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Diversity of the Biological and Proteinogenic Characteristics of Quinoa Genotypes as a Multi-Purpose Crop

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Abstract: Quinoa is a multi-purpose vegetable, grain, and forage crop, due in part to the high nutritional value of its aerial parts. This work evaluates quinoa genotype characteristics as a starting point for a better understanding of multi-purpose cultivation. Ten cultivars of quinoa were studied on soddy-podzolic soils: Brightest Brilliant, Red Faro, and Cherry Vanilla from the US (USA 1–3); Titicaca (KY1) from Denmark; Regalo (KY2), a cultivar selected by the Baer Seed Research Center for southern Chile; as well as Q1–Q5, UAE cultivars of various ecological and geographical origins. Quinoa plants were divided into three parts (lower, middle, and upper). The Q3 and Q4 cultivars produced the maximum fresh weight (38.7 g and 35.4 g, respectively) and dry matter (5.6 g and 5.3 g, respectively). The leaf mass and stems comprised 25% and 75% of the lower parts, versus 50–60% and 40–50% of the middle parts, respectively. Stems made up about 15% of the upper parts. The KY1 and Q5 cultivars produced the highest results (4.08 and 4.23 g, respectively). Protein concentrations of the quinoa grains were relatively high, with up to 14.0% grain protein in the USA2 cultivars. Leucine and isoleucine were the most abundant amino acids in quinoa grains, ranging from 6.7 to 9.2 g/100 g of protein. In contrast, methionine was the least abundant amino acid with less than 1.5 g/100 g of protein.

Keywords: quinoa genotypes; leafy vegetable; grain yield; forage; protein; amino acids

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1. Introduction

Quinoa (*Chenopodium quinoa* L.) is a herbaceous annual dicotyledonous plant belonging to the family *Amaranthaceae*, which also includes *Beta vulgaris* and *Spinacia oleracea*. Quinoa has been cultivated as a leafy vegetable, fodder source, and subsidiary grain crop in various world regions [1,2]. The grains are considered to make up a highly nutritious diet [3] due to their high levels of protein and essential amino acids [4,5]. Due to their abundant and affordable sources of vitamin C, protein, and pigments, the quinoa leaves are commonly used as a vegetable in human meals and for feeding cattle [6,7], while the grains provide an adequate supply of protein, minerals, and vitamins [8]. The plant originated on the Peruvian–Bolivian border. In these regions, quinoa represented an essential nutritional source for the Andean residents for thousands of years [6]. It was also valued for its tolerance and ability to grow under abiotic stresses in various agroecological environments [7] and adverse environmental conditions, such as salinity [8], drought, and frost [9,10]. This wide geographical distribution testifies to the remarkable adaptability of this species, which has had to develop various defence mechanisms to resist a wide range of environmental stresses [11–13]. In particular, the growing appeal, since 2013 as the

"Year of Quinoa," in "developed" countries for dietary, organic, or "fair trade" products, combined with the development of an organic quinoa supply chain, continues to drive increasing demand.

The countries that certified quinoa crop cultivation increased dramatically by more than three times (307%) in 2018, compared to 2010 [11]. Due to its superior nutritional content, compared to that of other cereals, quinoa is gaining in popularity around the globe. Generally, the yield of quinoa grains varies according to agroecological conditions. Data has been obtained from Iran (0.16–1.56 t/ha), Egypt (0.41–3.87 t/ha) [12], Morocco (0.84 t/ha) [13], Italy (0.11 t/ha–3.05 t/ha) [14], and Europe (1–3 t/ha) [15]. In particular, quinoa has been studied for its high content of protein, containing amino acids, minerals (K, Fe, Ca, Mn), saponins, dietary fibre, starch, and vitamins, but also its likely beneficial effects on health [16,17]. Quinoa's average protein content (15%) is greater than that of the most common cereals, such as rice (7.9%), barley (12.5%), or corn (9.4%); it is equivalent to that of wheat (13.7%). Conversely, this content is lower than the grains of certain legumes, such as beans (23.6%). Quinoa genotypes that can be successfully grown in areas outside the plant's naturalized area may provide an opportunity to boost agro-biodiversity and face increasing consumer demand [18].

Quinoa is a gluten-free food, therefore allowing the prevention of several diseases; it boosts the immune system and lowers cholesterol, blood pressure, and the risk of heart disease. It also prevents stroke and colon cancer [19]. Quinoa is used in various food, pharmaceutical, and cosmetic industries, hence the high demand for the product in international markets. It can also be used as fodder to feed animals, including poultry [20]. Recently, quinoa has also been cultivated for forage due to the high nutritional value of the different plant parts for livestock [21]. Quinoa residues have been used for feeding farm animals, including poultry [22], and the plant represents a valuable forage source for dairy farms, resulting in good milk quality and quantity [23]; whereas dry matter represents 19% of the whole quinoa, and this percentage (dry matter) has about 24% crude protein that enhances food quality [24].

In 2014, Russian scientists conducted the first trials of quinoa growing in the Krasnodar Territory in southern Russia [25], and then quinoa was registered in the Russian State Register of Breeding Achievements in 2017. In 2019, according to Russian foreign trade statistics, about 1.13 thousand tons of quinoa grains were imported into the country, representing $2.85 million, from Peru (98%), Spain (0.9%), and Italy (0.2%). Screening crop genotypes by researchers before releasing them to farmers still represents an effective method for selecting the appropriate cultivars based on the observed variations [26].

The current scenario necessitates screening a wide range of genotypes in order to identify the suitable cultivars before popularisation. However, the introduction and possibility of growing this crop on the territory of Russia is a promising and sought-after direction. Thus, this investigation hypothesizes that quinoa would be an effective, sustainable multi-purpose crop for the Russian Federation. To evaluate this hypothesis, we studied the impact of quinoa cultivation, as a grain-producing and feeding crop, by assessing the characteristics of ten genotypes, including fresh weight, dry matter, grain quantity, and quality.

