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Biochar-Amended Soils: A Water-Saving Strategy for Quinoa Cultivation in the Andes

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ABSTRACT

Introduction: Previous studies showed that biochar amended soils significantly enhanced the growth and yield of quinoa under water limitations. So it becomes an emerging agronomic strategy to consider for sustainable quinoa production. Biochar can specifically be considered for the area particularly receiving low annual rainfall and more vulnerable to current climate change conditions.

Materials and Methods: A field experiment was conducted using the quinoa variety INIA 415 Pasankalla, employing a factorial design to assess the effects of different application rates of biochar made of municipal pruning waste and agricultural waste (0, 1, 2, and 3 $t\cdot ha^{-1}$), and three irrigation intervals (irrigation every 5 days, irrigation every 10 days, and irrigation every 15 days). The volumetric soil moisture content, the soil hydraulic properties, and quinoa's biometric characteristics and yield components were evaluated.

Results: The results indicated that the longest irrigation intervals (10 and 15 days) resulted in soil moisture levels between 19% and 40% below the wilting point (soil matric potential: -1.5 MPa), creating water stress conditions. However, biochar application increased the field capacity from 0.31 to 0.38 g H_2O g^{-1} soil, raised soil air content from 22% to 29% at irrigation, and promoted the quinoa's soil water absorption below the wilting point. Furthermore, the application of 3 $t\cdot ha^{-1}$ of biochar significantly enhanced quinoa yield, increasing it from 3.18 to 4.22 $t\cdot ha^{-1}$, along with improvements in leaf area, total biomass, root length, and panicle length by 70.74%, 76.54%, 14.34%, and 16.55%, respectively.

Conclusions: It was concluded that a 3 $t\cdot ha^{-1}$ biochar application mitigated the negative effects of water stress caused by prolonged irrigation intervals. This biochar treatment improved the soil's physical properties and enabled the quinoa variety INIA 415 Pasankalla to achieve yields close to its theoretical productive potential.

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1 | Introduction

Quinoa (*Chenopodium quinoa* Willd.) is a pseudocereal native to South America and resistant to a wide range of abiotic limiting conditions such as drought and soil salinity (Hinojosa et al. 2018; Lesjak and Calderini 2017). Its wide adaptability capacity has allowed its production to spread in recent years to other continents and several altitudinal levels (0–4000 m.a.s.l.) (Hinojosa et al. 2018). The global expansion of quinoa production has been driven by its high nutritional value, leading to its recognition as a key crop for global food security (Romero-Benavides et al. 2023).

In Peru, quinoa is classified as a pseudocereal, with its cultivation ranking just below that of maize, rice, barley, and wheat (MIDAGRI Perfil Productivo y Competitivo de Los Principales Cultivos Del Sector 2024). It plays a significant role in the Gross Value of Production (GVP) in the Peruvian southern highland regions, particularly in Ayacucho (5.9% GVP), Puno (4.3% GVP), and Apurímac (3.5% GVP) (Livia Alejandro et al. 2021). In most high-Andean areas, quinoa is predominantly grown under rainfed conditions (97.1%), resulting in a national average yield of 1.805 $t{\cdot}ha^{-1}$ (MIDAGRI Perfil Productivo y Competitivo de Los Principales Cultivos Del Sector 2024; INEI IV Censo Nacional Agropecuario 2012). However, the inherent vulnerability of rainfed systems to variations in weather patterns (Flores-Marquez et al. 2024) could be mitigated by ensuring an adequate water supply during crop development (El-Tahan et al. 2024). To achieve this, efforts must focus on exploring alternatives that enhance the efficiency of irrigation water use in terms of quantity, availability, and timeliness. Among these, the use of climate-resilient crops complemented with agronomic strategies that increase soil moisture retention and availability, are important measures to ensure the agriculture sustainability (Wu et al. 2023). Examples of such technologies include the application of superabsorbent materials (Sroka and Sroka 2024), the use of mulches, and the incorporation of organic amendments, which improve the soil's hydrological properties (Akpinar et al. 2023). Organic amendments can originate from a variety of sources and be produced through different processes, resulting in diverse agronomic and environmental potentials (Urra, Alkorta, and Garbisu 2019). The various types of amendments—such as green manures, animal manures, biosolids, composts, and composts from anaerobic digestion—offer numerous benefits to agricultural productivity by altering the physico-chemical properties of soils, enhancing nutrient and water availability (Akpinar et al. 2023; Arévalo-Aranda et al. 2024), stimulating microbial activity (Stark et al. 2007), supporting pest, disease, and weed management (Kruidhof et al. 2011), and aiding in erosion control (Gholamahmadi et al. 2023). In the context of climate change, the sequestration and incorporation of atmospheric carbon into the soil has become a crucial area of focus. In this regard, biochar has emerged as a promising material for climate change mitigation due to its proven ability to immobilize carbon within soil structures (Campion et al. 2023), demonstrating greater efficiency than other mitigation materials such as compost and vermicompost (Farooqi et al. 2024). Biochar is defined as a carbon-rich material produced from the biomass of various feedstocks through pyrolysis at temperatures exceeding 250°C, under conditions of low or absent oxygen (Bolan et al. 2022). With its highly condensed carbon structure and significant stability, biochar resists decomposition in soil, making it an effective tool for carbon sequestration and reducing greenhouse gas emissions (Biederman and Harpole 2013).

Thus, the average residence time of biochar in soil is estimated to range from hundreds to thousands of years, depending on both the characteristics of the biochar itself and the environmental conditions to which it is exposed (Kuzyakov, Bogomolova, and Glaser 2014; Fawzy et al. 2021). Physically, biochar's porous structure and large surface area create a strong affinity for charged soil particles (Zhang, Wang, and Feng 2021). These properties enhance soil water retention, reduce nutrient leaching, and improve water and fertilizer use efficiency (Abhishek et al. 2022; Qiu et al. 2021; Razzaghi, Obour, and Arthur 2020).

Although biochar's benefits have generated significant interest at the academic and experimental levels, its large-scale production remains limited. This is primarily due to the economic and practical challenges associated with high application rates, as well as a lack of knowledge or skepticism regarding its effects among producers (Campion et al. 2023; Kamali et al. 2022; Atkinson 2018).

Several studies have demonstrated the effectiveness of biochar in enhancing the physicochemical properties of soils, leading to improved crop yields (Biederman and Harpole 2013; Graef et al. 2018; Sun et al. 2019). Its incorporation into the soil increases water use efficiency by enhancing soil water retention and extending irrigation intervals (Salinas et al. 2018). This feature could improve the efficiency of practices such as deficit irrigation (Oppong Danso et al. 2020). However, the impacts of biochar depend on several factors, including soil characteristics, the crop involved, the processing methods and raw materials used in its production, and the carbon content added to the soil (Fawzy et al. 2021; Razzaghi, Obour, and Arthur 2020). Evidence suggests that the increase in plant-available water is more pronounced in sandy soils than in clay soils (Atkinson 2018), with some studies indicating that biochar may have no effect, or even an opposite effect, on stress reduction in water-limited conditions (Mannan et al. 2021; Ramlow et al. 2019). These findings highlight the need for further field research to assess the effects of biochar under various conditions, evaluate the long-term impacts on soil and crops, and investigate the mechanisms through which biochar influences soil water retention. Such studies should include measurements of matric potential to better understand the structural differences between biochar-soil combinations (Razzaghi, Obour, and Arthur 2020; Atkinson 2018).

