



RESEARCH ARTICLE

Agroclimatic suitability mapping and seasonal phenotypic evaluation of quinoa (*Chenopodium quinoa*) in subtropical India

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Abstract

Quinoa (*Chenopodium quinoa*), a traditional Andean crop, has emerged as a climate-resilient and nutrient-dense crop, with significant potential for cultivation in resource-constrained environments. The present study evaluated the agro-climatic adaptability and phenotypic performance of eleven quinoa accessions across two cropping seasons, namely kharif (2023) and rabi (2023-24) under subtropical Indian conditions. Climatic suitability was assessed using temperature, precipitation and relative humidity layers modelled in Google Earth Engine based on global climate datasets. Suitability mapping indicated that extensive regions across Asia and Africa, including arid and semi-arid areas, are suitable for quinoa cultivation under supplemented irrigation conditions, despite low rainfall. Field evaluation under a randomized complete block design revealed strong seasonal effects on flowering, plant height, thousand grain weight and single-plant yield, with rabi significantly outperforming kharif for all major traits. Kharif grown quinoa crop showed a reduction of 7.47 % in DTF, 38.10 % in PHT, 85.76 % in TGW and 85.83 % in SPY in comparison to rabi grown crop. The results of ANOVA and PCA indicate that quinoa cultivation in subtropical India is substantially more suitable during the rabi season and that Co-407, D-12047 and BO-51 are promising candidates for cultivation and further breeding aimed at productivity and seasonal adaptation in non-traditional agro-ecologies.

Keywords: abiotic stress; agro-climatic suitability; climate resilient crops; differential performance; quinoa; sustainability

Introduction

Quinoa (*Chenopodium quinoa*), an ancient crop originated from the Andean region, has gained global attention due to its exceptional nutritional profile and adaptability to diverse and marginal environmental conditions. Its high protein content, balanced amino acid composition and resilience to abiotic stresses have positioned quinoa as a promising crop for enhancing food and nutritional security (1).

Traditionally cultivated across the Andean region, including Colombia, Ecuador, Peru, Bolivia and Chile, quinoa is considered one of the oldest domesticated crops in these regions. In recent decades, quinoa cultivation has been expanded beyond its native range with increasing research and promotion efforts in several Asian countries.

Nations such as China, India, Nepal and Pakistan have initiated programs to introduce and popularize quinoa under local agro-climatic conditions. Quinoa was first introduced into China in the 1960s (2), followed by selection and breeding efforts that led to the development of improved and locally adapted varieties. Despite its expanding global cultivation, approximately 80–85 % of quinoa production remains concentrated in Bolivia and Peru, followed by Europe and North America at second and third positions respectively. In contrast, Africa and Asia continue to exhibit lower rates of adoption and small-scale production of quinoa. Quinoa is an annual dicotyledonous species belonging to the family Amaranthaceae (previously Chenopodiaceae) which also includes economically important crops such as sugarbeet (*Beta vulgaris* L.) and spinach (*Spinacia oleracea* L.). Quinoa grains contain

approximately 4–9 % oil, about 16 % protein with a balanced amino acid profile and nearly 64 % carbohydrates (3). The substantial amount of starch (51–61 %) enables its utilisation in flour production as compared to cereals. Furthermore, the absence of gluten makes quinoa particularly suitable for developing food products targeting individuals with celiac disease or gluten intolerance (4). Although quinoa grain has excellent nutritional and health benefits, it has not achieved widespread adoption primarily because farmers are reluctant to shift from traditional cereal crops such as wheat, rye and barley as well as the limited availability of improved, farmer accessible varieties in the public domain. According to the Food and Agriculture Organisation of the United Nations, global quinoa production exceeded 165 thousand tonnes in 2024 harvested from approximately 182.0 thousand hectares (5).

Quinoa is increasingly considered as a promising alternative crop for enhancing nutritional sustainability particularly in regions such as Middle East, North Africa (MENA) and Central Asia, where rising soil and water salinity pose significant constraints to conventional agricultural systems. Breeding programmes in several Asian and African countries are focusing on expanding quinoa genetic diversity through hybridization and selection (6). Climate change has increased the need for quinoa varieties capable of performing under warmer environments such as the Indian Kharif season.