2. Materials and Methods

2.1. Experimental Site and Design

Ten quinoa cultivars with various ecological and geographic origins were grown on moraine loam in soddy, weakly podzolic medium-loamy soil. The thickness of the arable horizon was 20–22 cm (humus 2.0–2.2%; P_2O_5 230–250 mg; K_2O/kg 105–115 mg; pH −5.5). Groundwater was present at a depth of more than 3 m. Experimental data were obtained under the conditions of a small-plot field experiment. Quinoa seeds (45 × 10 cm) were sowed manually in mid-May at a depth of 1.3–1.5 cm. The experimental design consisted of a randomized complete block design (RCBD) with four replicates. Data were subjected

to analyses of variance using a one-way ANOVA ($p < 0.05$), using MINITAB v. 19 [27]. The results are expressed as mean ± SD obtained for differences between genotypes.

2.2. Plant Materials and plot Preparation

Ten commercial quinoa accessions were studied: Titicaca (KY1) from Denmark; Regalo (KY2), a cultivar selected by the Baer Seed Research Center for southern Chile; Q1-Q5 from the United Arab Emirates; and Brightest Brilliant, Red Faro, and Cherry Vanilla from the US (USA 1–3). The cultivation of several genotypes allowed for quantifying the intraspecific variability in temperature and photoperiodic responses and their interactions. The quinoa accessions were sown in mid-May 2019 and 2020. The average daily air temperatures during both growing seasons were similar (Figure 1). The sowing density was a 45 × 10 cm scheme (~222,000 plant/hectare). Fertilizers and pesticides were not applied in the experimental field.

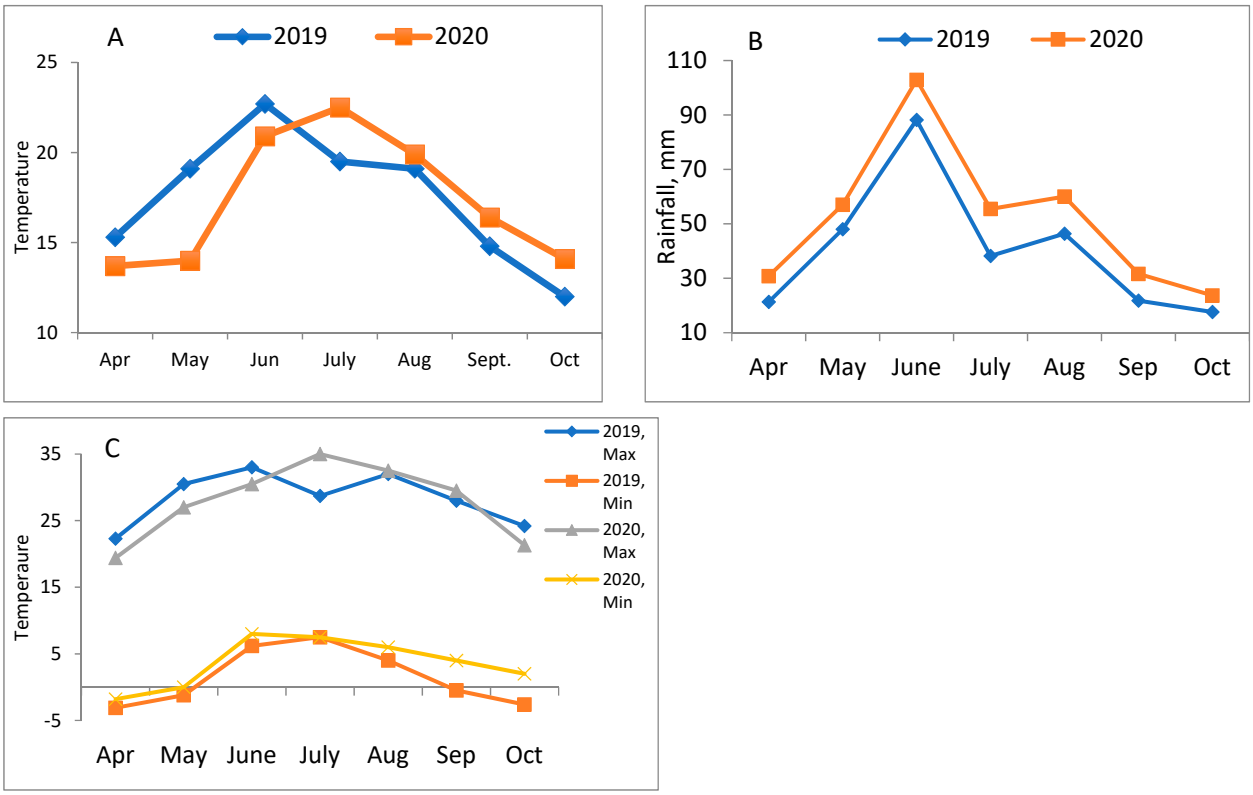

Figure 1. Meteorological conditions (temperature and rainfall) of the growing seasons (2019–2020) in the central region of the Russian Federation (Michelson Observatory, Moscow). (**A**) Average tem-perature; (**B**) average rainfall; (**C**) maximum and minimum temperature.

2.3. Growth and Productivity Characteristics

For a clear understanding and comparison, the biological and proteinogenic characteristics of the quinoa plant biomass and dry matter, including panicle weight (g), leaf weight (g), and stem weight (g), were determined at the beginning of the flowering stage. Dry matter content was determined by drying the samples at 60 °C until a constant sample weight was obtained. The panicle size, number of grains per inflorescence, grain weight per panicle (g), and average seed weight (1000 seeds) in each replicate were determined [28,29], and the quinoa crop per hectare (t ha^{-1}) rate was determined. For all quinoa genotypes, different grain yield parameters were recorded on ten randomly selected plants and plots, depending on the traits measured. Seeds were obtained from each of the ten tagged plants and dried to around 8.0% moisture content; they were then weighed and counted with a seed counter (Wintersteiger SEED COUNTER S 25+). Their weight was then measured. The

germination percentage (capacity) and germination energy were calculated in a separate laboratory experiment that follows.

