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Worldwide development of agronomic management practices for quinoa cultivation: a systematic review

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Quinoa (*Chenopodium quinoa* Wild.) is a drought and salinity-tolerant crop that originated in the Andes over 7000 years ago. It is adapted to different agroecological areas and can be grown from sea level to an altitude of 4000 m. The outstanding nutritional status of quinoa, with its high content of proteins, vitamins, and minerals, makes it a promising crop able to combat hunger and malnutrition in different countries in the 21st century. Quinoa cultivation has expanded from South America to Africa, Europe, Asia, and North America. Reviewing quinoa cropping practices will provide farmers with adequate recommendations for improving the agronomic and environmental sustainability of quinoa cultivation worldwide. For this reason, we conducted a systematic review of agronomic management practices in 148 field experiments conducted worldwide from 2000 to 2022. The collected data from the literature were analyzed and presented by location to determine high-performing genotypes, optimal planting dates, and other adequate cropping practices affecting quinoa performance and yield. Results showed that quinoa could be successfully cultivated in the new farming areas. Quinoa yields were higher than those reported in its place of origin, ranging from 108 kg ha⁻¹, obtained by KU-2 in Washington State, to 9667 kg ha⁻¹, obtained by Longli in China. Although quinoa is considered a crop with low input requirements, positive grain yield response was observed following increasing fertilization rates. Quinoa needs 2 to 4.6 kg of nitrogen to produce 1q of grain yield. In terms of phosphorus and potassium, quinoa needs 3.7 kg P₂O₅ and 4.3 kg K₂O to produce 1 ton of total biomass. Quinoa has low water requirements (300–400 mm). However, a positive response was recorded with water quantities up to 866 mm. During our investigation, weed control in quinoa crop is still undeveloped and usually done manually. Research addressing this issue can increase quinoa yields and decrease the production cost. Downey mildew and birds' attack are the major phytosanitary problems affecting quinoa grain yield. Other pests such as miners and aphids can also affect the health of quinoa, but their injury is not a serious problem. After the harvest, saponins found in the out layer of the seed can be

removed through washing and mechanical pearling process, but the latter technic was found to be efficient and cost effective to reduce the saponin content. Our results constitute the first recommendation base for the adequate worldwide agronomic practices of quinoa crop.

KEYWORDS

quinoa, systematic review, cultivar, planting date, fertilization, irrigation, postharvest

1 Introduction

Quinoa is originated from the Andean region of South America (Adolf et al., 2013). This crop has received much attention because of its high nutritional value and its high tolerance to frost, drought, and salinity (Jensen et al., 2000; Jacobsen, 2003; Jacobsen et al., 2005; Adolf et al., 2013; Hlásná Cepková et al., 2022; Shafiq et al., 2022; Terletsckaya et al., 2022). Besides the human consumption, quinoa could be used as a fodder crop of high quality in adverse environments (Liu et al., 2020). Recently, quinoa cultivation has expanded beyond the Andes to several countries across the world (Bazile et al., 2016). However, Bolivia and Peru are still the largest quinoa producers with a share of 80% (Bazile et al., 2015; Alandia et al., 2020). Knowledge on quinoa production techniques and its response to different environments are necessary to adapt this crop to new farming areas.

The diversified genetic pool of quinoa allowed its cultivation possible from sea level to more than 4000 m above sea level, from 2° North latitude to 40° South latitude, in alkaline soils up to pH 9 as well as in acidic soils up to pH 4.5 (Mujica et al., 2001; Jacobsen, 2003). Quinoa thrives when the temperature is between 10–25°C with an optimum growth when temperature ranges from 15–20°C (Mujica et al., 2001). However, quinoa withstands temperatures up to -8°C, especially at branching stage, but temperatures above 38°C cause flower abortion and pollen infertility (Mujica et al., 2001). In Australia, quinoa yield decrease was associated with temperatures above 17°C during the grain filling as well as with temperatures below 15°C during the flowering stage (Snowball et al., 2022). Regarding the relative humidity, quinoa grows normally from 40% to 100% relative humidity (Tapia, 2001).

Until the new millennium, most of the scientific studies on quinoa were carried out in the countries of origin and reported as written materials (Sellami et al., 2020). To our knowledge, review papers of the response of quinoa to different agronomic practices and environmental conditions are unavailable. With the expansion of quinoa cultivation to Africa, Europe, Asia, and North America (Alandia et al., 2020), there was a need to a systematic review on the cropping practices and strategies to increase yields in the new production areas. After 2000, the scientific production of agronomic techniques started to increase with a peak during 2019 (Sellami et al., 2020). Most of these studies were concentrated in Europe, followed by Africa, and Asia whereas few studies has been reported from the Australian continent. Quinoa yield ranged from

11 kg ha⁻¹ in North America to 11,000 kg ha⁻¹ in Asia (Sellami et al., 2020). The low yields recorded in North America reflect the poor adaptation of quinoa crop and the limited experiments and knowledge about the management practices in this continent.

To increase the productivity of quinoa, it is important to identify suitable cultivation guidelines for each region. In general, crop yields are the result of genetic and environment interactions (Kaya and Akcura, 2014). In some cases, genotypes screened for high yields and quality at one site occasionally don't perform well at another (Murphy and Matanguihan, 2015). Therefore, it is important to identify adapted quinoa genotypes that give high yields in various environments. Optimal planting date is also an important agronomic practice because it helps adjusting quinoa phenology to optimal environmental conditions, and enhances plant development and yields (Taaime et al., 2022). For this reason, adequate planting dates must be determined for each region, considering the rainy season, the plant growing cycle length, and frost and heat periods (Murphy and Matanguihan, 2015). In the context of climate change, sustainable irrigation strategies are also crucial to optimize water use, especially in arid and semi-arid regions. Other agronomic aspects of high importance, such as quinoa fertilization, planting density, pests and diseases, and postharvest techniques can highly affect quinoa production.

Quinoa's ability to produce grains with high protein content and quality under extreme environmental conditions makes it a promising crop for the diversification of agricultural systems in different countries worldwide (Bhargava et al., 2007). Reviewing appropriate agronomic practices for each region will help disseminate the information among farmers and industries and increase quinoa production to meet the increasing demand in the market. For this reason, we conducted a systematic review of field studies available in the literature to identify, gather, and optimize quinoa agronomic practices worldwide.

2 Materials and methods

2.1 Literature search and selection

A systematic review was conducted across Scopus Database to identify research related to the agronomic management practices of quinoa production worldwide. The studies selected were published

between 2000 and 2022 in peer-reviewed journals written in English, Chinese and Spanish. The identification of scientific published papers was performed on 7 August 2022. Quinoa was the key word used to search the scientific papers with the limitation to “Agricultural and Biological Sciences” subject area. PRISMA was the methodology followed to screen the papers reviewed in this study (Figure 1). This methodology consisted of evaluating the title of the article. After judging that the title was related to agronomic practices of quinoa, we studied the abstract then the full article to screen only experiments conducted under field conditions. The process of article selection resulted in 148 chosen papers from which the data (quinoa yield variation according to cultivars, planting dates, planting structure, irrigation quantities, fertilization, and organic amendment) was extracted, analyzed, and represented in graphs and tables. Literature on soil tillage, planting methods, weed control, quinoa pests, diseases, and harvest and post-harvest techniques was selected for traditional literature review.