On the other hand, the use of biochar as an amendment has been reported to have potential drawbacks in both agricultural and environmental contexts. These include a reduction in the effectiveness of agrochemicals, which may lead to the need for increased application rates (Kuppusamy et al. 2016), as well as an increase in electrical conductivity and pH—properties of biochar that can negatively affect the growth of sensitive crops (Fawzy et al. 2021). Additionally, biochar may impact germination and other biological processes in the soil, including changes in its microbial composition (Kuppusamy et al. 2016).

There is also an environmental risk associated with the release of heavy metals from biochar produced from nonvirgin materials (Zhao et al. 2018). Given these potential risks, it is crucial to understand the specific soil properties that need to be modified to determine the appropriate application rates for each case (Kamali et al. 2022). Moreover, these rates must be economically viable to ensure the sustainability of biochar use in agricultural systems (Patel and Panwar 2024).

Irrigation intervals are determined by the ratio of crop evapotranspiration and water depth, calculated based on the soil's moisture-holding capacity (Zhang et al. 2019). This ratio influences the total number of irrigations required during the cropping season and the water consumption over the entire phenological cycle of the crop (King, Stark, and Neibling 2020). Estimating the soil's moisture-holding capacity and available water for crops requires determining the soil moisture characteristic curve, also known as the retention curve (Assouline and Or 2013). The soil moisture curve is essential for understanding plant-available water, infiltration, drainage, hydraulic conductivity, and irrigation scheduling (Kern 1995). A common method for determining soil water characteristic curves in the laboratory is using a pressure plate extractor, where soil suctions are applied and changes in soil water content are measured (Richards 1941). This analysis is critical for characterizing soil hydraulic properties, which are influenced by several factors such as soil texture, structure, solution chemistry, and pore space geometry (Durner and Flühler 2005).

In Peru, limited access to irrigation in agricultural areas (36%) is a significant barrier to the competitiveness of agricultural producers (MIDAGRI Perfil Productivo y Competitivo de Los Principales Cultivos Del Sector 2024). This is compounded by the low efficiency of gravity-based irrigation systems, which are widely used in the Peruvian highlands, as well as the infrequent use of the traditional 'mita' system, a method of water distribution for irrigation in semi-arid areas (Guevara et al. 2020). Overcoming this gap is not an achievable goal in the short or medium term, so it is necessary to focus on alternative technologies that improve the responsiveness of producers to situations of limited water availability. Finally, the widespread presence of gravity irrigation justifies the need for more efficient water use at the plot level. Improving irrigation efficiency does not necessarily require a complete shift to pressurized irrigation systems but can be achieved through the modernization and technological enhancement of traditional gravity systems (Clemmens 1998). In this context, Li et al. (Li et al. 2021). recommend further studies on the benefits of biochar incorporation as a measure to mitigate climate variability effects. Previous studies on pots or greenhouse conditions have been carried out to evaluate quinoa's response to water stress under drying cycles until reaching the theoretical wilting point (soil matric potential:-1.5 Mpa) or with restricted irrigation intervals (Akram, Libutti, and Rivelli 2023; Rivelli, Akram, and Libutti 2023).

While the benefits of biochar as an amendment to mitigate water stress in quinoa have been documented under controlled conditions, there are few studies conducted at the field level (Akram, Libutti, and Rivelli 2024a). As a result, its effectiveness under real-world conditions remains insufficiently understood. Thus, there is interest in evaluating quinoa's performance under more severe water stress conditions (i.e. beyond the wilting point) considering the most sensitive phenologic stages (i.e. flowering and grainfilling (Geerts et al. 2008)) and the local field challenges to water access. Therefore, it is proposed that the application of biochar as a soil amendment enhances the soil's water storage capacity and increases the water available to the quinoa crop, thereby stimulating its growth and improving productivity. Therefore, this research aims to assess the effect of biochar incorporation into the soil, on soil water retention properties and its impact on *Chenopodium quinoa* Wild crop yield under varying irrigation intervals in high Andean valley conditions.

2 | Materials and Methods

2.1 | Location

The study was carried out in the field, at the Canaán Agrarian Experimental Station of the National Institute of Agrarian Innovation (INIA) located in the district of Andrés Avelino Cáceres Dorregaray, province of Huamanga, Ayacucho Region. The experimental plot was installed at 13°10'00.9 'S 74°12' 26.3 'W; at 2750 m.a.s.l. (Figure A1). The study area has an average annual precipitation of 573.8 mm; minimum temperatures between 5.2°C (July) and 10.6°C (January-February); maximum temperatures between 25°C (October-November) and 22.8°C (February). Historical averages were calculated based on information from the meteorological station Huamanga (13°9'S; 74°13'W; 2761 m.a.s.l.) of the Servicio Nacional de Meteorología e Hidrología del Perú (SENAMHI). Daily meteorological records were taken from the conventional INIA Canaan station installed near the experimental plot as part of the SENAMHI Hydrometeorological Network under the administration of the Regional Government of Ayacucho (Figure 1).

2.2 | Experimental Design

A randomized complete block design with a split-plot arrangement was used. The study factors were biochar dose as main plots (b0: 0 t·ha^{-1}, b1: 1 t·ha^{-1}, b2: 2 t·ha^{-1}, b3: 3 t·ha^{-1}) and gravity irrigation interval as subplots (F1: 5 days, F2: 10 days, F3: 15 days). Four replicates per treatment were considered. A total of 48 experimental units were implemented. Each experimental unit consisted of 6 furrows 3.5 m long and spaced 0.80 m apart based on local agricultural practices (FAO La Quinua: Cultivo Milenario Para Contribuir a La Seguridad Alimentaria Mundial 2011; INIA Manejo Del Cultivo de La Quinua 2012) (Figure A2).