Germination percentage was calculated [30] as follows:

$$(\mathrm{GP}) = \frac{\text{Germinated seeds}}{\text{total seeds}} \times 100$$

Germination energy (GE) was calculated for the first five days [31,32] as follows:

$$\mathrm{GE} = \frac{\text{Germinated seeds}}{\text{Total seeds}} \times 100$$

2.4. Determination of Amino Acids and Protein Contents in Quinoa Grains

To measure the amino acids (AAs) in the quinoa grains, 0.1 N HCl was added to a 1 g fresh sample, which was then homogenized and incubated at 4 °C for 12 h. After that, samples were centrifuged at 1200 rpm for 50 min, and supernatants were filtered through 0.22 µm. The supernatants were then transferred to vials for amino acid analysis in HPLC [33–35]. Briefly, Zorbax Eclipse-AAA 4.6 × 150 mm and 3.5 µm columns (Agilent 1200 HPLC) were used; the reading was obtained at 254 nm, and the AAs were determined by comparison with the standards O-phthaldialdehyde (OPA), fluorenylmethylchloroformate (FMOC), and 0.4 N Borate. The following were used as the mobile phase chromatography system: mobile phase A, 40 mM NaH_2PO_4 (pH-7.8); and mobile phase B, Acetonitrile/Methanol/Water (45/45/10, $v/v/v$) solutions. The flow rate of the mobile phase moved through the system at 2 mL min^{-1}, and the column temperature was 40 °C [31]. Valine, methionine, phenylalanine, isoleucine and leucine, lysine, and threonine were determined as g/100 g protein.

3. Results

Quinoa Growth Characteristics

The cultivated plants were divided into three parts (upper, medium, and lower) to understand the differences of formation biomass and dry matter among quinoa genotypes. The data (Table 1) show significant differences among quinoa genotypes. The data illustrate the accumulation of quinoa upper parts (panicle, leaves, stem, and total).

The highest panicle fresh weight (FW) was accumulated in Q3 with more than 1.422 g of biomass and 0.234 g of dry weight (DW). The Q3 cultivar recorded the heaviest biomass stem weight, while Q5 recorded the highest DW. Generally, the maximum result of the total FW (9.017 g) and DM (1.497 g) was obtained from Q3 and Q5, respectively, while the minimum results (FW-3.712 g and DW-0.644 g) were observed in USA1 and USA2, respectively. The percentage of dry matter of the upper parts (compared to the total) of quinoa genotypes varied from 13.4 in USA2 to 20.7% in Q5. Table 2 shows the fresh weight and dry matter of quinoa plants' middle parts; the highest volumes of DM from leaves (14.1 and 14.8%) were obtained from Q3 and Q4, respectively. The minor FW of leaves (4.58 g) was observed from USA2, and the DM represented 12.2%. In contrast, the lowest DM percentage (7.0%) was registered in Q2. The data from stems of quinoa genotypes indicate that the DM percentages ranged from 8.0% in USA1 to 12.0% in Q4.

The maximum FW (9.79 g) and DM (1.12 g) amounts in the middle stems were observed in the Q3 genotypes. In total, the Q4 genotypes gave the highest weights of FW (17.08 g) and DM (2.32 g), representing 13.6% as dry matter. The lowest fresh weight (7.83 g) and dry matter (0.86 g) amounts of the total middle parts of the studied genotypes were obtained from USA2. The data presented in Table 3 illustrate the fresh weight and dry matter of the lower parts of the quinoa plants; the highest DM percentages of leaves (19%) were attained from KY2, despite these genotypes giving the lowest fresh weights of leaves in the lower parts of the quinoa genotypes. The maximum FW of leaves (3.62 g) was observed in Q3, and the DM represents 13.4%. At the same time, USA1 had the lowest DM percentage (8.2%).

Table 1. Fresh weight (FW, g) and dry matter (DM, g) of the upper aerial parts of cultivated quinoa genotypes.

Genotype	Panicle, g		Leaves, g		Stem, g		Total, g	
	FW	**DM**	**FW**	**DM**	**FW**	**DM**	**FW**	**DM**
KY1	0.892 bc ± 0.078	0.118 b ± 0.010	6.109 ab ± 0.536	0.843 b ± 0.073	1.364 b ± 0.124	0.328 b ± 0.030	8.371 b ± 0.601	1.289 ab ± 0.095
KY2	0.683 c ± 0.058	0.086 bc ± 0.007	5.269 bc ± 0.331	0.713 c ± 0.045	0.954 bc ± 0.024	0.334 b ± 0.008	6.908 c ± 0.363	1.133 b ± 0.051
Q1	1.024 b ± 0.100	0.153 b ± 0.015	4.728 c ± 0.383	0.718 c ± 0.058	0.973 b ± 0.090	0.118 d ± 0.011	6.719 c ± 0.339	0.989 bc ± 0.052
Q2	0.809 bc ± 0.05	0.115 b ± 0.006	5.928 b ± 0.513	0.866 b ± 0.075	1.193 b ± 0.102	0.153 d ± 0.018	7.966 b ± 0.592	1.134 b ± 0.085
Q3	1.422 a ± 0.124	0.234 a ± 0.020	5.820 b ± 0.476	0.931 b ± 0.076	1.835 a ± 0.132	0.236 c ± 0.017	9.017 a ± 0.392	1.401 a ± 0.058
Q4	0.111 e ± 0.009	0.017 d ± 0.002	6.899 a ± 0.658	1.127 a ± 0.107	1.243 b ± 0.072	0.183 cd ± 0.011	8.253 b ± 0.726	1.327 a ± 0.118
Q5	0.728 bc ± 0.021	0.12 b ± 0.004	5.338 b ± 0.341	0.900 b ± 0.058	1.172 b ± 0.069	0.480 a ± 0.028	7.237 c ± 0.287	1.497 a ± 0.044
USA1	0.150 e ± 0.012	0.073 c ± 0.060	3.020 d ± 0.159	0.566 d ± 0.030	0.540 c ± 0.037	0.063 f ± 0.040	3.712 f ± 0.165	0.701 cd ± 0.031
USA2	0.213 de ± 0.0203	0.028 c ± 0.003	3.860 d ± 0.237	0.533 d ± 0.033	0.719 c ± 0.060	0.083 e ± 0.007	4.791 e ± 0.280	0.644 d ± 0.038
USA3	0.323 d ± 0.027	0.043 c ± 0.040	4.688 c ± 0.226	0.673 cd ± 0.032	0.881 bc ± 0.080	0.092 e ± 0.008	5.887 d ± 0.277	0.808 c ± 0.037

Means in the same column followed by the same letter are not significantly different ($p < 0.05$).

Table 2. Fresh weight (FW) and dry matter (DM) of the middle parts of quinoa genotypes.