2.2 Data extraction

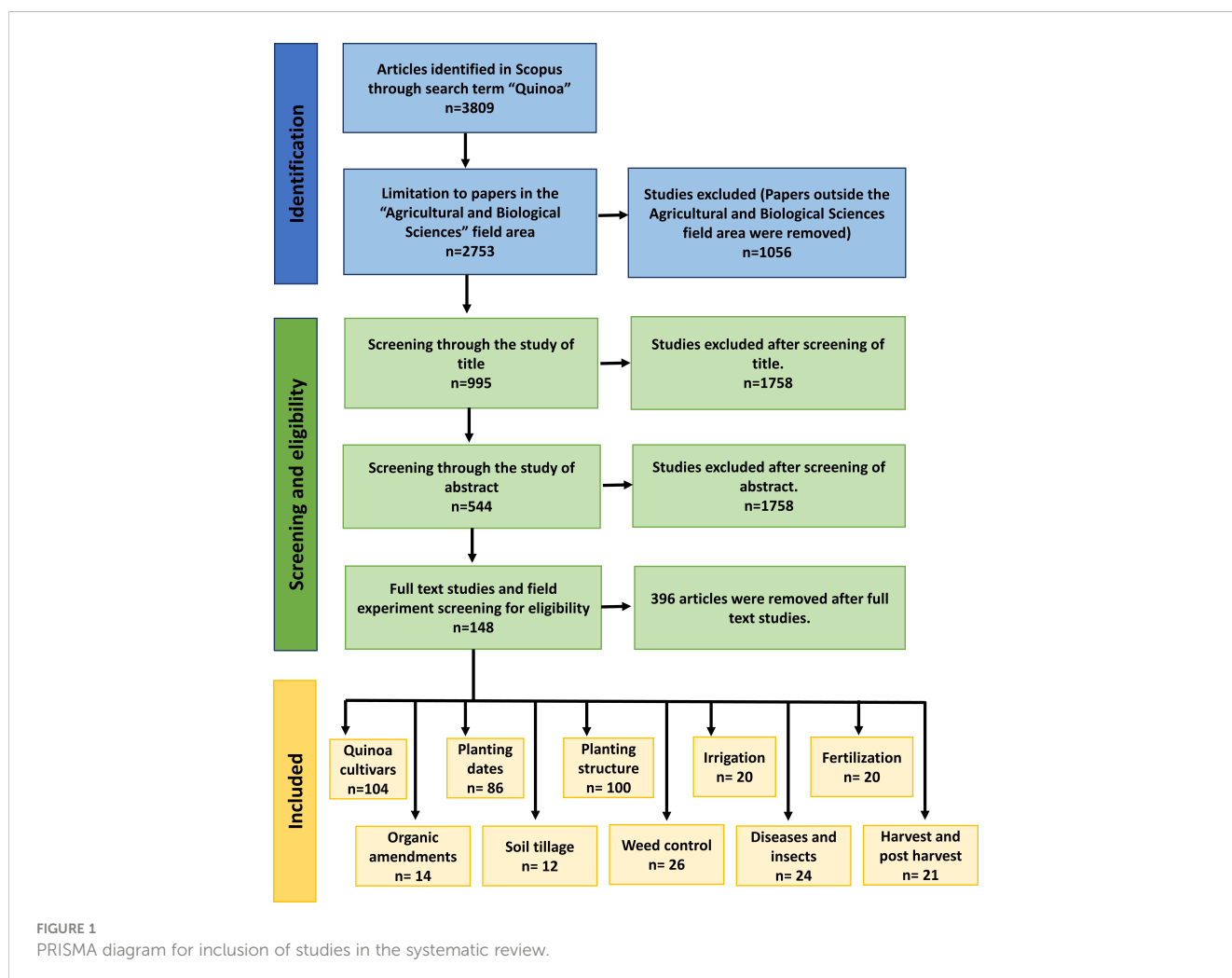
Quantitative data were collected from the selected papers and organized in Excel table. Table lines corresponded to the total

screened articles. From each article, quinoa grain yield and corresponding cultivar, planting date, plant and row spacing, irrigation quantities, and fertilizers and organic amendments’ rates were represented in the table columns. To reduce the effect of environmental variability, we calculated the yield means of quinoa cultivars in each country and represented them in histograms. Box plots of quinoa yield variation in response to planting dates in each country were performed using R software. The other agronomic practices: soil tillage, planting methods, weed control, pests and diseases, harvest and postharvest were reviewed, summarized, and discussed.

3 Results and Discussion

3.1 Genotypes and cultivars

The high genetic diversity of quinoa makes its cultivation possible under different environmental conditions. Quinoa genotypes are adapted to a wide range of soils with different pH varying from 4.7 to 9.7. This crop tolerates extreme temperatures from -8°C to 38°C in certain phenological stages and it is planted from sea level to about 4000 m above sea level (Mujica et al., 2001). Our evaluation focused



on screening genotypes from the reviewed papers and assessing their performance in different parts of the world. In order to reduce the variability, we analyzed quinoa yields according to cultivars and locations and results were presented by country and continent. Quinoa grain yields ranged from 108 kg ha⁻¹, obtained with KU-2 cultivar in Washington State, North America to 9667 kg ha⁻¹, obtained with Longli cultivar in China, Asia. It was found that during the last twenty years, quinoa gained more interest in the African continent where high genetic diversity was evaluated, especially in Morocco and Egypt (Figure 2). Titicaca, Puno, Q5, and DO708 were the cultivars most evaluated in Morocco with 14, 13, 20 and 20 replications, respectively. SW2 and Atlas were also well adapted to Moroccan conditions, with 7830 and 6370 kg ha⁻¹ of grain yield. However, these two cultivars were represented once in the literature, and we cannot rely on the obtained high yields for further recommendations. Evaluation of these cultivars in other regions of Morocco is important to test their yield stability in different environments. Pasankalla cultivar was less adapted to Moroccan conditions but performed very well in Burkina Faso reaching 1070 kg ha⁻¹ of grain yield. However, quinoa yields in Burkina Faso are still low compared to Morocco and more research are needed to explore the genetic variability and find adapted cultivars to

this country. Quinoa seemed to be well adapted to Egypt conditions and yields varied from 932 kg ha⁻¹ with Q1 to 3287 kg ha⁻¹ with CICA. Publications on quinoa in Zimbabwe and Kenya were scarce and only one cultivar, Cherry vanilla, was evaluated in Zimbabwe with an average yield of 533 kg ha⁻¹, and two quinoa cultivars were evaluated in Kenya, Nairobi L and Nairobi S, with an average yield of 2097 and 1583 kg ha⁻¹, respectively. Yields in Rwanda were low reaching only 960 kg ha⁻¹ with the high performing cultivar Kaslaea. Brightest B.R. was the cultivar most adapted to Malawi environment and produced an average yield of 2214 kg ha⁻¹.

Quinoa was well adapted to the environmental conditions of different countries in Europe (Figure 3). Most of the research were conducted in Denmark and Turkey and quinoa yields were above the average found in its area of origin. Titicaca, Puno, and Pasto were adapted to the diverse environmental conditions in Belgium, Germany, Greece, Italy, Spain, Turkey, and Denmark. The highest and lowest quinoa yields, 3200 and 200 kg ha⁻¹, were obtained in Italy by Regalona and DISPAA-Q47-CB, respectively.

According to the reviewed literature, quinoa cultivation was restricted to some parts of North America such as Washington and Utah states and Canada (Figure 4). Five genotypes were reported in the published literature and yields were low than those obtained in the place of

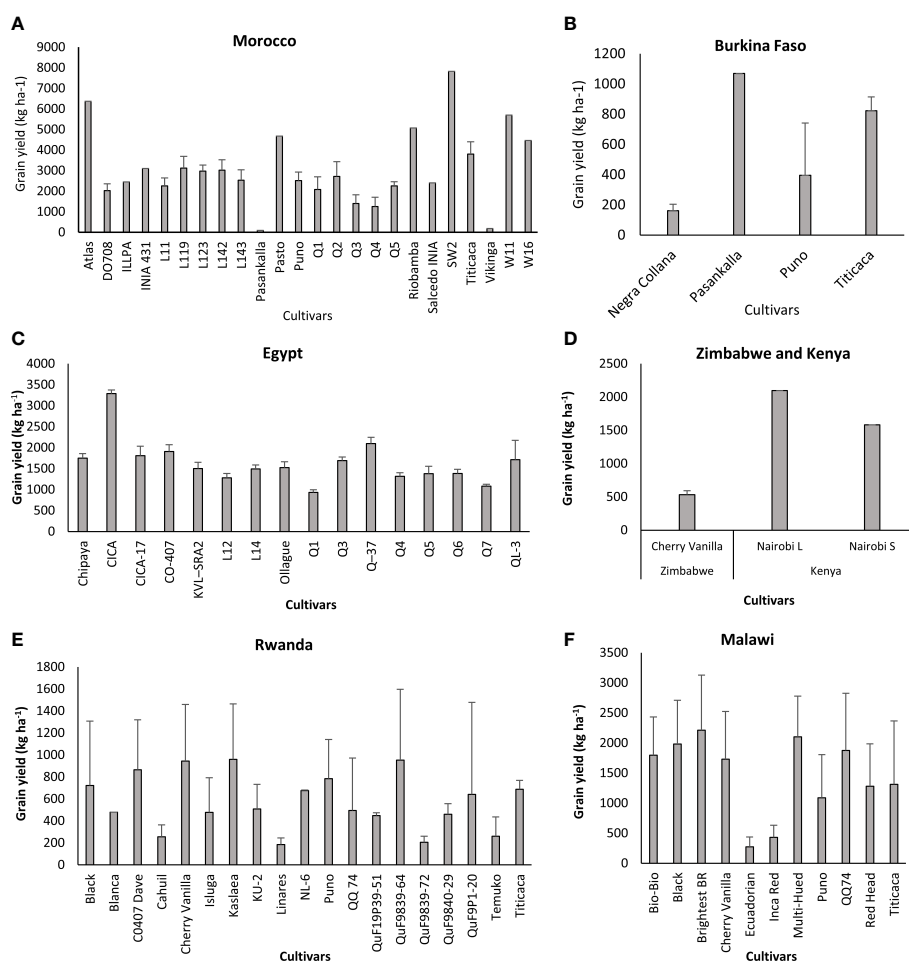


FIGURE 2 Performance of quinoa cultivars in Africa (A) Morocco, (B) Burkina Faso, (C) Egypt, (D) Zimbabwe and Kenya, (E) Rwanda, (F) Malawi.