Notably, quinoa exhibits a broad agro-ecological adaptation range reported to adapt across a wide altitudinal range, from near sea level to about 4000 m above sea level and to tolerate low temperatures down to about -8°C depending on genotype and developmental stage. Particularly during their reproductive stages (flowering and grain filling), the quinoa cultivars are vulnerable to high temperatures. Exposure of high temperatures ($35\text{--}40^{\circ}\text{C}$) in quinoa leads to significant yield losses, inefficient photosynthesis and increased pollen sterility. This thermal sensitivity currently limits its large-scale cultivation in tropical and subtropical Asian regions, especially during the Kharif (monsoon) season characterized by high temperature and humidity.

Developing quinoa cultivars adapted to relatively warmer, low-altitude environments represents a strategic approach to enhance agricultural resilience under climate change. Such cultivars would better withstand projected temperature increase while maintaining productivity. The extensive genetic diversity of quinoa offers a valuable resource for breeding programs to select parents having desirable attributes to initiate development of improved varieties suited for target environments. The development of quinoa cultivars suited to warmer Asian and Indian agro-ecologies represents a critical priority for regional food and nutritional security. This approach not only supports adaptation to climate change but also strengthens agricultural resilience and enables the wider utilisation of quinoa as a versatile nutrient-dense crop in environmentally stressed regions.

The present study aimed to evaluate the suitability of quinoa for cultivation under Indian agro-ecological conditions by assessing the seasonal performance of quinoa accessions during kharif and rabi, comparing their adaptation under contrasting environments

and determining their potential for crop diversification, climate adaptation and nutritional security in warmer regions of India through field evaluation and spatial suitability analysis.

Materials and Method

Establishment of a suitability map for quinoa

The suitability map for quinoa considered three major climatic parameters for identifying suitable areas for cultivation such as relative humidity, temperature and precipitation derived from publicly available climate datasets. Relative Humidity was calculated from available parameters of the Global Land Data Assimilation System (GLDAS), while temperature and precipitation data were obtained from world climate historical mean data (7). The datasets were obtained and overall spatial modelling was carried out in the Google Earth Engine (GEE) platform. Suitability maps were generated by assigning different weights to the climatic layers. Three maps were prepared on three weightage variations as per Table 1. The final suitability index was derived by summing the weighted layers and classified using a decision tree approach into five categories ranging from “highly suitable” to “least suitable”.

Quinoa germplasm

A total of eleven quinoa accessions were imported from International Centre for Biosaline Agriculture (ICBA), Dubai, UAE. These accessions included two improved pure-lines developed at ICBA i.e. ICBA-Q3 and ICBA-Q5, purple flowered variety developed through mutation at the Colorado state university, USA (Co-407), BO-51, a line known for compactness vigour and yield and medium to early maturing varieties Chen-254, D12377 (black seeded), D11912, D12401 & D12406. Originally, these accessions were collected from Andes probably before implementation of the convention on biodiversity (CBD) and stored at United State Department of Agriculture (USDA). A subset from these accessions was subjected to saponin estimation analysis and reported recently (8).

Experimental conditions and crop establishment of quinoa

Quinoa cultivation during the kharif (2023) season was carried out at the Agricultural Research Station, Ajmer Tabiji Farm, N.H. No. 8, Beawar Road, Rajasthan, which is geographically located at 26.42°N latitude and 74.62°E longitude, at an altitude of 430–450 m above mean sea level. The rabi season (2023–24) experiment was conducted at SGT University, Gurugram, Haryana, situated at 28.487°N latitude and 76.936°E longitude, with an altitude of 220–230 m above mean sea level. The soil at both sites was sandy loam in texture with 0.87 % organic carbon, available nitrogen (225 kg/ha), phosphorus (41.8 kg/ha) and potassium (261.2 kg/ha) under a subtropical climatic zone.