2.3 | Soil Physicochemical Characteristics

Before installation, a soil sample was collected from the arable layer at a depth of 30 cm (Sales Dávila et al. 2024) for physicochemical characterization at the Soil, Water, and Foliar Laboratory (LABSAF)-INIA Canaán. Texture (NOM-021-RECNAT-2000,021-RECNAT-2000 2002), pH (USEPA METHOD 9045D 2004), electrical conductivity (EC) (ISO International Organization for

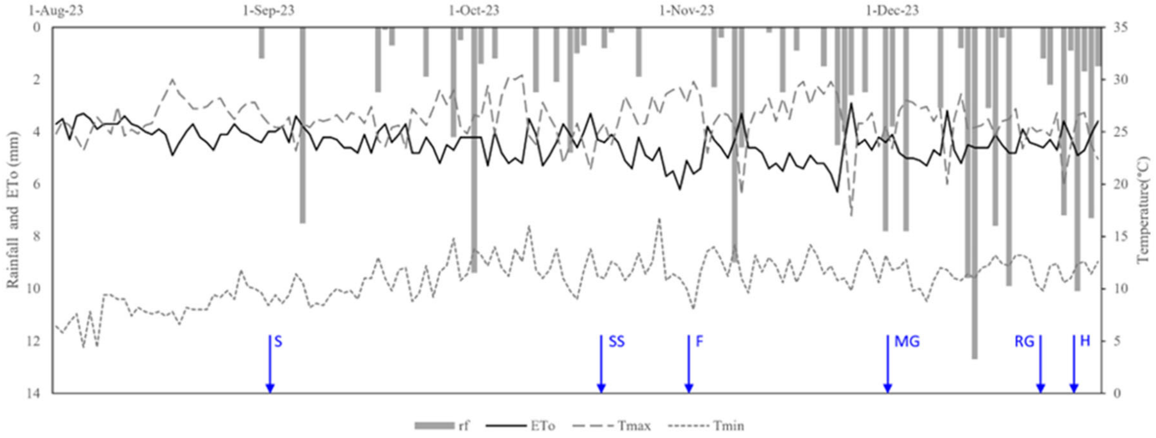

FIGURE 1 | Daily meteorological parameters obtained during the quinoa season. Phenological stages represented: Eto, evapotranspiration potential; F, flowering; H, harvest; MG, milky grain; Rf, rainfall; RG, ripe grain; S, sowing; SS, side shoots; Tmax, maximum temperature; Tmin, minimum tem-perature.

Standardization 1994), organic matter (OM) (NOM-021-RECNAT-2000,021-RECNAT-2000 2002), total N (ISO International Organization for Standardization 1995), available P (NOM-021-RECNAT-2000,021-RECNAT-2000 2002), available K (Bazán Tapia 2017), exchangeable cations concentration (Ca^{+2}, Mg^{+2}, K^{+}, and Na^{+}) (NOM-021-RECNAT-2000,021-RECNAT-2000 2002), and micronutrients concentration (Fe, Mn, Cu, and Zn) (Bazán Tapia 2017) were determined. In addition, an undisturbed sample was collected to calculate the bulk density of the soil by core method (ISO International Organization for Standardization 2017). The soil is generally loam-textured, with a pH of 7.5 and medium to low fertility (Table A1).

The dry bulk density is calculated using Formula (1) and Formula (2):

$$\rho_{b,s} = \frac{m_d}{V} \tag{1}$$

$$m_d = m_t - m_s \tag{2}$$

Where

$\rho_{b,s}$ is the bulk density, dry (g cm^{-3})

m_d is the mass of the sample dried at 105°C, (g)

V is the volume of the sample holder, (cm^3)

m_s is the mass of the empty sample holder, (g).

m_t is the mass of the sample holder together with the soil sample dried at 105°C, (g).

2.4 | Physicochemical Characteristics of Biochar

The biochar was purchased from the INKAN NEGRO S.A.C. Company (Inkan Negro - Biochar, s. f.), produced by pyrolysis (≈700°C) of municipal pruning waste and agricultural waste, ground and sieved through N°10 mesh (2 mm). The physicochemical characterization of the biochar was carried out at the Soil, Water, and Foliar Laboratory (LABSAF)-INIA Canaán: pH (USEPA METHOD 9045D 2004), EC (ISO International Organization for Standardization 1994), OM and organic carbon (Bazán Tapia 2017), N (ISO International Organization for Standardization 1995), Ca^{+2}, Mg^{+2}, K^{+}, Fe, Cu, Zn (Bazán Tapia 2017), and gravimetric moisture (ISO International Organization for Standardization 2001) were determined. Overall, the biochar exhibits a pH of 8.56 and contains 28.16% organic matter (Table A2).

2.5 | Conduction of the Experimental Plot

The experimental plot was established between August and December 2023. The soil was prepared by plowing and turning over the topsoil. Using a disc harrow and a tractor-driven furrower, the soil was plowed, leveled, and furrowed, with furrows spaced 0.8 meters apart. Biochar was manually incorporated according to pre-established treatment rates of 0, 1, 2, and 3 t·ha^{-1} along the dip furrow at an average depth of 0.3 meters. The incorporated material was subsequently mixed through hoeing and covered with a thin soil layer of 2 cm. Following biochar incorporation, fertilization was applied and calculated based on the soil's physicochemical characteristics (Table A1). The fertilization regimen consisted of 0.7 t·ha^{-1} island guano, 50 kg·ha^{-1} diammonium phosphate, kg·ha^{-1} potassium and magnesium sulfate, and 25 kg·ha^{-1} urea. All fertilizers, except urea, were applied at sowing. Urea was applied in two stages: 50% at sowing and 50% during hilling (50 days after sowing). After covering the fertilizers through hoeing, seeds of *Chenopodium quinoa*, variety INIA 415 Pasankalla, were inmediatly sown in a continuous stream at a 10 kg·ha^{-1} rate.

The first irrigation was applied immediately after sowing. Subsequently, the experimental plot was irrigated every 4 days until the branching stage (i.e., 50 days after sowing (DAS)). From that point until the end of the growing season, irrigation intervals were adjusted according to the distribution of the proposed treatments (F1: irrigation every 5 days, F2: irrigation every 10 days, F3: irrigation every 15 days). To ensure the independence of irrigation applications, collectors were placed at the end of each experimental unit.

Agricultural activities included manual weeding and thinning at 45 DAS (phenological stage of six true leaves according to field observations), leaving approximately twenty plants per linear meter. Additionally, hilling and the remaining 50% nitrogen incorporation were carried out at 50 DAS to prevent lodging during the branching stage.

Phytosanitary control of pests and diseases was tailored to each specific case. To control fungal infections during the vegetative emergence stage, Vitavax-300 was applied at a dose of 1000 g per cylinder dose. Downy mildew (*Peronospora variabilis*), which appeared during the branching period, was managed with Ridomil Gold MZ 68 WP at a rate of 3 kg·ha^{-1}. For diabrotica (*Diabrotica speciosa*), aphids, and Kcona Kcona (*Eurysacca quinoaae*) control, two applications of Cyperklin 25 EC were administered at a dose of 200 cc per cylinder, during the phenological stage of four true leaves and at the ripe grain stage, respectively.

2.6 | Determination of Soil Hydric Parameters

Non-disturbed soil samples were collected in metal core samplers (0.034 m length, 0.061 m diameter, 100 cm^3 sample volume) considering three replicates for each biochar treatment at the depth at which it was incorporated (0.30 m). The samples were taken to the Water and Soil Laboratory of the Faculty of Agricultural Engineering of the Universidad Nacional Agraria La Molina to consecutively determine the moisture contents (ISO International Organization for Standardization 2001) at saturation (SAT), field capacity (FC) (soil matric potential: −0.033 MPa) and theoretical wilting point (WP) (soil matric potential: −1.5 MPa) using the Richards pressure plate equipment (Richards 1941).