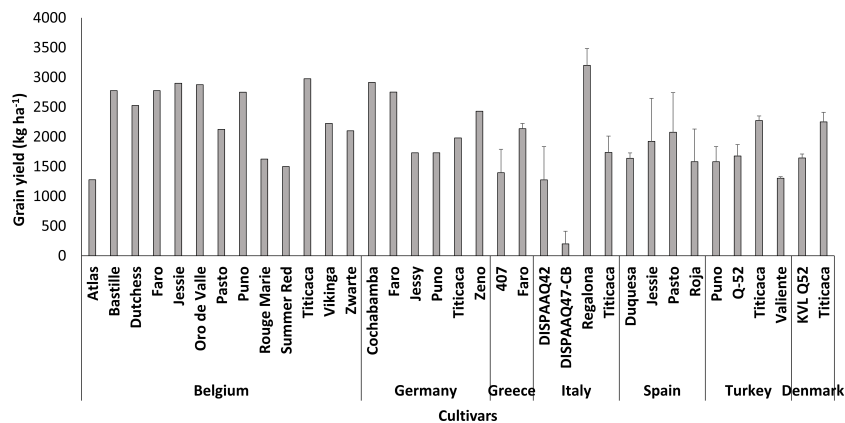


FIGURE 3 Performance of quinoa cultivars in Europe.

origin. The highest and lowest yields, 563 kg ha⁻¹ and 108 kg ha⁻¹, were obtained in Washington State with Cherry Vanilla and KU-2, respectively.

In South America, only local varieties were cultivated, and the highest yield was recorded in Argentina by 2-Want cultivar (Figure 5). Narino cultivar showed high performance in Colombia with a grain yield of 4317 kg ha⁻¹. On the other hand, Real Blanca seemed to be less adapted to the environmental conditions of Bolivia with a grain yield of 380 kg ha⁻¹.

The cultivation of quinoa has extended to different countries in Asia (Figure 6). In China, the evaluation of the studied genotypes showed that Longli was highly adapted to the country conditions and recorded a high average yield of 9667 kg ha⁻¹. Yields in India and U.A.E were also high with IHBT/Ac-1, IHBT/Ac-2, Q5 reaching 5750, 5950, and 5384 kg ha⁻¹, respectively. However, yields were lower in Pakistan, Syria, Uzbekistan and Vietnam ranging from 944 kg ha⁻¹ to 2538 kg ha⁻¹. Drought, heat stress, and salt-affected soils in these regions may have negatively affected quinoa grain yield (Abbas et al., 2023).

3.2 Planting date

Planting date is an important agronomic practice that helps adjusting the favorable environment for the cultivation of quinoa.

The first climatic factor that affects quinoa yield and quality is temperature (Gómez et al., 2021; Stoleru et al., 2022). This parameter is estimated to increase from between 1.5°C to 6°C to the end of the XXI century (IPCC, 2018). Thus, optimal planting date should be identified to escape the heat stress, especially during the most sensitive development stages of quinoa (Flowering and seed filling) (Dao et al., 2020; Garcia-Parra et al., 2020). This was recorded in Argentina where delay in planting date from October to November exposed quinoa to higher temperature and affected the grain yield. In a study conducted by Gómez et al. (2021) in Argentina, 20°C was considered the threshold above which seed weight was negatively affected.

Optimal planting date should also allow enough time to the plant for its growth and development (Taaima et al., 2022). Under the agro-climatic conditions of Pakistan, planting in mid-November allowed long development period and gave higher biological and grain yield than planting earlier or later (Hamza et al., 2021). During this planting date, favorable temperature coincided with the grain filling stage and resulted in high yield.

Great attention should also be paid to the quinoa cultivar growing cycle length. It was found that quinoa long cycle cultivars are more susceptible to heat stress because of their long cycle. Planting these cultivars between November-December and

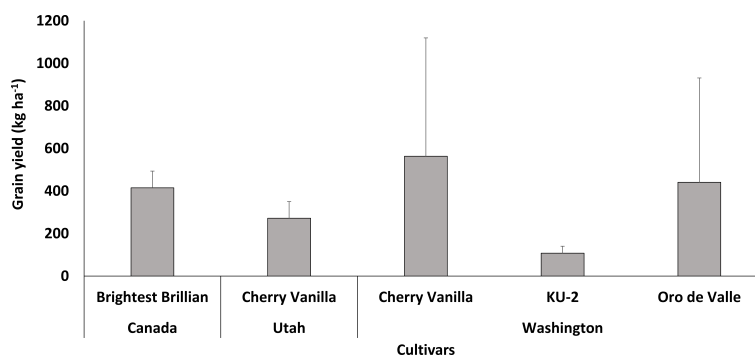


FIGURE 4 Performance of quinoa cultivars in North America.

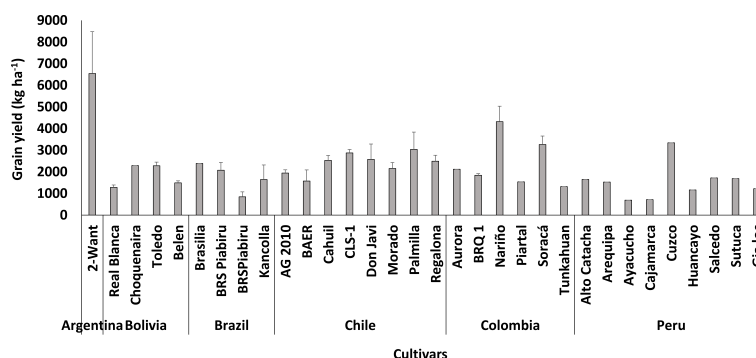


FIGURE 5 Performance of quinoa cultivars in South America.

October-December is suitable for quinoa short cycle varieties in the Soudano-Sahelian and Soudanian zones, respectively (Dao et al., 2020).

High temperature also affects quinoa at the early development stages. It was found that the suitable planting date of quinoa in Greece is early March and late sowing coincides with high temperature, which dried the soil after each irrigation and affected the germination rate (Noulas et al., 2017). In Brazil, autumn-winter was optimal for planting quinoa, due to optimal temperature and range between night and day values, which increased grain yield and large seed size (Spehar and da Silva Rocha, 2010).

In addition, water is another important factor that conditions quinoa growth and yield. For instance, April planting of quinoa

when grown as a leafy green in Poland produced greater biomass and chlorophyll a + b than August planting, due to the availability of water (Adamczewska-Sowińska et al., 2021). In another study, planting during the first week of April month received the highest precipitations and represented the appropriate time for a successful quinoa cultivation in Turkey-Mardin ecology condition (Altuner, 2019).

In other regions prone to frost, planting quinoa should be done in order to avoid the cold conditions occurring at late growing stages of quinoa. In fact, early planting of quinoa (before August) enhanced plant height and total biomass and helped escaping the frost damage in Midwestern China (Liu et al., 2020). In another study carried out in the northern foothills of Yinshan Mountains, China, the optimum sowing time of quinoa was from mid-April to

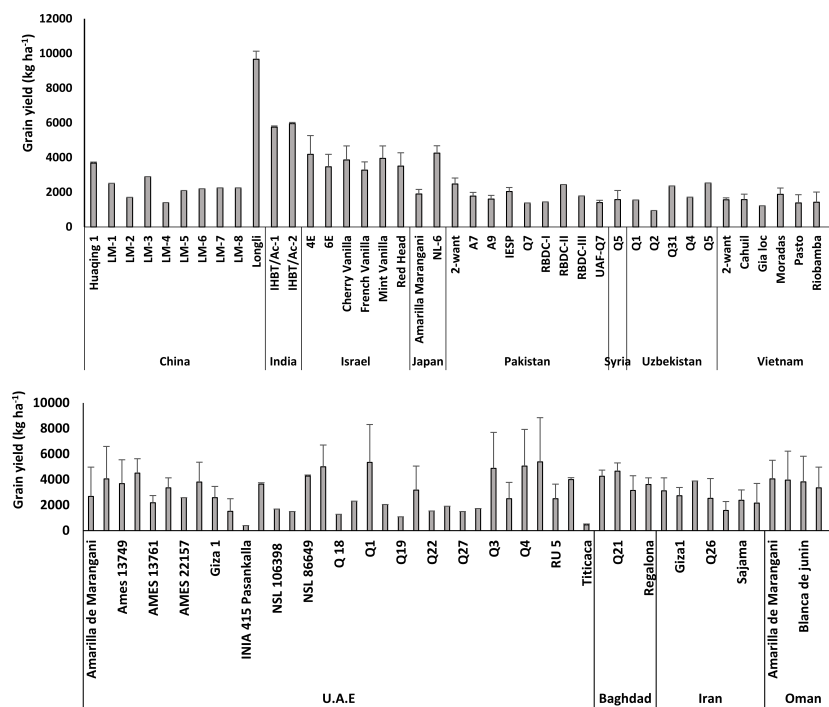


FIGURE 6 Performance of quinoa cultivars in Asia.

early May (Ren et al., 2018). Similarly in Canada, mid-May to mid-June planting was suitable for the cultivation of quinoa (Nurse et al., 2016).