Genotype	Leaves, g		Stem, g		Total, g	
	FW	DM	FW	DM	FW	DM
KY1	6.05 bc ± 0.48	0.79 c ± 0.06	5.92 c ± 0.54	0.48 e ± 0.04	11.96 cd ± 0.91	1.27 d ± 0.10
KY2	5.49 bc ± 0.54	0.70 d ± 0.07	5.42 c ± 0.34	0.57 d ± 0.04	10.92 d ± 0.85	1.27 d ± 0.10
Q1	4.58 c ± 0.44	0.64 de ± 0.06	4.93 d ± 0.35	0.51 de ± 0.03	9.52 e ± 0.69	1.15 d ± 0.09
Q2	6.74 b ± 0.65	0.47 f ± 0.05	7.01 b ± 0.60	0.72 c ± 0.06	13.75 b ±1.04	1.19 d ± 0.09
Q3	6.41 b ± 0.42	0.91 b ± 0.06	9.79 a ± 0.56	1.12 a ± 0.06	16.20 a ± 0.85	2.02 b ± 0.11
Q4	10.1 a ± 0.77	1.49 a ± 0.11	7.00 b ± 0.50	0.84 b ± 0.06	17.08 a ±1.16	2.32 a ± 0.16
Q5	5.84 c ± 0.13	0.85 c ± 0.02	6.78 b ± 0.26	0.79 b ± 0.03	12.62 c ± 0.35	1.63 c ± 0.04
USA1	6.13 b ± 0.42	0.76 cd ± 0.05	4.85 d ± 0.17	0.38 f ± 0.02	10.98 d ± 0.55	1.14 d ± 0.06
USA2	4.58 c ± 0.43	0.56 e ± 0.05	3.24 f ± 0.40	0.30 f ± 0.03	7.83 f ± 0.37	0.86 e ± 0.05
USA3	5.94 bc ± 0.59	0.81 c ± 0.08	4.18 e ± 0.37	0.35 f ± 0.03	10.13 de ± 0.86	1.16 d ± 0.10

Means in the same column followed by the same letter are not significantly different ($p < 0.05$).

Table 3. Fresh weight (FW) and dry matter (DM) of the lower parts of the quinoa genotypes.

Genotype	Leaves, g		Stem, g		Total, g	
	FW	DM	FW	DM	FW	DM
KY1	2.718 c ± 0.220	0.290 c ± 0.023	6.618 c ± 0.310	0.735 d ± 0.034	9.336 bc ± 0.400	1.025 e ± 0.044
KY2	1.704 e ± 0.169	0.324 bc ± 0.032	5.085 e ± 0.467	0.740 d ± 0.068	6.788 d ± 0.592	1.064 e ± 0.092
Q1	3.099 b ± 0.140	0.360 b ± 0.016	5.634 d ± 0.271	0.790 d ± 0.038	8.733 c ± 0.269	1.150 e ± 0.037
Q2	2.996 b ± 0.259	0.350 b ± 0.030	7.096 c ± 0.629	1.111 b ± 0.099	10.089 b ± 0.791	1.461 d ± 0.117
Q3	3.621 a ± 0.345	0.487 a ± 0.046	9.900 a ± 0.849	1.690 a ± 0.145	13.461 a ±1.038	2.173 a ± 0.154
Q4	2.178 d ± 0.211	0.289 c ± 0.028	7.923 b ± 0.638	1.309 b ± 0.105	10.101 b ± 0.806	1.601 cd ± 0.128
Q5	1.358 e ± 0.128	0.175 d ± 0.071	6.765 c ± 0.272	1.108 c ± 0.044	8.123 c ± 0.359	1.858 b ± 0.103
USA1	2.018 d ± 0.190	0.165 d ± 0.016	4.748 e ± 0.197	0.593 e ± 0.025	6.766 d ± 0.258	0.758 f ± 0.028
USA2	3.207 b ± 0.273	0.338 b ± 0.029	4.206 f ± 0.371	0.670 de ± 0.059	7.412 cd ± 0.513	1.008 e ± 0.072
USA3	2.595 bc ± 0.119	0.311 c ± 0.014	4.153 f ± 0.414	0.478 f ± 0.048	6.747 d ± 0.491	0.799 f ± 0.057

Means in the same column followed by the same letter are not significantly different ($p < 0.05$).

Data from quinoa genotype stems indicated that the DM percentages ranged from 11.1 to 17.1%.The maximum FW (9.900 g) and DM (1.690 g) in the middle stems were observed in the Q3 genotypes. Overall, Q3 genotypes had the highest weights of FW (13.461 g) and DM (2.173 g), with 16% as dry matter. The lowest fresh weight (6.747 g) and dry matter (0.758 g) amounts of the total middle parts of the studied quinoa genotypes were obtained from USA3 and USA1, respectively. Generally, in each tier of plant biomass, the shares of panicles, leaves, and stems in the weight equivalents were separately estimated. Leaves occupied 25% of the lower parts; branches occupied the rest. Leaves formed about 50–60% of the middle layer, and stems formed 40–50%. In the upper layer, the stems accounted for 15% of the total mass. The mass of panicles as a percentage varied greatly by cultivar. The Q3 and Q4 cultivars produced the maximum fresh weight (38.7 g and 35.4 g) and dry matter (5.6 g and 5.3 g), respectively, compared to other genotypes (Figure 2A), while the lowest weights (FW-20 g and DM-2.5 g) were obtained from USA2. Figure 2B shows the ratio between the dry matter and the fresh weight of the aerial parts of the studied quinoa genotypes. The highest ratio (0.16) was obtained from the Q4 and Q5 genotypes, while the KY1 and USA3 genotypes registered the minimum ratio (0.12), compared to the other genotypes.