Additionally, during the application period of treatments F1, F2, and F3, soil moisture contents were evaluated before each irrigation at a depth of 0.20 m for each experimental unit (ISO International Organization for Standardization 2001). Samples were taken with metal core samplers (0.034 m length, 0.061 m diameter, 100 cm^3 sample volume), which also allowed the bulk density per treatment to be determined (ISO International Organization for Standardization 2017).

2.7 | Determination of Biometric and Physiological Variables

At the vegetative stages of flowering (FLO) (63 DAS), milky grain (MG) (93 DAS), and ripe grain (RG) (116 DAS), biometric parameters were assessed. Three plants per experimental unit were extracted with part of the soil around them through a pick mattock, they were placed in plastic bags to be washed and air-dried. After that, the height of the plant (cm) was measured with a 5 m tape measure from the neck to the apex of the plant, and the length of the root (cm) from the neck of the plant to the apex of the main root. Leaf fresh weight (g), total fresh weight (g), and total dry weight (g) per plant were determined using an oven (65°C—until steady weight observed). To determine leaf area, ten fresh leaves from the middle third of seven representative plants were collected from each experimental unit between 8:00–9:00 a.m. The set was weighed using an electric balance (Type: Explorer™ Pro Precision; Ohaus; USA; measurement accuracy 0.001 g) and photographed with a semi-professional Nikon D3500 camera using a ruler to allow scaling. The RGB images were then processed in AutoCAD 2021 to delimit the leaf area per leaf (cm^2). After determining a correlation between fresh weight and leaf area per leaf, the leaf area per plant was estimated based on the previously determined leaf fresh weight.

2.8 | Determination of Performance and Its Components

To evaluate the crop yield per unit area (kg·ha^{-1}), plants were harvested in a 2 × 2 m furrows area in the central part of each experimental unit. To avoid possible pigeon infestation, the plants were cut at the ripe grain stage for subsequent drying in polycarbonate-covered dryers, placed in the same EEA Canaan. Three plants were randomly selected to determine the total seed weight per plant (g) and the weight of 1000 seeds using a precision balance (Type: Explorer Pro Precision; Ohaus; USA; measurement accuracy 0.001 g). The number of seeds per plant was calculated as:

$$S = \frac{TSW_p}{W_{1000s}} \times 1000 \tag{3}$$

Where

S number of seeds per plant

TSW_p total seed weight per plant

W_{1000s} weight of 1000 seeds selected for each plant.

In addition, panicle length (cm) and diameter (cm) were measured following the methodology described by Bioversity International et al (Bioversity International; FAO; PROINPA; INIAF 2013).

2.9 | Statistical Analysis

Differences between treatments were evaluated using two-way ANOVA ($\alpha = 0.05$) for biometric and physiological variables at each phenological stage and to characterize yield at harvest. Model assumptions were checked with the Shapiro-Wilk test (normality) and Bartlett's test (homoscedasticity) using the stat package for R (Kartikeya Bolar STAT: Interactive Document for Working with Basic Statistical Analysis 2019). The comparison of means for variables with significant differences was carried out using the Least Significant Difference Test ($\alpha = 0.05$) via the LSD test function of the agricolae library for R (Mendiburu 2023) and the adjustment of p-values with the Benjamini-Hochberg procedure for interaction analysis.

3 | Results

3.1 | Effect of Biochar and Irrigation Interval on Soil Moisture

Statistical soil moisture content analysis was performed at 77 DAS, when F1, F2, and F3 irrigation intervals coincided (Table A3). At the main effects level, irrigation frequency (F) and biochar doses (b)

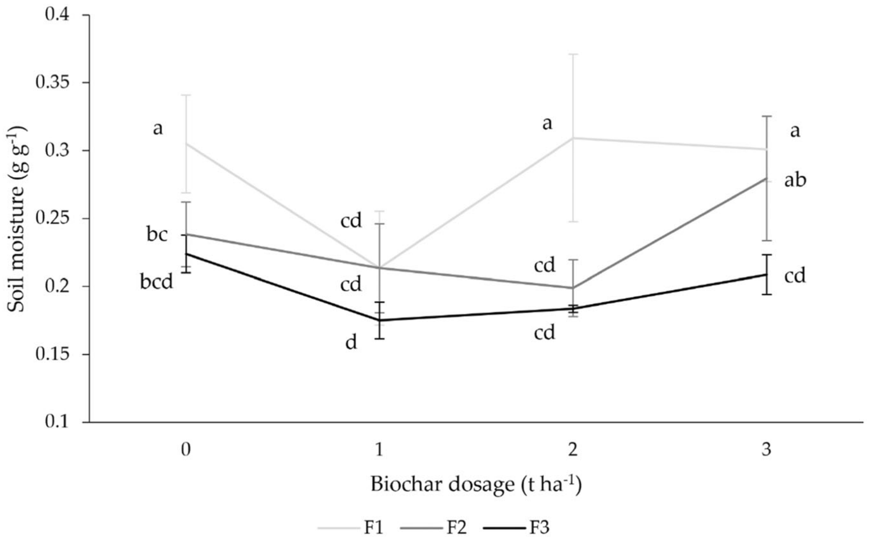

FIGURE 2 | Interaction between incorporated biochar dosage and irrigation frequencies on volumetric soil moisture content (biochar dosage b0: 0 t•ha^{-1}; b1: 1 t•ha^{-1}; b2: 2 t•ha^{-1}; b3: 3 t•ha^{-1}; and gravity irrigation interval F1: 5 days; F2: 10 days; F3: 15 days). Means with different letters are statistically different (LSD test, $\alpha = 0.05$).

significantly affected soil volumetric moisture content. A statistically significant interaction between these two factors was also observed (p-value 0.0078). As expected, shorter irrigation intervals resulted in higher soil moisture content. On the other hand, treatments with biochar incorporated at 1 and 2 t·ha^{-1} doses showed lower moisture content than those without biochar, with values equal to the 3 t·ha^{-1} dose (Figure 2). Incorporating biochar at the lowest dose reduced moisture content for all three irrigation frequencies while increasing the dose helped recover moisture levels. The treatments with the highest soil moisture content corresponded to the 5-day irrigation frequency, with no significant differences between the 3 t·ha^{-1} biochar dose and the control (no biochar application). This was followed by the 10-day irrigation frequency and the 3 t·ha^{-1} biochar dose. The lowest moisture content was recorded for the combination of low irrigation frequency and low biochar doses.

The incorporation of biochar at 2 and 3 t·ha^{-1} significantly increased moisture content at the evaluated water constants (i.e., saturation (SAT), FC (−0.033 MPa), and WP (WP, −1.5 MPa) (Figure A3). However, this did not result in significant differences in the total available water (TAW), calculated as the difference between FC and WP moisture contents. On the other hand, significant differences were observed in aeration percentage, defined as the difference between SAT and FC, with higher values in treatments incorporating biochar at doses of 2 and 3 t·ha^{-1}. For the control treatment without biochar incorporation, soil moisture content during longer irrigation intervals remained near the WP (Figure 3). In treatments with biochar incorporation, soil moisture extraction below the WP was observed for irrigation intervals of 10 days onwards.