Besides the environmental factors, weed infestation is an important biotic stress to take into consideration while planting quinoa. Under Mediterranean climate conditions (Turkey), the adequate time to sow quinoa is April. The increasing temperature of late sowing exposed quinoa to high infestation of weed during the plant establishment, decreased the crop population and subsequently the grain yield (Zulkadir, 2020). In Morocco, seed and dry matter yields were highest when quinoa was sown in November and early December (Hirich et al., 2014a). Planting in these dates helped avoiding weed infestation and downy mildew occurring with late quinoa planting dates. Similar results were found in England whereas late sowing results in high weed competition and sowing in March was adapted to this region (Risi and Galwey, 1991).

Quinoa sensitivity to photoperiod has been studied by several authors. It is well known that quinoa genotypes cultivated in the tropics have longer vegetative phases and are more photoperiod sensitive than genotypes grown by the sea and on the Andean altiplano (Jacobsen, 2003).

We analyzed the collected quinoa yields from the selected literature according to planting dates and locations (Figure 7). Switching from spring to winter cultivation can be an essential criterion for the success of quinoa cultivation (Maamri et al., 2022). In Egypt, quinoa was sown in the rainy season between October and December, with optimal date occurring in November. In Kenya, two planting dates were evaluated and results showed that March planting gave higher yield than October planting with 2097 kg ha⁻¹. Planting during the cool dry season in Malawi (May) gave higher yield than planting during the hot rainy season (December), probably due to the effect of temperature on quinoa development and yield. In Morocco, quinoa was planted in different dates from

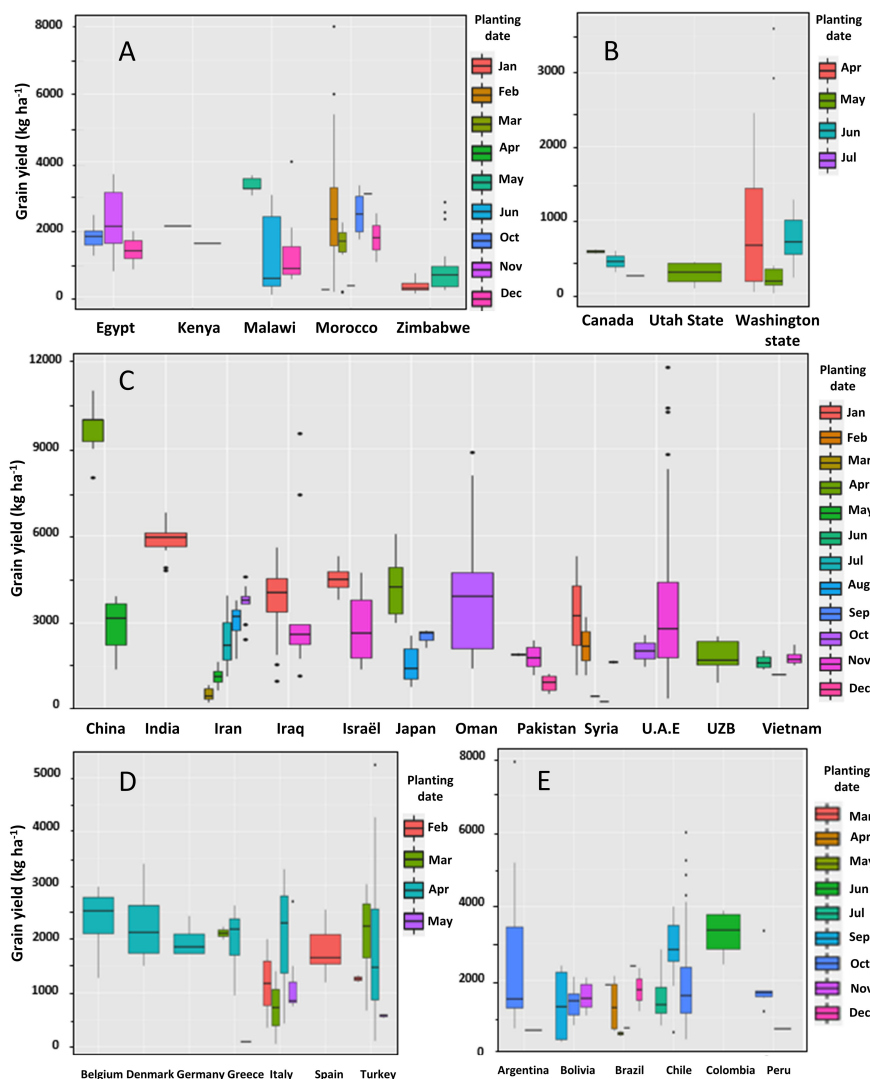


FIGURE 7 Worldwide quinoa grain yield variation according to sowing dates (A) Africa; (B) North America; (C) Asia; (D) Europe; (E) South America.

October to April. The highest average grain yield was November planting with 3050 kg ha⁻¹. In Zimbabwe, planting in May produced a grain yield three time higher than planting in January.

There was no big difference between planting dates in Europe with planting in April gave the highest grain yield in Belgium, Denmark, Germany, Greece, Italy, Spain, and Turkey. In North America, the analysis of yields showed that planting in May was suitable for the cultivation of quinoa in Canada and Utah State whereas planting quinoa during April in Washington State gave higher yields.

In the South America, planting in October was suitable for the cultivation of quinoa with a grain yield of 2786, 1416, 1883 and 1850 kg ha⁻¹ in Argentina, Bolivia, Chile, and Peru, respectively. However, Planting in December gave the highest yield in Brazil with an average of 1750 kg ha⁻¹. Analysis of quinoa yields in Asia showed that January was the optimal date for planting this crop in India, Iraq, Israel, and Syria. Regarding other countries, quinoa gave high yields when planted during October in Iran and Oman, during November in Pakistan, and U.A.E, and during April in China, Japan, and Uzbekistan.

3.3 Soil tillage

Quinoa grows well in loamy soils, with good drainage and high content of organic matter (Mujica et al., 2001). Quinoa can also adapt to different soils, but it is very susceptible to water logging and to excess humidity, especially in the first development stages (Mujica et al., 2001). In general, deep ploughing using moldboard or disc plow was used to prepare the soil for deep root system development. Before planting, a second tillage is recommended to prepare the seedbed.

TABLE 1 Land preparation for the cultivation of quinoa.

Soil texture	Land preparation	References
Clay loam	Ploughing at 30 cm depth and hoeing at 15 cm	El-Shamy et al., 2022
Clay Loam	Deep ploughing in winter with plowing using second-class tillage equipment before sowing	Zulkadir, 2020
Sandy loam	Plowing to a depth of 30 cm, discs, and leveling	Ebrahimikia et al., 2021
Sandy Loam	A handheld mechanical plough at 20 cm depth	Alvar-Beltrán et al., 2021
Sandy loam	Two ploughings to a depth of 12 cm followed by planking to conserve moisture suitable for emergence	Iqbal et al., 2018
Sandy coarse	Disc ploughing followed by harrowing in order to obtain a good seedbed	Hussain et al., 2020
Sandy	Disc ploughing followed by harrowing to ensure an even seedbed	Hussain et al., 2018
silt loam	Disking the soil to a depth of approximately 15 cm and hallow tillage (approximately 2.5 cm) was used to incorporate the compost and kill emerged weeds	Buckland et al., 2018
Loam	Moldboard ploughing and two rounds of vertical tillage with harrow disking	Nadali et al., 2021
Loam	Plowing was carried out with a reversible plow to a depth of 30 cm. To completely crush the lumps, the soil was disked twice, perpendicular to each other	Mansouri et al., 2021
Silty clay	Disk plow followed by a tiller and rotavator	Hamza et al., 2021

Recent work comparing two tillage systems showed that the minimum tillage, chiseling at 25 cm depth followed by chiseling at 10-15 cm, gave lower grain yield than the conventional tillage where moldboard plowing at 20-25 cm followed by one rotary hoeing at 10-15 cm were used. This yield difference was essentially due to enhanced crop growth parameters (Kakabouki et al., 2019).