The experiment was laid out in a randomised complete block design with two replications. Each genotype was grown in 2 m row length with 45 cm row spacing 20 cm of plant-to-plant spacing. Prior to sowing, quinoa seeds were subjected to cold treatment by refrigeration for one week to improve and synchronise germination. Sowing was carried out manually in mid-July for the kharif season and mid-november for the rabi season at a seed rate of 15 kg/ha.

Table 1. Climatic variables and weighting schemes used for quinoa suitability modelling

Layer	Suitable Conditions	Weightages_1	Weightages_2	Weightages_3
Relative humidity	48 % to 88 %	1.5	1.5	1.5
Temperature	-4°C to 38°C	2.5	3	3.5
Rainfall	100 to 200 mm	1	0.5	0

Seeds were dibbled at a depth of 1–2 cm, placing 6–7 seeds per hill. Standard package of practices was followed to obtain uniform and healthy crop stand during both seasons. At physiological maturity, indicated by grain hardening, the crop was harvested manually. The harvested plants were air-dried for 7 days, followed by manual threshing and winnowing to obtain clean grain samples from each plot.

Phenotyping of grain characteristics and other parameters

The grain length and width of quinoa under kharif and rabi seasons were evaluated. Grain length was measured by placing 10 seeds in a straight line and measuring the total length using a ruler, which was then divided by 10 to obtain the mean grain length. Similarly, mean grain weight was estimated by weighing a sample of 1000 seeds per accession and later dividing the total weight by 1000. The other phenotype characters were recorded following standard protocols as described by (9). All observations were averaged across two replications.

Statistical Analysis

All phenotypic data recorded from the field experiments during the rabi and kharif seasons were subjected to statistical analysis to assess the significance of seasonal and genotypic effects. Analysis of variance (ANOVA) was performed using a Randomised complete block design model, where genotypes were treated as fixed effects and blocks as random effects. Seasonal effects (rabi vs. kharif) were analysed separately as well as in a combined analysis to evaluate genotype $\times$ environment interactions. All statistical analyses were performed using the R statistical software (version 4.4.1), employing package “agricolae” for ANOVA and mean separation was obtained by performing “Fisher’s LSD”.

$$Y_{ijk} = \mu + G_i + L_j + (GL)_{ij} + Rk(j) + \epsilon_{ijk}$$

Where, Y_{ijk} denotes the observation of the i^{th} genotype in the k^{th} replication within the j^{th} season, μ is the grand mean, G_i is the genotype effect, L_j is the season effect, $(GL)_{ij}$ is the genotype $\times$ season interaction, $Rk(j)$ is the replication effect nested within season and ϵ_{ijk} is the experimental error.

Principal Component Analysis (PCA) was conducted using “metan” package to assess the multivariate relationships among traits and to quantify the contribution of different traits to total variability. PCA was performed using standardized (z-score normalized) data to eliminate scale differences among variables, results were visualized through biplots representing the first two principal components (PC1 and PC2), which explained the maximum proportion of total variance.

Results

Suitability mapping of quinoa cultivation based on weightages

Suitability maps generated using three weighting schemes revealed low suitability in extreme northern regions, particularly northern Russia and Canada. Among the five suitability classes, i.e., least suitable, marginally suitable, moderately suitable, suitable and highly suitable, the majority of the countries were categorized as ‘suitable’ based on weightages 1 and 2. In contrast, application of weightage scheme 3 resulted in a higher proportion of countries being classified as ‘highly suitable’, relative to other weightage schemes. Furthermore, most African regions (excluding desert areas) were categorized as moderately suitable for quinoa cultivation under weightage schemes 1 and 2. Desert regions of Africa, previously categorized as marginally suitable under schemes 1 and 2, were classified as suitable under weighting scheme 3 when rainfall was assigned lower importance (Fig. 1, Table 1).