3.2 | Effect on Biometric Characteristics of Quinoa

Based on the evaluated parameters, higher biochar doses were found to enhance the biometric characteristics of the crop starting from the flowering stage (Figure A4). Treatments with longer irrigation intervals (15 days) showed above-average values, particularly towards the final stages of the crop's phenological development (RG). For a biochar dose of 1 t·ha^{-1} (b1), shorter irrigation intervals favored crop development, while for intermediate doses (b2), irrigation intervals longer than 10 days had this effect. At an irrigation frequency of 10 days, no significant differential effect of biochar was observed throughout the crop's development. During the RG stage, under a lower irrigation frequency (15 days), increasing biochar doses had a direct impact on biometric parameters, with values surpassing the average, starting from the b3 dose compared to other treatments.

Significant differences were observed for individual effects, but not for interactions. Biochar treatments at 3 t·ha^{-1} resulted in greater vegetative development (leaf area, and biomass) across the evaluated phenological stages compared to other biochar treatments (Figure 4). As expected, plants irrigated every 5 days showed better vegetative development, significantly outperforming those irrigated every 15 days. Significant differences in plant height were observed starting from the milky grain stage, with a direct correlation between biochar dose and height at the ripe grain stage. Leaf area was significantly and progressively affected by irrigation frequency throughout crop development, with notable differences between the most and least frequent irrigation treatments at the ripe grain stage. Biochar doses of 1 and 3 t·ha^{-1} produced similar leaf areas across the three evaluated phenological stages, and at the ripe grain stage, this similarity also included the intermediate biochar dose, differing from the treatment without biochar. Additionally, biochar incorporation significantly increased biomass, with the highest dose producing the most positive effects across the three stages. At the milky grain stage, all biochar doses produced significant differences compared to the control, with higher doses yielding better results. While irrigation frequency affected biomass at the milky grain stage, this effect was not significant in the later stages. In terms of root length, shorter irrigation intervals led to greater root depth as the crop

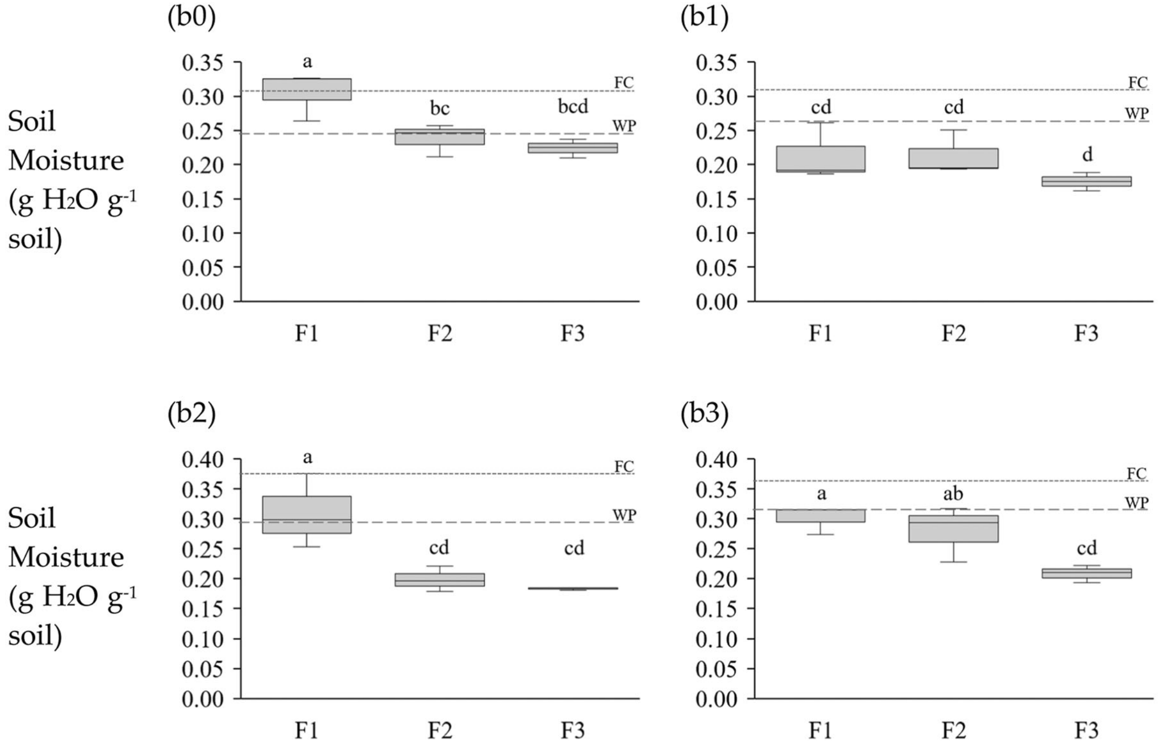

FIGURE 3 | Moisture contents according to the dose of biochar incorporated into the soil and irrigation frequency. FC: soil moisture at field capacity (−0.033 MPa); WP: soil moisture at wilting point (−1.5 MPa); F1, F2, F3: levels of the irrigation interval variable; b0, b1, b2, b3: levels of the incorporated biochar variable. Different letters in each testing parameter represent statistical significance among interaction treatments at $p < 0.05$ for the LSD test.