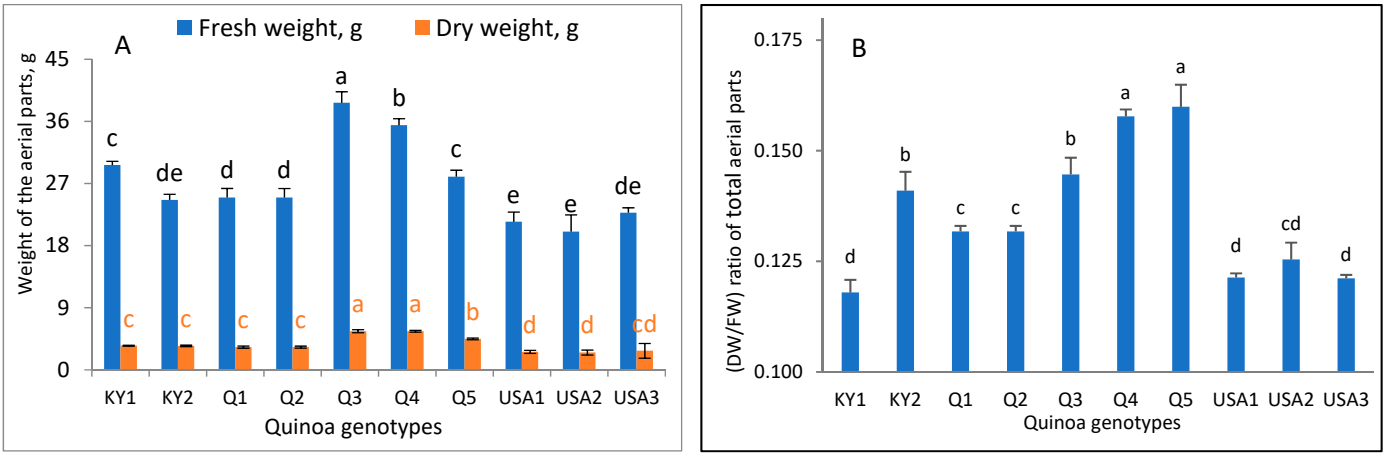

Figure 2. (**A**): The fresh weight and dry matter of the above-ground parts of the quinoa genotypes; (**B**) DW/FW ratio of the whole aerial parts of the quinoa genotypes. The same letter(s) statistically not different ($p < 0.05$).

By harvesting time, most plants had reached full maturity and acquired the characteristic colour of each cultivar (Figure 3). The panicle length in the experiment varied from 20 to 94 cm (Table 4). According to the averaged indicators, cultivars Q2, Q3, and Q4 had the longest panicles (56–62 cm). The cultivars Brightest Brilliant (USA1) and Red Faro (USA2), under the experimental conditions, formed an inflorescence 31–33 cm long; the most petite average panicle length (29 cm) was recorded in Regalo (KY2).

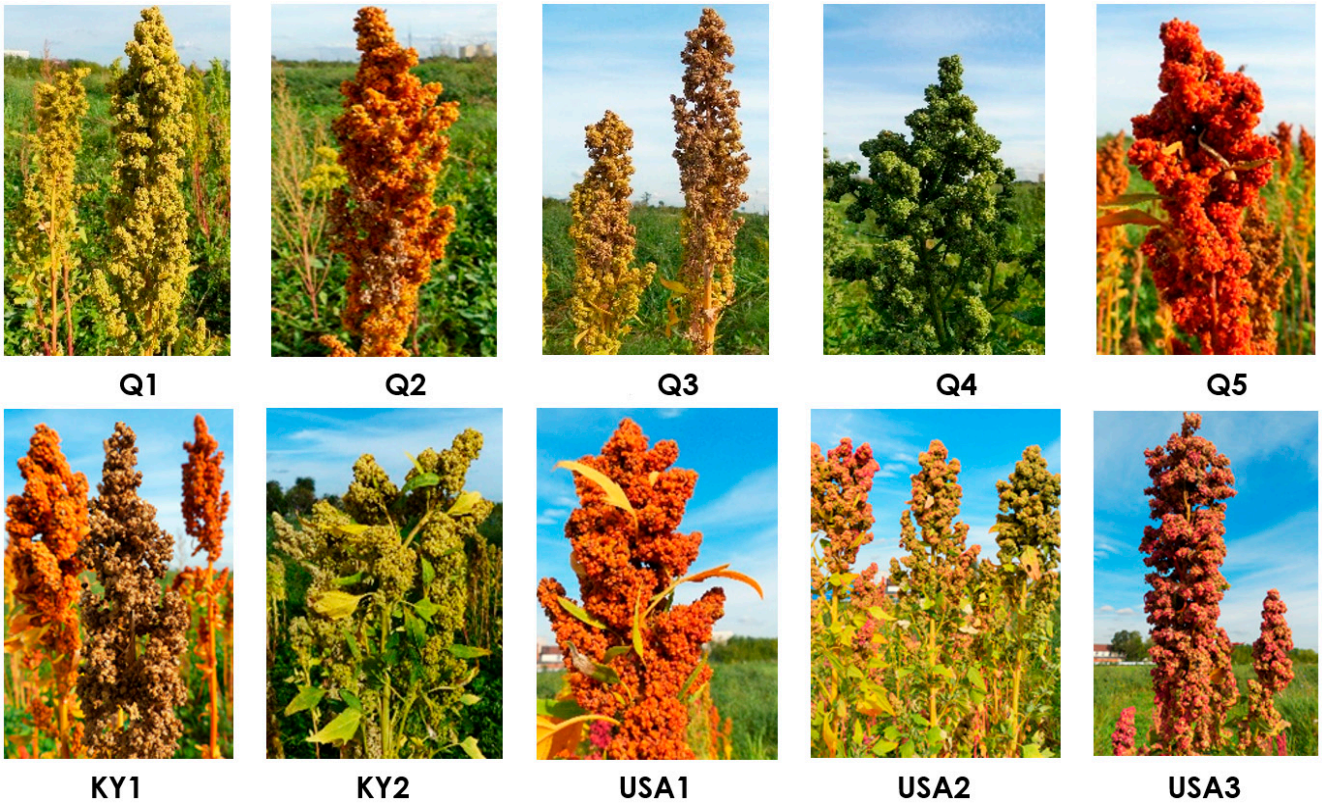

Figure 3. Inflorescences (panicles) of the studied quinoa genotypes during the grain ripening stage.

Table 4. Average yield and yield components of quinoa genotypes.