Phenotypic evaluation of *Chenopodium quinoa* in two seasons

Distinct morphological differences were observed among quinoa accessions grown during the rabi and kharif seasons (Fig. 2). Plants grown during the rabi season exhibited superior vegetative growth compared to those cultivated in the kharif season across all accessions (Table 2). Rabi-grown plants were characterized by darker green foliage, a wider canopy spread and taller in height, indicating enhanced biomass accumulation. In addition, they developed longer and more compact inflorescences indicating improved reproductive development. In contrast, kharif grown plants were comparatively shorter, with narrower and lighter-coloured leaves, reduced branching and smaller less compact inflorescences, suggesting suboptimal growth and reproductive development under these conditions. Combined ANOVA across rabi and kharif revealed highly significant effects of genotype, season and genotype $\times$ season interaction for days to flowering (DTF), plant height (PHT), 1000 grain weight (TGW) and single plant yield per plant (SPY), whereas season $\times$ replication was non-significant for all traits, indicating stable replication effects across seasons (Table 3 a). Fisher’s LSD further showed that rabi was superior to kharif for all traits, with higher seasonal means for DTF (47.55 vs 44.00 days), PHT (87.82 vs 54.36 cm), TGW (2.936 vs 0.418 g) and SPY (24.13 vs 3.42 g), confirming the more favourable growth and grain-filling conditions of rabi (Table 3c). Genotypic means also indicated marked variability, with genotypes ICBA-Q3 and Chen-254 being the late in flowering and D-12047 the earliest overall, while ICBA-Q3 and Co-407 were tallest and D-12406 was shortest. Seasonal means showed that DTF ranged from 39 to 56 days in rabi and 35 to 52 days in kharif; Titicaca and D-12401 were the earliest genotypes in rabi and kharif, respectively, whereas ICBA-Q3 and Titicaca recorded the highest

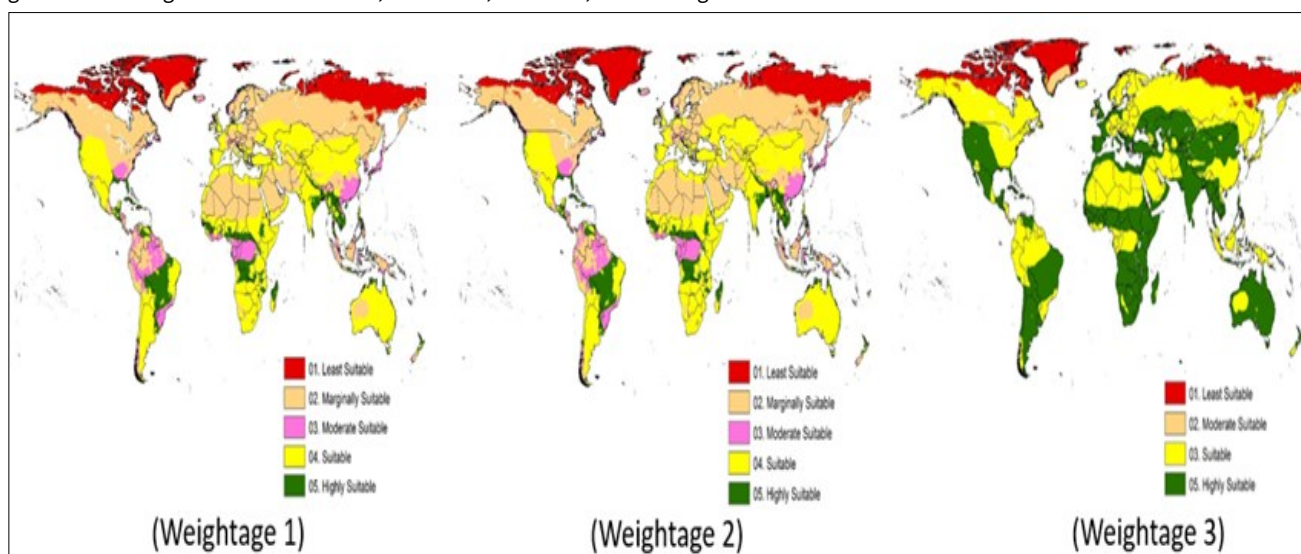
Table 2. Table presenting phenotypic variations in *Chenopodium quinoa* lines evaluated in kharif and rabi seasons. R-Rabi, K-Kharif, DTF- Days to 50 % flowering, PHT-Plant Height, TGW-1000 Grain Weight, SPY-Single Plant Yield