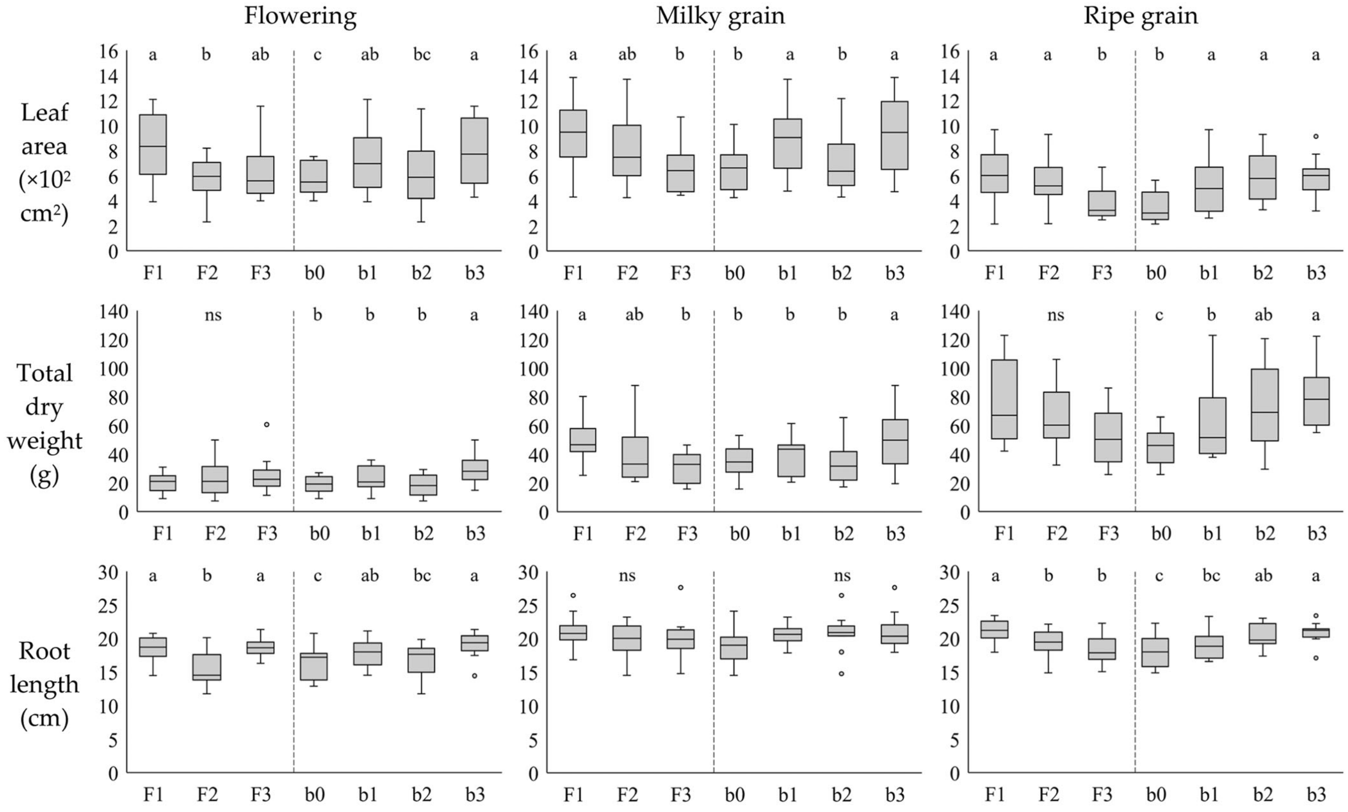

FIGURE 4 | Biometric parameters across phenological stages of development. F1, F2, F3: levels of the irrigation frequency variable; b0, b1, b2, b3: levels of the incorporated biochar variable; ns: indicates not significant ($p > 0.05$); different letters in each testing parameter represent statistical significance among groups at $p < 0.05$ for LSD test.

developed. At the ripe grain stage, no significant differences in root length were observed for irrigation intervals of 10 days or longer. However, biochar incorporation consistently resulted in plants with longer roots, in direct proportion to the dose applied.

3.3 | Effect on Quinoa Yield Components

Regarding the main effects of the tested factors, irrigation significantly affects panicle length, with notable differences observed between F1, F2, and F3 (Table 1). All evaluated parameters show a highly significant effect when varying the biochar dose. No significant effects are noted for any variables when considering the interaction between irrigation frequency and biochar dose. However, a general trend is observed where reduced irrigation frequency (from F1 to F3) leads to lower values in yield variables, particularly in panicle length (Figure 5). Higher biochar doses (b2 and b3) tend to enhance yield parameters, with the highest values achieved at b3. Additionally, more frequent irrigation (F1) promotes greater panicle length. Therefore, the treatments with the best yield outcomes (Cluster 2) correspond to medium and low irrigation intervals with biochar doses of 2 and 3 t·ha^{-1}, while treatments without biochar (Cluster 1) are associated with the lowest yield results.

4 | Discussion

The results of the biometric evaluation indicate that a longer irrigation interval (15 days) reduces the leaf area of quinoa, particularly during the grain formation and maturation stages. However, the incorporation of biochar into the soil promoted quinoa growth and development under water stress conditions, as evidenced by a larger leaf area and increased biomass across the various phenological phases evaluated. Notably, the increase in total biomass was primarily attributed to a higher

TABLE 1 | Quinoa yield parameters by irrigation frequency and incorporated biochar dose.

Treatment		Seed weight per plant (g plant^{-1})	Thousand seeds weight (g)	Panicle length (cm)	Panicle diameter (cm)	Yield (t·ha^{-1})
F		ns	ns	**	ns	ns
b		***	***	***	***	***
F × b		ns	ns	ns	ns	ns
Irrigation frequency (F)						
F1		35.88 ± 10.41	3.15 ± 0.43	84.37 ± 4.76	11.48 ± 1.4	3.72 ± 0.76
F2		32.31 ± 8.68	3.05 ± 0.26	78.6 ± 7.85 ^{b}	11.14 ± 1.55	3.99 ± 0.64
F3		28.14 ± 8.57	3.2 ± 0.3	73.65 ± 5.82 ^{c}	10.06 ± 1.47	3.71 ± 0.49
Biochar dose (b)						
b0		23.23 ± 3.57 ^{c}	2.82 ± 0.34 ^{b}	72.1 ± 7.28 ^{c}	9.46 ± 1.11 ^{c}	3.18 ± 0.44 ^{c}
b1		33.17 ± 6.66 ^{b}	3.1 ± 0.25 ^{a}	79.33 ± 5.36 ^{b}	10.71 ± 1.03 ^{b}	3.87 ± 0.48 ^{b}
b2		33.23 ± 9.11 ^{b}	3.31 ± 0.27 ^{a}	80.03 ± 5.54 ^{b}	11.28 ± 1.5 ^{b}	3.96 ± 0.74 ^{ab}
b3		38.81 ± 10.81 ^{a}	3.31 ± 0.25 ^{a}	84.03 ± 7.2 ^{a}	12.12 ± 1.37 ^{a}	4.22 ± 0.38 ^{a}
F × b						
F1	b0	26.45 ± 1.47	2.76 ± 0.49	78.78 ± 2.79	9.73 ± 0.85	3.02 ± 0.49
	b1	33.4 ± 3.58	3.07 ± 0.27	84.4 ± 2.64	11.4 ± 0.67	3.88 ± 0.25
	b2	37.08 ± 7.39	3.36 ± 0.44	85.18 ± 4.28	11.95 ± 1.2	3.64 ± 1.05
	b3	46.58 ± 13.83	3.43 ± 0.21	89.13 ± 2.78	12.85 ± 0.54	4.35 ± 0.51
F2	b0	22.49 ± 4.05	2.85 ± 0.32	70.3 ± 7.96	9.7 ± 0.18	3.34 ± 0.62
	b1	32.29 ± 5.16	2.97 ± 0.15	77.75 ± 2.1	10.83 ± 0.68	3.94 ± 0.62
	b2	37.64 ± 9	3.19 ± 0.18	80.48 ± 1.76	11.65 ± 1.68	4.56 ± 0.27
	b3	36.83 ± 7.68	3.21 ± 0.23	85.88 ± 8.33	12.38 ± 1.86	4.13 ± 0.45
F3	b0	20.75 ± 2.36	2.87 ± 0.25	67.23 ± 5.26	8.95 ± 1.79	3.18 ± 0.08
	b1	33.83 ± 11.02	3.27 ± 0.25	75.85 ± 6.34	9.9 ± 1.21	3.78 ± 0.61
	b2	24.97 ± 5.64	3.39 ± 0.11	74.43 ± 3.69	10.25 ± 1.35	3.67 ± 0.33
	b3	33.01 ± 6.88	3.3 ± 0.32	77.1 ± 3.11	11.13 ± 1.02	4.19 ± 0.18

Note: ns: indicates not significant ($p > 0.05$); different letters (a, b, c, and ab) in each testing parameter represent statistical significance among groups for the LSD test.
*implies statistical significance at 5%.
**implies statistical significance at 1%.
***Implies statistical significance at 0.1%.