Genotypes	Panicle, cm	Number of Grains/Panicles	Grain Weight, g/Panicle	Weight of 1000 Grains, g	Grains Yield t/ha
KY1	34 d ± 1.1	6855 a ± 335	18.37 ab ± 1.00	2.68 c ± 0.04	4.08 a ± 0.22
KY2	29 e ± 1.4	4610 c ± 287	13.00 d ± 0.88	2.82 bc ± 0.03	2.89 d ± 0.19
Q1	39 c ± 2.1	4226 c ± 305	12.89 e ± 0.92	3.05 b ± 0.04	2.86 d ± 0.20
Q2	43 c ± 1.4	4990 bc ± 414	14.97 c ± 1.20	3.00 b ± 0.04	3.33 b ± 0.27
Q3	49 b ± 2.0	4322 c ± 373	13.96 cd ± 1.15	3.23 a ± 0.05	3.10 c ± 0.25
Q4	56 a ± 1.7	4482 c ± 414	7.44 g ± 0.74	1.66 d ± 0.03	1.65 f ± 0.17
Q5	32 de ± 0.8	6476 a ± 507	19.04 a ± 1.61	2.94 b ± 0.03	4.23 a ± 0.36
USA1	32 de ± 1.8	3690 d ± 272	10.25 f ± 0.69	2.75 c ± 0.04	2.23 e ± 0.15
USA2	30 e ± 1.1	4852 bc ± 250	13.04 d ± 0.58	2.86 bc ± 0.02	2.87 d ± 0.13
USA3	37 cd ± 1.7	5891 b ± 481	17.79 b ± 1.56	3.21 a ± 0.03	3.89 a ± 0.25

Means in the same column followed by the same letter are not significantly different ($p < 0.05$).

The highest number of grains per panicle was observed in the Cherry Vanilla (USA3), Titicaca (KY1), and Q5 cultivars. The most telling element of yield structure is the grain weight per quinoa panicle. The lowest values (from 9 to 13 g) were noted in cultivar Q4 (6.68 g and 7.44 g). High productivity in the accumulation of grain mass from one panicle (17 to 20 g) was noted in the cultivars Cherry Vanilla (USA3), Titicaca (KY1), and Q5.

The 1000 grain weight measure ranged from 1.6 g in Q4 to 3 g in Q3, Cherry Vanilla (USA3), Q1, Q2, and Q5. One of the most important indicators for evaluating the effectiveness of crop cultivation in certain agroecological conditions is its yield (t/ha). A yield (Table 4) of less than 2 t/ha was observed in the US and Q4 cultivars. The cultivars demonstrating the highest yields (more than 3 t/ha) were USA3 (for both variants), cultivars Q2 and Q3, KY1 4.08 t/ha, and Q5 4.23 t/ha. Based on the results (Figure 4), it is clear that cultivar USA1 has the highest germination energy (90%). Low germination energy was observed in cultivar KY1 (71.5%); the lowest value was recorded in cultivar USA2 (68.8%). High laboratory seed germination was registered in cultivars USA1 (92.8%) and Q3 (93.8%), and the highest value was identified in cultivar Q4 (95.3%). The lowest laboratory germination was observed in cultivar KY1 (72.3%). Cultivar USA2 also had low values for this indicator (73.5% and 73.0%). Germination vigour and the seed germination of the quinoa seeds are presented in Figure 2. Protein content in the quinoa grains of the studied genotypes was relatively high, 13.5% (USA3) and 14.0% (USA2), and these are close to FAO/WHO protein values. The protein contents of quinoa grains ranged from 12.5–14%, and the highest result was from cultivar USA2 (Figure 5).

The Q1 and USA1 cultivars had the highest amounts of lysine (5.64 g/100 g protein), while Q4 had the lowest percentage (4.4 g/100 g protein). The contents of valine and threonine were almost similar, and they ranked between 3.5–4.5 g/100 g protein, except for KY2, which registered minor amounts (3.2 g/100 g protein) of valine compared to other genotypes, whereas the same cultivar (KY2) had the highest contents of phenylalanine (3.84 g/100 g protein) compared to the other studied genotypes. Methionine content in quinoa grains is expressed as the minimum amino acid. Its results ranged from 0.85 in Q3 to 1.3 g/100 g protein in USA1. Leucine and isoleucine are the most abundant amino acids in quinoa grains, compared to other AAs. Their results varied between 6.7 and 9.2 g/100 g protein (Figure 5).

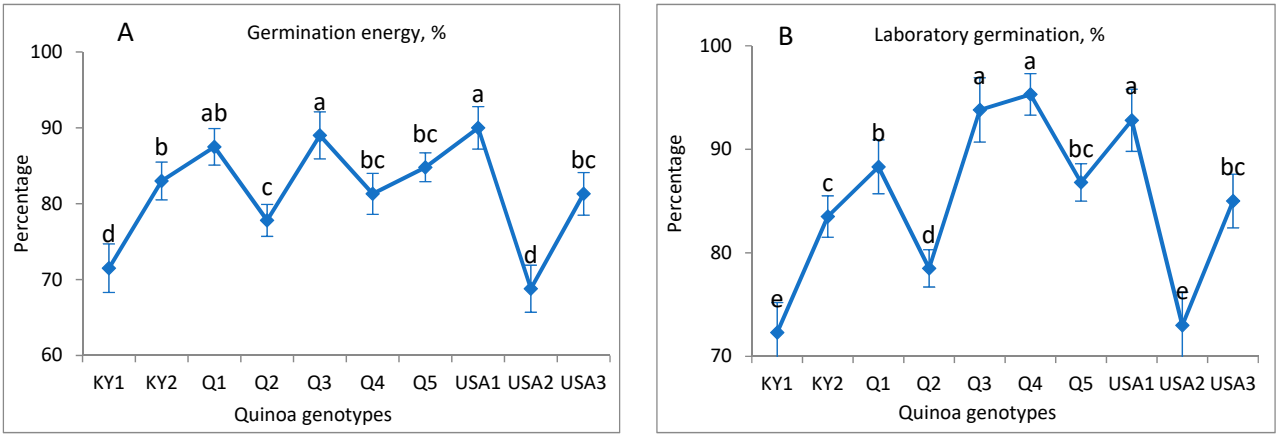

Figure 4. Germination energy and laboratory germination of quinoa seeds genotypes. (**A**) Germination energy percentages; (**B**) laboratory germination percentages. The same letter(s) statistically not different ($p < 0.05$).