Genotype	DTF (Rabi)	DTF (kharif)	PHT (Rabi, cm)	PHT (kharif, cm)	TGW (Rabi, g)	TGW (kharif, g)	SPY (Rabi, g plant ⁻¹)	SPY (kharif, g plant ⁻¹)
BO-51	51	40	121	40	3.2	0.6	44	7.4
Chen-254	49	50	94	60	2.2	0.0	7.6	1.6
Co-407	43	43	113	70	4.1	0.4	61	10
D-11912	49	45	75	54	2	0.6	6.3	0.6
D-12047	44	35	96	55	3.7	0.7	56	7.0
D-12377	50	45	83	64	2.2	0.0	21	0.0
D-12401	51	35	70	42	2.1	0.4	11	0.0
D-12406	49	43	49	45	1.9	0.4	3.2	0.3
ICBA-Q3	56	46	118	68	3.5	0.6	35	6.1
ICBA-Q5	42	50	89	55	3.8	0.4	9.3	1.6
Titicaca	39	52	58	45	3.6	0.5	11	2.9

Table 3 (a). ANOVA and LSD for genotypes and seasons across traits

Source	Df	DTF_MSS	PHT_MSS	TGW_MSS	SPY_MSS
Trt	10	40.273***	912.564***	0.951***	601.221***
Season	1	138.273***	12311.273***	69.754***	4715.874***
Trt:season	10	73.073***	436.273***	0.606***	322.390***
Season:rep	2	0.364ns	19.405ns	0.021ns	0.453ns
Residuals	20	1.364	36.429	0.034	8.178

Significance coding on MSS: *** $P \leq 0.001$, ** $P \leq 0.01$, * $P \leq 0.05$, ns = non-significant.

**Fig. 1.** Global agroclimatic suitability maps for quinoa cultivation generated using three weighting schemes based on relative humidity, temperature and rainfall layers.**Fig. 2.** Morphological differences among quinoa accessions grown during the rabi and kharif seasons under field conditions.

DTF in rabi and kharif, respectively (Table 3b; Fig. 3). Most genotypes flowered earlier in kharif, although ICBA-Q5, Titicaca and Chen-254 flowered later and Co-407 showed no seasonal change. Plant height ranged from 49 to 121 cm in rabi and 40 to 70 cm in kharif, with all genotypes showing reduced stature under kharif conditions (Fig. 4). TGW ranged from 1.9 to 4.1 g in rabi and 0.0 to 0.7 g in kharif; D-12406 and Co-407 recorded the lowest and highest TGW in rabi, respectively, while D-12047 had the highest TGW in kharif (Fig. 5). SPY ranged from 3.2 to 61.0 g in rabi and 0.0 to 10.0 g in kharif; D-12406 remained consistently inferior and D-12377 and D-12401 failed to produce seed under kharif (Fig. 6). Overall, Co-407, D-12047, BO-51 (Figure-7,8) and ICBA-Q3 retained relatively better performance across seasons, whereas D-12406 remained consistently poor.

The Principal component analysis was done using singular value decomposition approach for four traits, total 4 Principal Components were computed out of which 2 had eigen values greater than 1. The highest variation was explained by PC1, viz. 59.2 % followed by PC2 with 29.39 %. The principal component PC1 had positive correlation with variables DTF (0.2817), while negative correlation with variables PHT cm (-0.4762), TGW (-0.5532) and SPY (-0.6228). The principal component PC2 had positive correlation with variables DTF (0.8047) and PHT (0.5863), while negative correlation with variables SPY (-0.0011) and TGW (-0.0937) (Table 4). Thus, genotypes with more negative PC1 scores are the desirable ones for higher plant height, grain weight and seed yield, while genotypes with more positive PC2 are relatively later flowering. Accordingly, the