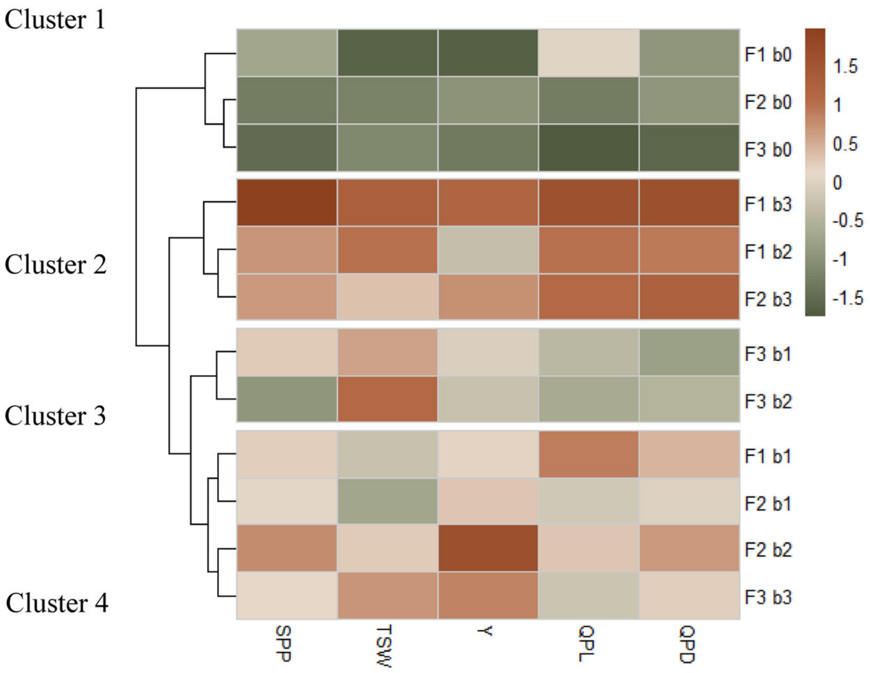

FIGURE 5 | Clustered heat map for quinoa yield parameters. The Y-axis indicates the applied treatments (irrigation frequency - biochar dose). The X-axis indicates the evaluated parameters (SPP: Seed weight per plant; TSW: Thousand seeds weight; Y: Yield; QPL: Panicle length; QPD: Panicle diameter).

accumulation of panicle biomass. In a recent review, Bekchanova et al (Bekchanova et al. 2024). report that the positive effect of biochar on total biomass is largely due to greater dry matter accumulation in the panicle compared to vegetative biomass. Furthermore, the increase in leaf area enhances light interception and the plant's photosynthetic capacity (Hu et al. 2020). These positive outcomes on quinoa growth and development under water stress conditions are closely linked to biochar's impact on soil nutrient dynamics and its stimulation of physiological processes related to root growth and nutrient uptake (Fallah et al. 2023). One of the main reasons for the positive effects of biochar is its influence on nitrogen release and fixation dynamics, which helps reduce nitrogen leaching and prolongs its availability to plants (Guo et al. 2021). Additionally, the microporous structure and large specific surface area of biochar have been shown to enhance both total and available soil nitrogen (Yao et al. 2017). The beneficial effects of biochar are also linked to an increase in the soil's Cation Exchange Capacity (CEC), which results from the high density of oxygen functional groups and the large surface area of biochar particles (Li et al. 2023). In this regard, Xu et al (Xu et al. 2015). report that biochar applications ranging from 43 to 85 t·ha^{-1} in soils with a CEC of 3.43 mEq·100 g^{-1} can increase the potential CEC and nutrient availability in the soil. On the other hand, the findings of this study revealed that the use of biochar increased the percentage of air in the soil during irrigation, which contributed to the biostimulation of root growth. This increase in soil aeration promotes greater root respiratory activity and enhances active nutrient uptake via ATPase transporters (Hawkesford et al. 2023). Additionally, higher doses of biochar stimulate various plant metabolic pathways, particularly oxidative phosphorylation and benzoxazinoid biosynthesis, both of which are involved in cellular respiration and root branching (Cui et al. 2024). Furthermore, biochar application has been shown to alter the metabolite profile in the plant rhizosphere, increasing concentrations of metabolites such as isoleucine, malonate, and acetate. These compounds are associated with root growth under nitrogen-deficient conditions (Cheng et al. 2018). In quinoa, biochar has been shown to increase fresh biomass, dry biomass, and root length in three different varieties under water deficit conditions (Akram et al. 2024b). Additionally, the increase in root branching due to biochar application enhances the water status of quinoa by improving water potential, stomatal conductance, and water use efficiency (Akram et al. 2024b; Ramzani et al. 2017). Furthermore, doses of 10 t·ha^{-1} of maize straw biochar have been reported to boost leaf photosynthetic activity (Wang et al. 2021). In our study, the positive effects of biochar on root growth, leaf area, and total biomass were observed at lower doses (3 t·ha^{-1}) using material from municipal prunings and crop residues.

The results demonstrate a direct relationship between increasing biochar doses and quinoa yield. Specifically, the application of 3 t·ha^{-1} of biochar resulted in an average yield of 4.22 ± 0.38 t·ha^{-1}, which is close to the theoretical potential yield of the INIA-Pasankalla variety (4.5 t·ha^{-1}) (INIA Quinua INIA 415 Pasankalla 2012). Several studies suggest that biochar's positive effect on quinoa yield is due to the taproot growth stimulation, which enhances water and nutrient absorption (Kammann et al. 2011). In this context, Ramzani et al (Ramzani et al. 2017). found that acidified biochar uses increased quinoa seed yield by 62%, driven by a 55% increase in root biomass. A similar effect was observed in the present study, where biochar doses of 2 and 3 t·ha^{-1} promoted greater root length, likely due to the higher percentage of air in the soil. These findings suggest that biochar's biostimulatory effect on root growth is linked to increased oxygen availability, supporting the hypothesis that biochar enhances the porosity and aggregate stability of soil (Mukherjee and Lal 2013).

The results align with findings reported in the literature for biochar incorporated at doses higher than 1% w/w in water stress conditions for quinoa cultivation (Akram, Libutti, and Rivelli 2024a). Notably, even with doses lower than those typically reported, yield increases were observed for the quinoa variety Pasankalla. This suggests that agronomically and economically viable recommendations could be developed (Patel and Panwar 2024).