Table 1 represents the different soil tillage techniques used by researchers according to soil texture.

3.4 Planting structure

Row and plant spacing of quinoa crop were collected from the selected published literature and represented in Table 2. Results showed that quinoa was cultivated around the world in different crop structures. Row spacing varied between 15 and 100 cm and plant spacing varied between 2 and 60 cm. High row spacing was more suitable for mechanical weeding. The highest average quinoa yield, 5122 kg ha⁻¹, was obtained with 35 row to row spacing and 20 cm plant to plant spacing. However, 38% of the studied cases have evaluated quinoa cultivation with 50 cm row to row spacing.

3.5 Population density

Optimal planting rate varies according to climatic conditions and soil fertility (Asik et al., 2020). In China, quinoa grain yield increased by 27% with a planting density varying from 20 to 40 plants m⁻² (Wang et al., 2021). Plant densities in Colombia were lower, with quinoa grain yield decreasing by 38% from 7 to 16 plant m⁻² (Diaz et al., 2021). In another study conducted in Zimbabwe, quinoa grain yield increased from a plant density of 3 plants m⁻² to 6 plants m⁻²

TABLE 2 Quinoa grain yield (kg ha⁻¹) according to plant and row spacing.

		Row to row spacing (cm)														Average grain yield (kg ha ⁻¹)
		15	20	24	30	35	40	40,6	45	50	60	70	75	80	100	
Plant to plant spacing (cm)	2										1982					1982
	3				1788											1788
	4									3352						3352
	5		1055	2139	1733					3025						1988
	7	1907														1907
	8							482								482
	8						1596							3260		2428
	10					2127				2040		826				1664
	15				1403				1580	1789				4410		2296
	20					5122				1820				3555		3499
	25									998						998
	30									2592	877		1688			1719
	40									2327						2327
	45												488			488
	50						3829								1330	2580
	60											1802				1802
	Average grain yield (kg ha ⁻¹)	1907	1055	2139	1641	3693	1596	482	1580	2243	1554	826	1088	3742	1330	1777

then decreased with higher densities (Parwada et al., 2020). The plant density of 8 plants m⁻² seemed to be the optimal density for quinoa cultivation under Vietnam conditions (Minh et al., 2020).

3.6 Planting methods

Quinoa was planted in the peer-reviewed papers by different methods. Hand sowing in holes of 3 to 10 seeds per hole was the first reported method (Deng et al., 2021; González et al., 2021; Hirich et al., 2021). Mechanical sowing was also practiced for large areas in order to reduce the amount of labor and time needed for this operation (Matías et al., 2021). Quinoa was also planted in ridges, probably to increase the water infiltration, reduce runoff and hasten the plant growth (Hamza et al., 2021; Mansouri et al., 2021). Another method is to grow quinoa plants in the nursery during the first development stages and transplant it in the field when the climatic and soil conditions become suitable for its cultivation (Ludvigson et al., 2019).

3.7 Irrigation and water requirements

Water is one of the major limiting factors for crop production, especially in arid and semi-arid regions. Cultivating drought

tolerant crops, such as quinoa is important to valorize marginal soils and increase agricultural productivity. Quinoa water needs for optimal development and yield are low and estimated to 300-400 mm (Fghire et al., 2012). The response of quinoa to deficit irrigation was evaluated in Egypt using 100% ETc, 85% ETc and 65% ETc (Badran, 2022). Results showed that the highest yields, 1680, 1846, 1691, 1811 and 1800 kg ha⁻¹ were obtained under full irrigation (303 mm) with the cultivars L12, L14, Q3, Q5 and Chipaya, respectively. Applying 65% of ETc (197mm) resulted in a yield decrease of the same cultivars by 45, 36, 43, 40 and 33%, respectively. Quinoa gave higher yield (3993 kg ha⁻¹) in Morocco when receiving 356 mm of irrigation water (Fghire et al., 2021). Applying 50% ETc (140 mm) and 33% ETc (93 mm) reduced quinoa yields to 2500 and 1138 kg ha⁻¹, respectively. In Chile, quinoa grain yield increased with higher water application levels recording 583, 1356, 1375, 1919, 2294, 2250, 3055, 3112 and 3286 kg ha⁻¹ when receiving 25, 222, 280, 345, 369, 447, 505 and 537 mm, respectively (Pinto et al., 2021). In Iran, the average grain yield increased from 903 kg ha⁻¹ with the application of 354 mm to 1142 kg ha⁻¹ with 530 mm (Nadali et al., 2021). Higher water level (707 mm) resulted in a grain yield of 1409 kg ha⁻¹. When quinoa was conducted under rainfed conditions in India, there was no big difference between receiving 530 or 658 mm of rainwater, with yields reaching 5928 and 5814 kg ha⁻¹, respectively (Rathore and

Kumar, 2021). In Israel, quinoa yielded 2893 and 4521 kg ha⁻¹ with 364 and 420 mm of irrigation water, respectively (Asher et al., 2020).

Quinoa has high tolerance to water salinity up to 30 dS m⁻¹ (Peyghan et al., 2020). In this experiment, quinoa reached 3293, 3515 and 5360 kg ha⁻¹ with the application of 139, 208, and 278 mm. In Vietnam, quinoa recorded 1761 kg ha⁻¹ when the crop has received 866 mm (Minh et al., 2020). According to Salim and Hadeethi (2020), the average quinoa water requirement was estimated to be 231 mm. In Burkina Faso, quinoa grain yields were low and application of 246 and 410 mm resulted in similar yields, 635 and 631 kg ha⁻¹, respectively (Alvar-Beltrán et al., 2019). In addition, application of 250 mm of water in Greece resulted in a grain yield of 2283 kg ha⁻¹ (Kakabouki et al., 2019). Quinoa received higher amounts of water in an experiment conducted in Egypt with grain yields of 1480, 1855 and 2071 kg ha⁻¹ under 237, 550 and 820 mm irrigation water (Al-Nagggar et al., 2017).

Quinoa exhibits high tolerance to water stress during the vegetative growth, followed by flowering stage but a substantial loss of yield was noticed if the stress occurs during the seed filling (Hirich et al., 2012; Lavini et al., 2014). Water stress in the initial period can significantly increase the tolerance to drought during later phases (Oudou et al., 2019).

The drought tolerance of quinoa is attributed to morphological adaptations such as reducing leaf area and increasing root growth (Hirich et al., 2012; Lavini et al., 2014). Physiological adaptations are also noticed. Quinoa increases its antioxidant activity to cope with the reactive oxygen species (ROS) generated by water stress. The activity of the antioxidant enzyme superoxide dismutase (SOD) increased by 90% and 322.42% at 33% ETc and under rainfed conditions, respectively. The catalase (CAT) activity increased significantly by 87.4% under rainfed conditions when compared to full irrigation (Fghire et al., 2013). The plant also decreased its Leaf water potential, closed its stomata, increased the chlorophyll a and b content and had a great ability to repair them for rapid restoration of photosynthetic functions during post stress recovery (Oudou et al., 2019; Maestro-Gaitán et al., 2022). Anatomically, the plant increased the number of its stomata under stressed conditions in order to allow better control of transpiration (Oudou et al., 2019).

3.8 Fertilization

3.8.1 Nitrogen fertilization

Nitrogen (N) deficient quinoa plants exhibit pale green or yellow leaf color, small inflorescence, and grains with low protein content (Pando and Castellanos, 2016). Because of its structural role in the chlorophyll as well as in nucleic and amino acids composition, insufficient quantities of N result in very slow growth, stunted plant, and light green to yellow foliage color (Benton Jones, 2012).

For an optimum yield, quinoa internal N requirement, based on N content of total biomass at harvest, was estimated to 1.015% (Berti et al., 2000). In another study, quinoa absorbed approximately 2 kg N to produce 1 q of grain (Deza, 2018). In Germany, Schulte aufm Erley et al. (2005) declared that quinoa absorbed 4.6 kg N ha⁻¹ to produce 1 q of grain.