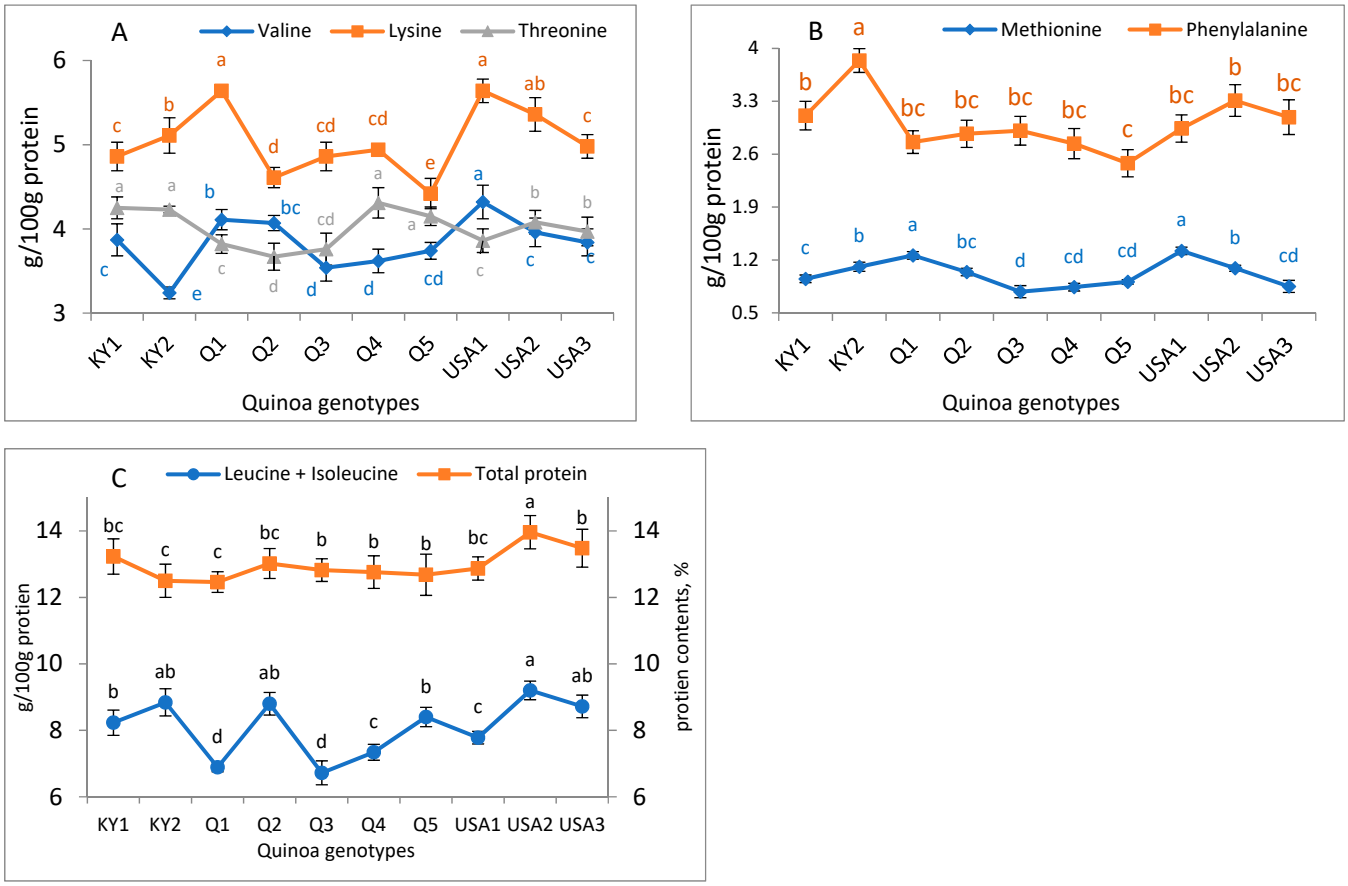

Figure 5. Protein percentages and amino acid contents (g/100 g protein) in quinoa grains. (**A**) Valine, lysine, and threonine contents; (**B**) methionine and phenylalanine contents; (**C**) leucine and isoleucine contents and protein percentages. The same letter(s) statistically not different ($p < 0.05$).

4. Discussion

The food crisis is mainly triggered by climate change and trade restrictions [32]. In addition to traditional crops, new alternative crops or species must be identified and used for future food security [33]. The marginal crops can be used as high-quality food sources, especially those cultivated for their parts (grains, leaves, and straw). A better

understanding of crops such as quinoa, with its high resilience to extreme environmental conditions and its qualities as a functional food source [34,35], will help ensure food security and sovereignty [36]. In addition, quinoa genotypes could represent a breeding tool for crop diversification [15].

Quinoa is an annual, dioecious plant with an erect stem and alternating leaves of various colours due to the presence of betacyanins, and the plants show promising growth. Many cultivars reach 1.5 m in height and form many branches and large leaves. The plants have a taproot with a well-developed, highly branched root system, which penetrates to a depth of 1.5 m below the surface, protecting against drought. The leaves show polymorphism; the upper leaves are lanceolate, while the lower leaves are diamond-shaped [37,38]. Quinoa is a herbaceous plant in the same botanical family as sugar beet, table beet, and spinach. The plant is similar to buckwheat and amaranth, and amaranth is in the same family. The disc-shaped seeds are black, brown, yellow, and white. This resemblance can be explained by the plant's leaves and panicles of similar shapes and colours. It has the particularity of adapting to unfavourable conditions, which allows it to resist frost, drought, wind, salinity, and poor soils [39]. According to [40], quinoa can grow in various climatic conditions. However, the soils on which the experiments were carried out were relatively rich in organic matter, with pH −5.5, and the sum of the temperatures was ≥10 °C; the total rainfall during the growing season was 216 mm in 2019 and 526 mm in 2020. Thus, several studies indicate that quinoa can be grown in different growing environments with a humidity range of 40–90%, at altitudes varying from sea level to 4500 m, and quinoa can tolerate temperature variations from −8 °C to 38 °C [41].

The life cycles of the quinoa genotypes ranged from 135 to 140 days. These are similar to the results for Europe (109–182 days) [42], South America (110–190 days) [43], Brazil (80–126 days) [44], Turkey (119–141 days) [45], Bhutan (92–197 days) [41], and Oman (84–149 days) [46]. The quinoa cultivation cycle therefore varies according to regions, climatic conditions, and genotypes. An ideal quinoa cultivar should have a uniform and early maturity with a growing period of fewer than 150 days under northern European conditions [40].