The yield increase is further supported by a higher harvest index, reflected in greater dry matter accumulation in productive organs, with a 16.5% increase in panicle length and 28.12% in panicle diameter. Recent studies have validated biochar's positive effect on stimulating photosynthesis and enhancing the sink capacity of productive organs (He et al. 2020). Additionally, it has been shown that the increase in sink capacity and biomass of quinoa's reproductive organs is directly linked to potassium uptake and accumulation, particularly under abiotic stress conditions (Turcios, Papenbrock, and Tränkner 2021). Potassium plays a crucial role in reducing cellular osmotic potential, allowing water to enter the stomatal guard cells and open the ostioles (Hasanuzzaman et al. 2018). This process is essential for gas exchange between the plant and the atmosphere (Johnson et al. 2022). Under water stress conditions, guard cells pump potassium into the surrounding cells, causing the stomata to close tightly, thereby regulating transpiration. Concurrently, potassium translocates and accumulates in root cells, reducing root water potential and promoting water uptake (Johnson et al. 2022). An adequate supply of potassium enhances leaf stomatal conductance and increases intracellular CO_2 concentration, which in turn boosts the activity of ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCo), the enzyme responsible for carbon fixation and photosynthetic activity in the leaf (Mostofa et al. 2022). In this regard, a recent review of the relationship between biochar and soil potassium indicates that biochars produced at temperatures above 500°C significantly increase the soil's total potassium content (Bilias et al. 2023). Moreover, current evidence highlights biochar's positive effect on enhancing quinoa's leaf stomatal conductance by increasing potassium accumulation, which lowers cellular water potential and promotes water uptake (Yang et al. 2020).

Based on the obtained results, it is estimated that the incorporation of biochar (pyrolyzed at approximately 700°C) stimulated an increase in panicle biomass by enhancing the availability of potassium in the soil. Another analyzed yield indicator was the weight of 1000 seeds, where biochar application resulted in a 9.93–17.38% increase, with the effect being more pronounced at a 10-day irrigation interval. However, no significant differences were observed between different biochar doses in terms of seed weight, though there were notable differences in total grain weight per panicle. This suggests that biochar's positive impact on quinoa yield is primarily linked to an increased number of grains per plant. This increase may be attributed to the stimulation of sucrose phosphate synthase activity, a key enzyme involved in sucrose biosynthesis and the translocation of assimilates to sink organs, which enhances the plant's capacity to maintain production (Zhu et al. 2019). Furthermore, the improvement in quinoa growth and productivity due to biochar application can be explained by increased intrinsic water use efficiency, expressed in higher photosynthetic activity and stomatal conductance, particularly under water deficit conditions (Akram, Libutti, and Rivelli 2024a; Yang et al. 2020). In essence, biochar enhances water and nutrient uptake, even under extended irrigation intervals (15 days).

Biochar's incorporation into soil has long-term effects on pore size distribution (macro-, meso-, and micro-pores) and soil particle aggregation (Acharya et al. 2024), which significantly impacts irrigation and nutrient management in agricultural systems (Xiao et al. 2018). In this context, parameters related to water management, such as bulk density and soil moisture content, were evaluated. Biochar treatments reduced bulk density by 1-5%, proportionate to the increased biochar dose; however, no significant differences were observed (Table A3). This may be due to the low doses applied and the soil texture (Acharya et al. 2024). The stable organic carbon content in soil is closely tied to clay content, as both act as balancing factors within soil colloids (Burke et al. 1989). As such, higher biochar doses may be necessary in loam soils with high clay content, like those in this study ($> 22\%$), to exert a more substantial influence on bulk density.

Incorporating biochar into the soil creates new pores, increasing the specific surface area of soil-water contact (Atkinson, Fitzgerald, and Hipps 2010; Yang, Liu, and Lu 2021). However, this effect must be considered alongside the hydrophobicity of biochar, which can be enhanced or reduced depending on the chemical processes occurring during pyrolysis and its particle size (Adhikari, Timms, and Mahmud 2022). This study processed biochar derived from vegetable feedstock at temperatures around 700°C, likely increasing its hydrophobic properties (Ghorbani et al. 2022) and generating a large surface area (Yang, Liu, and Lu 2021; Adhikari, Timms, and Mahmud 2022). Interestingly, the soil moisture content in treatments with lower biochar doses ($1\ t{\cdot}ha^{-1}$) was lower than that of the control without biochar. However, at higher doses (2 and $3\ t{\cdot}ha^{-1}$), the trend reversed, with moisture levels rising to match the control treatment. This shift in moisture content was more pronounced in treatments with shorter irrigation intervals (5 days), whereas for longer intervals, the differences were less conclusive (Figure 4).

According to the preliminary analysis, biochar incorporation enhanced leaf growth and increased water use efficiency, alongside the potential hydrophobic effect that biochar introduces into the soil. However, these effects were likely counterbalanced and surpassed by the larger surface area, increased storage capacity, and improved contact points provided by higher biochar doses, ultimately enhancing the water-holding capacity of the soil-biochar (SB) mixture (Fallah et al. 2023). This trend was most significant for the shortest irrigation interval (5 days), where the SB mixture retained moisture closer to field capacity (FC) compared to longer intervals (10 and 15 days), allowing biochar pores to be more easily filled with water. Once biochar's inter- and intra-particle pores are saturated, the retention forces within the soil increase, raising the matric potential of the SB mixture for a given moisture content and slowing soil desiccation (Fallah et al. 2023). It was also observed that biochar presence facilitated water uptake by the plants, even below the theoretical wilting point (WP). Evaluating the increase in theoretical FC relative to this extended water consumption capacity suggests that total available water for quinoa plants rises with increasing biochar doses. This finding aligns with Kirkham (Kirkham 2023), who noted that water stress-tolerant plants can extract moisture below the WP. In summary, biochar not only improved the soil's water retention capacity but also encouraged the plants to consume water at levels below the WP, which translated into increased crop yield.

5 | Conclusions

The results indicate that incorporating low doses of biochar, derived from pruning residues and produced at high pyrolysis temperatures, positively impacts quinoa yield under irrigation intervals of 10 to 15 days in field conditions. Specifically, applying 2 and 3 $t \cdot ha^{-1}$ of biochar increases soil moisture content at both field capacity (FC) and wilting point (WP), while also promoting the soil water absorption of the quinoa below the WP. This allows quinoa crops to improve their yield even under water stress conditions. The study highlights that biochar, when used in conjunction with tailored irrigation strategies, can enhance both the productivity and sustainability of quinoa cultivation—a crucial crop for food security. This approach could lead to more efficient and sustainable agricultural practices, particularly in addressing climate change challenges through the optimal use of water and carbon-storing amendments. Thus, lower biochar doses, such as the used in this research, could lead to recommending practices that are more viable for field conditions. To build on these findings, further field research should be conducted focusing on the long-term effects of biochar on soil health and crop quality. It is also essential to explore different sources of biochar, experiment with its application across various crops, and develop optimized irrigation models to maximize biochar benefits under diverse climatic and soil conditions. These efforts will contribute to more resilient and productive agriculture in the Andes and similar regions.

Author Contributions

Tatiana Condori-Ataupillco: conceptualization, methodology, investigation. **Ricardo Flores-Marquez:** conceptualization, methodology, formal analysis, investigation, writing—original draft preparation, visualization. **Kenyi Quispe:** investigation, writing—original draft preparation. **Juan Quispe-Rodriguez:** writing—review and editing. **José Velásquez-Mantari:** project administration. **Richard Solórzano-Acosta:** writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.