Quinoa can grow in soils with low fertility and is considered as a crop with low input requirement. Under moderate temperate condition of Denmark, a slight increase of quinoa yield of 24.1% was achieved when the N supply increased from 40 to 160 kg N ha⁻¹ and an increase of only 2.7% from 120 to 160 kg N ha⁻¹ (Jacobsen et al., 1994). In a silty-clay loam soil under Mediterranean climatic conditions, N at 150 kg ha⁻¹ was proved to be the best level for N supplementation for grain yield of 2950 kg ha⁻¹, being increased by 357% compared to the control (Geren, 2015). Related results were obtained by Almadini et al. (2019) when evaluating the response of quinoa to N fertilization levels from 0 to 160 kg N ha⁻¹. N at 160 kg ha⁻¹ enhanced vegetative growth and increased yield by 759.6% compared to the control. Schulte aufm Erley et al. (2005) indicated that grain yield of quinoa (3495 kg ha⁻¹) was enhanced by 194% at the highest N rate (120 kg ha⁻¹). In Burkina Faso, application of 100 kg N ha⁻¹ increased quinoa grain yield by 37%, reaching 1380 kg ha⁻¹ (Abdolahpour et al., 2021). In Iran, 100 kg N ha⁻¹ seemed to be the optimal N rate producing 2790 kg ha⁻¹ (Keshtkar et al., 2022). Under arid conditions in Syria, N fertilization at 90 kg N ha⁻¹ resulted in the highest grain yield (5320 kg ha⁻¹) whereas higher N rates decreased quinoa grain yield. In Iraq, the grain yield of quinoa increased with N application rates up to 120 kg N ha⁻¹ and decreased with higher N rates (Salim et al., 2019).

High fertilization rates are recommended with high potential cultivars and optimal environmental conditions. In fact, water availability increases quinoa nitrogen uptake (Wang et al., 2020). According to Berti et al. (2000), quinoa grain yield increased with N fertilization up to 225 kg ha⁻¹ producing 2268 and 3555 kg ha⁻¹ of grain yield with the cultivars FARO and UDEC10, respectively. Shams (2011) also tested the response of quinoa to higher N rates in sandy soils. He found that maximum economic yield 1145 kg ha⁻¹, was achieved by application of 360 kg ha⁻¹, being almost eleven times over control. In Greece, 200 kg N ha⁻¹ increased quinoa grain yield with only 14% (Kakabouki et al., 2019). In Denmark, quinoa responded positively to the highest N application rate (180 kg N ha⁻¹) with a yield increase of 25%.

Because of its high mobility in the soil, N should be split to ensure high utilization efficiency. Partitioning of nitrogen fertilization depends mainly on soil type and climatic conditions. N application time differed in the reviewed papers. In Argentina, 20% of N rate was applied before planting and 80% at 30-35 days after emergence (Mez MB et al., 2011; Curti et al., 2014). Similarly in Baghdad, N was split into two equal rates and applied before planting and at branching stage (Salim et al., 2019). In Brazil, 40% of total N was applied before planting and 60% at 40 days after emergence (Spehar and da Silva Rocha, 2010).

Generally, N fertilization affected negatively the N use efficiency (NUE) and the application of N rates higher than 100 kg N ha⁻¹ did not increase the NUE (Kakabouki et al., 2019). The highest NUE of 13.92 kg kg⁻¹ was recorded with the lowest N rate 75 kg ha⁻¹ (Berti et al., 2000). In agreement with that, Almadini et al. (2019) reported that N fertilization and NUE have an inverse relationship, with highest value recorded at 80 kg N ha⁻¹. Related results were found by Shams (2011) where application of 90 kg N ha⁻¹ corresponded to maximum NUE. This parameter also differs among quinoa cultivars. Deza (2018) recorded that LM

89-77 genotype had the highest NUE with 46.02 kg of grain per kg of applied N.

3.8.2 Phosphorus fertilization

Unlike N, studies evaluating phosphorus (P) nutrition of quinoa were scarce. Phosphorus deficiency was manifested by dark green or red tips of leaves (Pando and Castellanos, 2016). It reduces plant height, delayed flowering and ripening with small and twisted inflorescences and very small or poorly developed grains (Pando and Castellanos, 2016). P deficient quinoa plants display necrosis of the lower leaves, and the upper leaves became pale green (Sales et al., 2021).

The evaluation of quinoa P requirements showed that quinoa needs 3.7 kg P₂O₅ to produce 1 ton of biomass (Alvar-Beltrán et al., 2019). The high demand of this crop in P requires an adequate fertilization to attain high yields. Llaca Ninaja (2014) studied the effect of four P rates 0, 40, 80 and 120 kg P₂O₅ ha⁻¹ and found that 88 kg P₂O₅ ha⁻¹ was the optimal level to obtain 2890 kg ha⁻¹. Higher P rates reduced quinoa yield. In another study, increasing P rate from 90 to 180 kg P₂O₅ ha⁻¹ did not significantly affect growth characteristics and yield of quinoa, with an average of 4101 kg ha⁻¹ (Quispe and León, 2018).

Plants need P in early stages of development to build good root system. For this reason, P was applied at sowing in all studied cases, except when the P was applied with water in the irrigation system.

3.8.3 Potassium fertilization

Potassium (K) deficiency is manifested by poor root system and weak stems (Pando and Castellanos, 2016). It is also found that this deficiency is observed with chlorosis at the margins of older leaves followed by necrosis (Sales et al., 2021).

In terms of K requirements, quinoa needs 4.3 kg K₂O to produce 1 q of quinoa biomass (Alvar-Beltrán et al., 2019). This indicated how much quinoa is demanding in K and adequate fertilization is necessary to fulfill the crop needs and enhance quinoa yields. Despite the importance of this nutrient, research studying the response of quinoa to K was scarce and optimal fertilization program should be established for this crop.

3.9 Organic amendment

Quinoa strongly responded to organic fertilizers. The amendment did not only improve yields, but also enhanced soil structure and fertility (Mujica et al., 2001). The combination of three types of biofertilizers (Manure at 36 t ha⁻¹; biol at 600 l ha⁻¹ and nitrifying bacteria at 108 UFC) ameliorated vegetative growth of quinoa and resulted in high yield of 2445 kg ha⁻¹, being 7 times over the control (Neyra, 2014).

Organic matter also acts as water retaining agent, facilitates the dissolution and the absorption of other applied minerals and thus enhances the quality of the seeds (proteins, carbohydrates, and fats content) (García-Parra et al., 2018). The application of organic fertilizers (4 q ha⁻¹) along with mineral fertilizers (45-45-45 kg ha⁻¹ NPK) resulted in the highest yield (2280 kg ha⁻¹) (García-Parra et al., 2017). This is due to maintaining the balance between organic and chemical fertilizers and increasing the availability of nutrients throughout the productive cycle of the plant.

Organic matter enhances the water holding capacity of the soil, improves its structure, facilitates the soil aeration and favor the development of microbial flora for a prompt humification (Mujica and Jacobsen, 1999). Osco Limachi (2009) points out that increasing levels of sheep manure up to 12 t ha⁻¹ favored the growth and development of the plant and improved the physical characteristics of the soil by avoiding its compaction and maintaining its humidity. However, 8 t ha⁻¹ of sheep manure was considered the optimal rate for obtaining an economic yield of 2300 kg ha⁻¹.

We summarized in Table 3 all the reviewed research papers evaluating the effect of organic amendment on quinoa grain yield, and we presented them according to locations. In Iran, quinoa responded positively to the application of organic manure with yield increasing by 23% compared to the control. Some organic amendments slightly decreased quinoa grain yield. This may be due to field heterogeneity or nitrogen immobilization by soil organisms, which make nitrogen unavailable to crops. Thus, adequate amendment management is important for enhancing soil quality and increasing crop yields. In addition, the phosphogypsum was 7 tested as an amendment and its effect on quinoa grain yield was highly significant, with an increase from 1940 kg ha⁻¹ with no application to 2670 kg ha⁻¹ with 9 t ha⁻¹ of phosphogypsum. Different studies evaluating manure and compost effect on quinoa growth and yield were found. The highest yield was recorded with the application of 10 t ha⁻¹ of compost. In addition, the vermicompost highly affected quinoa grain yield in India and applying 5 t ha⁻¹ increased yield by 28%.

3.10 Weed control

Weed management in quinoa cultivation is the most difficult operation, because at present, it is almost done manually. The absence of chemical treatments makes the weeding operation expensive and represents a large part of quinoa production costs. The development of weed control techniques and the identification of adequate herbicides is a necessity for the development of the cultivation techniques of this crop. In the reviewed literature, weeds were controlled by hand or using manual tools. The frequency of these operations differed from once a week to once during the growing season (Table 4).

