–2022 growing season. For each nutrient, means followed by the same small letters are not significantly different at $p \leq 0.05$

is one of the most significant sources of income for the rural population in the region. According to the Chamber of Commerce, Industry, and Services of the Marrakech Safi Region, the livestock population totals approximately 5,223 thousand heads, representing 20% of the total nationwide. Recognizing the importance of manure availability from these livestock can foster sustainable farming techniques that enhance soil fertility and quinoa yields and promote circular agriculture practices in this region.

Two and three years after the application, manure at 40 t ha⁻¹ resulted in the highest quinoa plant height, CCI, grain yield, total plant biomass, and nutrient uptake. The plant

height and CCI were probably enhanced due to improved soil organic matter (SOM) that have improved soil health and fertility and increased nutrient availability. Soil organic matter plays an important role in enhancing the soil cation exchange capacity and water holding capacity (El-Gamal et al. 2020). When studying the effect of organic fertilizers on quinoa growth, the height of plants increased with increased cattle manure rates up to 9 t ha⁻¹ (Parwada et al. 2020). The added manure enhanced plant available nitrogen after mineralization and resulted in increased vegetative growth and plant height. The significant increase in total plant biomass and grain yield could be due to the improvement in quinoa

yield attributes, including plant height and TSW. Panwar et al. (2010) showed that the application of organic manure helped maintaining SOM over a long-term period. These results were in harmony with those obtained by Widowati et al. (2020) when comparing the response of corn to a variety of organic fertilizer types, including chicken manure and compost. They reported that two years after the application, manure resulted in the highest corn yield (6.6 t ha^{-1}). Similar trend was recorded for wheat crop where the residual effect of poultry manure applied at 10 t ha^{-1} lasted over 3 years (Bodruzzaman et al. 2002).

Average quinoa grain yield over the three years showed that 10 and 20 t ha^{-1} of compost and 20 and 40 t ha^{-1} of manure were not significantly different and resulted in the highest grain yields. When taking into consideration the cost and accessibility of organic fertilizers, the use of 20 t ha^{-1} of manure was optimal to increase quinoa grain yield. However, special attention must be directed to weed management post-manure application, as current strategies for quinoa cultivation lacks robust solutions in this regard.

Regarding nutrient uptake, manure carryover with 40 t ha^{-1} also enhanced N, P, K, Cu, Zn and Mn uptake by the plant in both subsequent growing seasons, which resulted in high yields. Soils in arid regions usually have high pH and active Ca, which limit the P uptake (Reeve et al. 2012). The slow mineralization of nutrients associated with manure and composts applications can increase plant nutrient uptake in calcareous soils (Braschi et al. 2003; Ramzani et al. 2017). Reduced soil pH may also occur as a result of increased manure and compost mineralization and solubilize the nutrients in precipitated forms, and therefore contribute to improve their bioavailability in the soil and their uptake by the plant. Application of organic fertilizers also enhanced quinoa seed nutritional quality (Fawy et al. 2017). Abdroubou et al. (2022) found that organic manure increased the concentrations of P and K in quinoa seeds.

Our results indicated that the application of organic fertilizers sustainably enhanced quinoa yield under arid conditions. Compost had an immediate effect on quinoa growth and productivity and recorded the highest yield during the first season. However, its residual effect was low compared to manure. In our study, the use of manure as organic fertilizer was more convenient to enhance quinoa yield over the three seasons. However, weed control has emerged as one of the challenging problems associated with manure applications, especially that, until now, no herbicide is available in the market for weed control in quinoa crop.

5 Conclusion

The use of organic fertilizers represented a good strategy to enhance soil fertility and quinoa productivity over the medium to long term. The present study provides better understanding of the direct and residual effect of different rates of organic fertilizers, namely manure and compost, on the growth and yield of quinoa. During the first growing season (2019–2020), compost at 20 t ha^{-1} enhanced quinoa growth parameters and resulted in the highest grain yield (4.6 t ha^{-1}). The residual effect of the organic fertilizers two and three years after the application was higher with manure at 40 t ha^{-1} . This treatment resulted in the highest soil organic matter, plant height, chlorophyll content index, total biomass, grain yield, thousand seed weight, and nutrient uptake. Average quinoa grain yield over the three years showed that 20 t ha^{-1} of manure was optimal and economically viable to increase quinoa productivity in the Rehamna region. The addition of organic fertilizers and irrigation water in our experiment was translated into high quinoa yields, which may not reflect the real farming conditions in arid regions where quinoa yield varied from 0.3 to 1 t ha^{-1} . However, our results provide a promising starting point for exploring sustainable agricultural techniques tailored to the unique challenges of arid environments. Understanding how organic fertilizers persist and continue to benefit soil organic matter and quinoa yield over multiple years is essential for promoting sustainable agricultural practices. Our results will help farmers make informed decisions about organic fertilizer management to improve their systems efficiency and crop resilience in the face of changing economic and environmental conditions. In addition to the insights gained from our study, further research into weed management strategies in organic systems is essential to understand the interactions between weed dynamics, soil fertility, and quinoa performance for a holistic management approach that complement organic fertilizer strategies.

Author Contributions Conceptualization: Nawal Taaime, Khalil El Mejahed, Cameron Pittelkow, Redouane Choukr-Allah, Rachid Bouabid, Mohamed El Gharous; methodology and investigation: Nawal Taaime, Khalil El Mejahed, Abdallah Oukarroum, Redouane Choukr-Allah, Rachid Bouabid, Mohamed El Gharous; data analysis: Nawal Taaime; writing—original draft: Nawal Taaime; writing—review and editing, all authors; Funding Acquisition: Mohamed El Gharous; Resources: Mohamed El Gharous, Khalil El Mejahed, Abdallah Oukarroum.

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Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

Conflict of Interest The authors declare no competing interests.

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