Quinoa has a high residue content, making it ideal for feeding farm animals. Because of its protein content and digestibility, its biomass can be utilised as fodder. [47]. In this study, the leaf mass occupied 25% of the lower parts of the plant, and the mass of the stem occupied about 75%. In the middle parts, about 50–60% of the mass falls on the leaves and 40–50% on the stems. In the upper parts of the plant, the stems made up about 15% of the mass. Studies have demonstrated that for feeding non-ruminating animals, quinoa must be less than 30% of the diet [47]. The dry matter contents factor is the principal selection criterion to enhance forage nutritional value of quinoa as animal fodder [48]. In our experiment, considerable variation in parameters related to FW and DM among the cultivated genotypes was identified. Improvements in dry matter may also be enhanced by choosing the optimal cultivation management approach [49].

The cultivar of Regalo (KY2) had a panicle weighing 15.29 g and a grain weight per panicle of 13 g. These results are similar to those of Manjarres-Hernández et al. [50], in which the Blanca de Jericó Tuta 2 accession showed the most extended panicle length of 72.4 cm and had a below-average yield (18.17 g/panicle). Quinoa Peruana had the shortest panicle length of 39.0 cm and had an above-average yield (62.02 g/panicle). Moreover, Q14, Q15, and Q4 were the tiniest productive lines and recorded low values for most traits. The highest lines were very poor or non-productive; they extended their vegetative period, showed irregular flowering, and, in most cases, they did not reach full anthesis and maturity [14]. The average number of grains per panicle was highest in Cherry Vanilla (USA3), Titicaca (KY1), and Q5 despite their not being among the cultivars with the longest panicles. Simultaneous studies on the effects of the sowing date (May, June, and July) and planting density (15, 30, 45, and 60 plants per m^2) were studied on the vegetative and reproductive growth of the quinoa cultivar Titicaca (KY1), and the results showed that the highest and lowest grain yields were obtained from the May (380 kg ha^{-1}) and July

(25 kg ha^{-1}) planting dates. The main reason for the reduced grain yields from the June and July sowing dates was the occurrence of high temperatures during the pollination period of the plant [51]. The seed weight is a critical characteristic of the life cycle of higher plants [52,53], and its role in plant fitness is widely discussed [54]. Seed weight is also strongly impacted by the surrounding agroecological conditions where plants grow [55]. These environmental factors may regulate the plant's ability to develop embryos, causing variation in seed weight [56].

Quinoa's importance as a food relates to its high nutritional value, as it is the primary protein source for some rural populations, substituting for the lack of animal protein [57]. Moreover, because of its high protein and amino acid content, quinoa may serve as an alternative to dairy products [58]. Seed yield therefore represents a crucial issue for the seed industry [59]. Generally, the grain yields of the cultivars obtained in Russia are encouraging compared to the yields achieved in other regions despite using fertilizers. For example, the average yield of quinoa is in Yemen (0.24–1.9 t/ha), Iran (0.16–1.56 t/ha), Mauritania (0.03–0.23 t/ha), Iraq (0.11–0.96 t/ha), Lebanon (1.50–7.50 t/ha), Egypt (0.41–3.87 t/ha) [12], Morocco (0.84 t/ha) [13], Italy (0.11 t/ha −1 to 3.05 t/ha) [14], and Bhutan (0.61 to 2.68 t/ha) [41]. In Europe, the yields ranged between 1 and 3 t/ha [15] and between 1.7 and 2.4 t/ha [60]. The increase in grain yield per area can be mainly attributed to different plant densities; therefore, a higher proportion of grain yield was produced from the main panicle [61,62].

Germination is an important stage in the life cycle of a plant, and it is the first step toward successful plant establishment, especially in adverse environments [63]. Therefore, special attention should be paid to high-quality seeds in the complex agro-technical measures implemented to achieve high and stable yields. In this study, a meagre germination rate and germination energy were noted in KY1 and USA2, unlike those in Brightest USA1, Q1, Q3, and Q4. These results are similar to those of Bazile et al. [11] when evaluating the adaptability of selected quinoa genotypes in different environments outside the Andean region (Kyrgyzstan, Tajikistan, Algeria, Egypt, Iraq, Iran, Lebanon, Mauritania, and Yemen). This could be due to storage conditions where high humidity reduces the quality of seeds between seasons. Germination considers the initial and essential determinant of plant success which can be used as a fundamental tool for yield improvement [64]. The number of germinated seeds dropped as the storage period increased, meaning that more extended storage periods of quinoa grains under ambient conditions resulted in more significant deterioration [65].

Quinoa seeds look like small flattened discs about 2 mm in diameter. Pleasant in flavour and lightly fragrant, quinoa is also nutritious. Thus, the protein content of quinoa grains of the studied cultivars grown without nitrogen fertilizers was relatively high: 13.5% (Cherry Vanilla cultivar) and 14.0% (Red Faro cultivar). Several researchers reported that quinoa protein contents range from 7 to 24% [66]. Quinoa protein and amino acid levels can vary dramatically depending on the cultivar and the external factors. [67]. The balance of AAs in quinoa proteins is excellent [68] and is explained by the nature of these storage proteins, albumins, and globulins, whose amino acid composition differs significantly from that of common cereal prolamins. For some world populations, incorporating high-quality protein into the diet is a concern, especially for people who rarely eat animal protein and need to find it in other foods, such as cereals and legumes [69,70]. Indeed, even when the energy intake of these foods is adequate, insufficient levels of essential amino acids can increase the prevalence of malnutrition, and it seems to meet these expectations [71,72]. Quinoa, as a multi-purpose crop, may enhance environmental sustainability and reduce the impact of the agricultural sector on climate change [73].

5. Conclusions

This study assesses the genetic biodiversity of ten quinoa genotypes. The results indicate that growing quinoa in warm and humid conditions allows for obtaining high results without fertilizer application. Despite the absence of fertilizers and pesticides, the attained vegetative and seed yields were higher than those in other studies. The

experiment, therefore, opens "promising" prospects for the extension of quinoa cultivation and its generalization in the region. The agricultural services in Russia are working on this by planning campaigns to raise awareness among farmers on the interest of this type of culture, as it is "inexpensive" and has a "relatively short" growth cycle, to supply both the domestic market of the country and the export of products. Additional studies are warranted to further investigate quinoa cultivation, assess a wide range of cultivars, and determine the most appropriate cultivation density in different regions.

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