Applying herbicides during the previous cropping season to the cultivation of quinoa may also cause harmful effects on the seedling. Results showed that applying Imazaquin had negative effect on quinoa seedling even after 206 days of its application, followed by clomazone applied before 15-38 days. However, trifluralin and pendimethalin had no residual effect (Santos et al., 2003).

3.11 Pests and diseases

Several insects were reported to be associated with quinoa crop in the Andes, some of them can highly reduce the yield and result in considerable economic losses. On the other hand, several natural enemies were also observed in quinoa, and they can be used in the

TABLE 3 Effect of organic amendment on quinoa grain yield around the world.

Location	Organic amendment	Quinoa grain Yield (kg ha ⁻¹)	References
Iran	Control	2534	Fatemi Kiyani et al. (2022)
	10 t ha ⁻¹ of livestock manure	3225	
	20 t ha ⁻¹ of livestock manure	3279	
Italy	Control	844	Alvar-Beltrán et al. (2022)
	50 kg ha ⁻¹ of Digestate	750	
	100 kg ha ⁻¹ of Digestate	792	
Egypt	Control	1940	El-Shamy et al. (2022)
	9 t ha ⁻¹ of phosphogypsum	2670	
Morocco	Control	2900	Toubali et al. (2022)
	10 t ha ⁻¹ of Compost	4200	
Morocco	Control	2680	Hirich et al. (2021)
	5 t ha ⁻¹ of compost	2220	
	10 t ha ⁻¹ of compost	2240	
	20 t ha ⁻¹ of compost	2355	
	10 t ha ⁻¹ of manure	2405	
	20 t ha ⁻¹ of manure	2365	
	40 t ha ⁻¹ of manure	3500	
Morocco	10 t ha ⁻¹ of olive mill waste compost	2650	Hirich et al. (2014b)
	5 t ha ⁻¹ of olive mill waste compost	2450	
	Control	2300	
India	Control	4875	Rathore and Kumar (2021)
	2,5 t ha ⁻¹ of vermicompost	6075	
	5 t ha ⁻¹ of vermicompost	6775	
Zimbabwe	0 t ha ⁻¹ cattle manure	272	Parwada et al. (2020)
	18 t ha ⁻¹ of cattle manure	494	
	9 t ha ⁻¹ of cattle manure	833	

biological control of this crop (Yabar et al., 2002). Quinoa shoots were subjected to sapsuckers (Aphididae, Cicadellidae), leaf miners (Agromyzidae), and chewing insects attack (Yabar et al., 2002). Studies showed that the insect attacks were abundant in the early season of quinoa cultivation (Yabar et al., 2002). In the Andes, the temporal dynamic of Aphididae population recorded two peaks, at the beginning and at the end of the growing season (Yabar et al., 2002). The low abundance of this enemy in the mid-season was probably associated with the peak of Coccinellidae population, which resemble the traditional predator-prey dynamics (Hassell, 1978). Braconidae and chrysopterid larvae were also reported to be the enemy of aphids (Mackauer and Volk, 1993; Cruces et al., 2020). Chemical control of aphids using methomyl + dimethoate was efficient to control the Aphididae (Cruces et al., 2020).

During the process of quinoa adaptation to the environmental conditions of Europe, it was attacked by several insects native to this continent (Sigsgaard et al., 2008). Heavy attacks of *Scrobipalpa*

atriplicella in the maturing inflorescence of quinoa and *Cassida nebulosa* in Denmark were reported as serious problems (Sigsgaard et al., 2008). In the Mediterranean basin, *Nysius cymoides* constitutes a polyphagous species that sucks plant sap and may cause high economic losses (Rivnay, 1962). This bug attacks the inflorescence and pods when seeds are in the milky stage (Rivnay, 1962).

Quinoa moth, *Eurysacca melanocampta*, was detected in Argentina, Bolivia and Peru (Rasmussen et al., 2003; Cruces et al., 2020). The economic threshold level was found to be three to 15 larvae per plant (Villanueva, 1978; Blanco, 1994). In higher infestation levels, this insect was controlled with emamectin benzoate + methomyl, leading to its suppression in the field. The biological management using sprays of *Bacillus thuringiensis* var. *kurstaki* to control low population of this insect was less effective (Cruces et al., 2020). The caterpillars infested the plants 43 days after planting.

TABLE 4 Weed control methods of quinoa crop.

Weeding method	Reference
Weed were controlled manually	Nadali et al. (2021); Hamza et al. (2021); Thiam et al. (2021); Hussain et al. (2018); Lesjak and Calderini (2017); Lavini et al. (2014); Garrido et al. (2013); Pulvento et al. (2012); Mez MB et al. (2011); Martínez et al. (2009)
Broadleaved weeds and grasses were controlled with glyphosate (N-phosphonomethyl glycine) in preemergence, applying 0.96 a.i. l ha ⁻¹	Pinto et al. (2021); Valdivia-Cea et al. (2021)
Hand hoeing was done once after emergence and fluzifop-p-butyl (500 g ha ⁻¹ of a.i.) was applied at 3-5 leaf stage of quinoa crop to control narrow leafed weeds	Geren (2015)
Weeds were removed manually once during the growing period	Asher et al. (2020)
Weeds were controlled manually twice until the peak of flowering stage	Isobe et al. (2021)
Weed were controlled manually 3 times during the growing period	Hirich et al. (2021)
Weed were controlled manually at an interval of 15 days	Rathore and Kumar (2021)
Weeding was done manually approximately once a week	Razzaghi et al. (2020)
Weed were controlled manually at the early stages when the plants were growing slowly	Mansouri et al. (2021)
Weed removal was carried out manually every 3-4 weeks	Alvar-Beltrán et al. (2019)
Weed were controlled manually at 4-6 leaf and the second when the plant has 30 cm	Ji-kai et al. (2019)
Weeds were removed manually 30 days after sowing	Iqbal et al. (2018)
Weeds were controlled by hand hoeing and when needed and before canopy closure	Kakabouki et al. (2019)
Weed were controlled by hoeing one month after the sowing	Altuner (2019)
Weed were controlled manually twice, 35 and 55 Days After Emergence	Casini (2019)
Weed were controlled manually 30 days after sowing	Bilalis et al. (2012)

Birds attack is a serious problem in quinoa cultivation and can cause potential damage to the crop with losses up to 60% (Rasmussen et al., 2003). In the Peruvian highlands, *Patagioenas maculosa*, *Zenaida auriculata*, *Sicalis uropygialis*, and *Zonotrichia capensis* are the major observed bird species and they attack quinoa seeds from the milky stage to physiological maturity (Loza et al., 2016). Birds attack quinoa in the early morning, in the mid-day and in the afternoon (Loza et al., 2016).

Concerning quinoa diseases, downy mildew, caused by *Peronospora farinose*, is the most damaging disease of quinoa and may reduce yield by 20 to 99% (Alandia et al., 1979; Danielsen and Munk, 2004). This disease has been reported in all areas of quinoa cultivation, and it causes chlorotic lesions on the upper leaf surface and grays spores' development on the lower leaf surface, an often leading to early defoliation (Danielsen et al., 2002; Choi et al., 2014). These lesions may turn to reddish and purple in some cultivars and may develop to small necrotic flecks in hypersensitive cultivars (Danielsen et al., 2003). Downy mildew is seed transmitted and the presence of free water and RH>85% are optimal conditions for the development of the causal pathogen of downy mildew (Danielsen et al., 2003; Danielsen et al., 2004). To control this disease, metalaxyl fungicide are used as the traditional control method. However, attention should be paid to the environmental and human risks and

to the possibility of resistance development by this pathogen (Danielsen et al., 2003).

Quinoa Anthracnose caused by *Colletotrichum nigrum* and *C. truncatum* were observed in the United State in 2009. This disease causes stem bleach to dark lesions, oval to linear with slightly tapered tips and may cause stem lodging (Pal and Testen, 2021). Other quinoa diseases, probably of minor importance as quinoa production constraints, were reported around the world. These reports include: Rhizoctonia damping off and Fusarium wilt in Peru and Italy, seed rot and damping off in the United State, damping off in Japan and leaf spot and brown stalk rot in the Andean region of South America (Bechman and Finch, 1980; Barboza et al., 2000; Ikeda and Ichitani, 1985; Boerema et al., 1977; Otazu and Salas, 1977; Beccari et al., 2021).

Leaf spot of quinoa, caused by *Ascochyta hyalospora*, is transmitted by the seed (Danielsen et al., 2003). The symptoms of this disease include circular spots with light color and light brown edges. The spots may develop to necrotic black pycnidia visible to the naked eyes (Boerema et al., 1977; Alandia et al., 1979). Quinoa may lose its foliage in high infestation cases (Danielsen et al., 2003). The geographic distribution of this disease is not known, and it is not considered a major constraint to quinoa production.

Brown Stalk Rot is another quinoa disease caused by *Phoma exigua* var. *foveata* and it was reported for the first time in Peru (Otazu and Salas, 1977). The symptoms of this disease include lesions in the stem and inflorescence, chlorosis in the leaves and the stem bends downward and become easily fracturable (Danielsen et al., 2003). This disease is transmitted to the crop from the soil when the plant is injured and it develops rapidly with low temperature and high humidity (Danielsen et al., 2003).

Seed Rot and Damping Off of quinoa caused by *Sclerotium rolfsii* and *Pythium* were reported for the first time in California. Plants affected by this disease display stem girdling, and collapse appeared in erratic areas in the field (Danielsen et al., 2003).

Leaf spot caused by *Pseudomonas syringae*, a pathogenic bacterium, was observed in Colombia in 2020 (Fonseca-Guerra et al., 2021). This disease causes considerable yield losses and induces the formation of apical necrosis and dark brown spots (Fonseca-Guerra et al., 2021). Lesions in the stem giving a vitreous appearance and smooth consistency were also reported (Fonseca-Guerra et al., 2021).

Nacobbus aberrans and *Thecavermiculatus andinus* are two parasitoid nematode that attack quinoa in the Andean region (Franco, 2003). The first enemy, *N. aberrans*, also referred to as False Root Knot nematode causes quinoa roots nodules that contained the females along with protruding gelatinous matrix containing the eggs (Franco, 2003). This pathogen can cause considerable yield loss of quinoa (Franco, 2003). The second nematode, *T. andinus* is commonly known as the “nematode of the oca” (Astocaza and Franco, 1983). It was observed surrounding Lake Titicaca and negatively affected vegetative development and quinoa grain yield (Franco, 2003).

3.12 Harvest and post-harvest

Various postharvest operations, and the combination of several, have been developed to act on the quinoa seeds, to prepare them for processing procedures taking place at a later stage. This section aims to describe the main harvest and post-harvest operations and their influence potential on the quinoa quality as referred to universal standards. This assessment is based on the comparison of composition profile before and after the concerned operation procedure.

At harvest time, the leaves of quinoa plants turn to yellow or red depending on the variety (Garcia et al., 2015). It is crucial to determine the optimal harvest time of quinoa crop, because quinoa grains start to drop from the panicle when quinoa plants exceed maturity (Garcia et al., 2015). It is assumed that physiological maturity is attained when the seeds can be seen in the panicle through the opening of the perigonium (Aroni, 2005), or when the grains fall out when taping the panicle with the hand. Harvest can be done manually using a sickle and cutting the plant 10–15 cm above the soil (Garcia et al., 2015). However, it was found difficult to cut the quinoa plants because of their thick stems and pulling out the plants is preferred and commonly used by farmers. This method is labor consuming and high harvest losses are expected.

After the harvest, natural drying of quinoa plants can be done in the field and threshing can be done manually or mechanically (Salas, 2003). From a commercial requirement, additional ventilation can be carried out to reduce the grain moisture under 10% (Garcia et al., 2015).

Quinoa contains antinutritional compounds such as saponins (Mora-Ocación et al., 2022). They present a wide group of glycosides found in different plants and play an important role in protecting seeds from insect and fungal attack (Simmonds, 1965). They are normally found in a range of 0.1% to 5% (Chaudhary et al., 2023) and are located in out layer of the seed. These compounds confer to quinoa bitter taste but are easily removable through washing process as they are hydrosoluble. The procedure of washing quinoa grains hold not only hygienic importance, but also further ensures the reduction of saponin content and elimination of bitterness associated with saponins. Traditional process of washing involves the soaking of the quinoa seeds, which permits the water-soluble saponin to be washed away (Shi et al., 2009; Quispe-Fuentes et al., 2012). However, this procedure demands the use of significant amounts of water that make disposal of wastewater an issue, and may raise pollution concerns (Taylor and Parker, 2002; Repo-Carrasco et al., 2003; Rafik et al., 2021a). There is also high cost associated with subsequent drying of the product (Repo-Carrasco et al., 2003). Additionally, inefficiency in saponin removal by washing has also been mentioned (Quispe-Fuentes et al., 2012; Carrasco et al., 2021). However, improper technologies can cause poor grain germination, fungi and mold damage, and color and odor change. The combined method of abrasive dehulling and washing together has been suggested as an effective way to address the issues listed above while achieving efficient saponin removal, during which the quinoa grains are quickly burnished and briefly washed, to minimize the loss of nutrients, lower the cost of drying, and lower the saponin content in the wastewater (Repo-Carrasco et al., 2003; Rafik et al., 2021a).

The saponin of quinoa grains can be removed by mechanical pearling (Rafik et al., 2021b). Pearling, which is also referred to as debranning, has yet to be properly and specifically characterized for quinoa, but the technology has been developed to wheat kernels and other cereal grains in order to remove the outer layer through a frictional and abrasion force (D'Amico et al., 2019). It has been suggested that insignificant change has been detected in the macronutrient content of the pearled grains, micronutrient alongside antioxidant capacity are altered significantly in quinoa grains after the pearling process depending on the extent of pearling (D'Amico et al., 2019; Jiang et al., 2021; Rafik et al., 2021a). One of which such change is the reduction of the bitter antinutritional compound saponin to an acceptable level of palatability and digestibility, that is achieved through mechanical pearling as compared to manual abrasion (Mhada et al., 2020; Jiang et al., 2021; Rafik et al., 2021a). It has been found that pearling quinoa at a degree of 30% reduced the saponin by 79% compared with the original whole quinoa (Gómez-Caravaca et al., 2014). Another study has stated that depending on the quinoa variety, the total saponin content has been reduced from a starting range of 0.37% to 0.57% to merely 0.07 to 0.1%, with a pearling duration of two minutes (Rafik et al., 2021b).

4 Conclusion and recommendations

Quinoa is a promising alternative crop to cereals in arid and saline environments. It has gained considerable interest, especially from health-conscious consumers, because of its high nutritional value. The increasing demand for quinoa along with limited agricultural resources urges developing technologies to increase yield and productivity. The Andean region, especially Bolivia and Peru, is the center of origin of quinoa. However, quinoa has high genetic variability and plasticity, which make its cultivation possible in a large range of environments. Making quinoa more popular would require dissemination of information about the crop among farmers as well as consumers. The present study helps identifying adapted quinoa genotypes and assesses their performances in different countries around the world. Results showed that quinoa can be successfully cultivated in Africa, Europe, Asia, North American and Australia. Quinoa production techniques differed according to the area of its introduction. The sowing times markedly differ from one location to another, and the optimal date was determined in each region in order to escape harsh environmental conditions, especially drought, heat, and frost. Additionally, plant thinning is required to avoid intraspecific competition. If planted in rows, it is recommended that quinoa plants should be spaced by 20 cm with a row to row spacing of 35 cm. Early weeding (\pm 30 days after sowing) is important in quinoa fields in order to reduce plants competition for limited nutrients. Additional weeding associated with high level of weed infestation is recommended before quinoa canopy closure. Weeding is almost done manually, and further research is needed to develop adapted chemical techniques in order to optimize quinoa production. To ensure an adequate nutrient supply for quinoa, a good balance of nutrients in the soil should be maintained. Quinoa needs 2 to 4.6 kg of N to produce 1q of grain yield. In terms of P and K, quinoa needs 3.7 kg P₂O₅ and 4.3 kg K₂O to produce 1 ton of total biomass. Quinoa has low water requirements, and it is a suitable crop for arid and semi-arid regions. However, drought tolerance is often translated to low yields because quinoa sacrifices yield in order to survive and adapt. Under this consideration, several research studied the impact of irrigation on quinoa performance and deficit irrigation is shown to be highly beneficial

in various experimental location. Although quinoa can withstand harsh growth conditions, pests such as birds, insects, and several diseases caused by fungi, bacteria, nematodes, and viruses can cause significant yield losses. Quinoa is an interesting cash crop and had a great potential to enhance the livelihood of smallholder farmers in marginal areas. Our work represents the first review paper identifying the adequate agronomic practices for quinoa cultivation worldwide.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

NT, MG, KM, RC-A, AO, and RB contributed to the conception and design of the manuscript. NT, SR, and RC-A collected and organized the data. NT and SR wrote the first draft of the manuscript. All authors contributed to the manuscript revision, read, and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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