best genotype is Co-407 (PC1 = -2.6431, PC2 = -0.0231), D-12047 (PC1 = -2.1894, PC2 = -1.5217) is also desirable, with strong association to the productivity traits and a tendency toward earliness. BO-51 (PC1 = -1.1794, PC2 = 0.2521) is another good genotype, ICBA-Q3 (PC1 = -0.9938, PC2 = 2.1037) is favourable for the productivity but late in flowering, so it is useful where longer duration of crop is acceptable. The most average or balanced genotype is ICBA-Q5 (PC1 = -0.0653, PC2 = 0.0124), because it lies very close to the origin; however, this indicates general average behaviour, not superiority (Fig. 9). Genotypes namely D-12406 (1.9853, -0.7750), D-11912 (1.2693, 0.1289), Chen-254 (1.2656, 1.2864), D-12401 (1.1348, -1.2060) and D-12377 (0.8987, 0.6428), are relatively poorer for SPY, TGW and PHT. Titicaca (0.5172, -0.9006) is relatively earlier, but shows poor performance for productivity traits (Table 5).

Discussion

This study demonstrates that quinoa is a potentially climate-resilient and nutritionally superior crop for non-traditional regions; however, its yield performance is strongly influenced by seasonal- and environmental conditions. The global suitability assessment, which classified most countries as suitable to highly suitable across different weighting schemes, supports previous findings on quinoa suggesting the potential for its adoption across a wide range of semi-arid and sub-humid environments (10–12). The persistent low suitability of extreme northern latitudes, despite quinoa's stress

Table 3 (b). Genotype mean performances (PHT = Plant Height; DTF = Days to Flowering; TGW = Thousand Grain Weight; SPY = Single plant Yield; Superscripts (a, b, c) indicate grouping differences based on Fisher-LSD)

Genotype	DTF	PHT	TGW	SPY
ICBA-Q3	51.00 ^a	93.00 ^a	2.050 ^{ab}	20.55 ^c
Chen-254	49.50 ^a	77.00 ^b	1.100 ^c	4.60 ^{ef}
D-12377	47.50 ^b	73.50 ^b	1.100 ^c	10.50 ^d
D-11912	47.00 ^{bc}	64.50 ^{cd}	1.300 ^c	3.45 ^{ef}
D-12406	46.00 ^{bc}	47.00 ^f	1.150 ^c	1.82 ^f
ICBA-Q5	46.00 ^{bc}	72.00 ^{bc}	2.100 ^{ab}	5.45 ^{ef}
BO-51	45.50 ^c	80.50 ^b	1.900 ^b	25.70 ^b
Titicaca	45.50 ^c	51.50 ^{ef}	2.050 ^{ab}	6.95 ^{de}
Co-407	43.00 ^d	91.50 ^a	2.250 ^a	35.50 ^a
D-12401	43.00 ^d	56.00 ^{de}	1.250 ^c	5.50 ^{ef}
D-12047	39.50 ^e	75.50 ^b	2.200 ^a	31.50 ^a

Superscripts (a, b, c) indicate grouping differences based on Fisher-LSD at alpha = 0.05.

Table 3 (C), Seasonal mean comparison with LSD (PHT = Plant Height; DTF = Days to Flowering; TGW = Thousand Grain Weight; SPY = Single plant yield; Superscripts (a,b,c) indicate grouping differences based on Fisher-LSD)

Season	DTF	PHT	TGW	SPY
Rabi	47.55 ^a	87.82 ^a	2.936 ^a	24.13 ^a
Kharif	44.00 ^b	54.36 ^b	0.418 ^b	3.42 ^b

Table 4. Table presenting principal component values using phenotype variables (DT, PHT, TGW and SPY)

Traits	PC1	PC2	PC3	PC4
DTF (days)	0.2817	0.8047	0.318	0.4148
PHT (cm)	-0.4762	0.5863	-0.3054	-0.5798
TGW (g)	-0.5532	-0.0937	0.8244	-0.0746
SPY (g plant ⁻¹)	-0.6228	-0.0011	-0.3549	0.6973

Table 5. Principal component scores of quinoa genotypes across four principal components (PC1–PC4)

Observations	PC1	PC2	PC3	PC4
BO-51	-1.1794	0.2521	-0.1861	0.2473
Chen-254	1.2656	1.2864	-0.4565	-0.1731
Co-407	-2.6431	-0.0231	-0.351	0.0021
D-11912	1.2693	0.1289	-0.0828	-0.116
D-12047	-2.1894	-1.5217	-0.347	-0.0611
D-12377	0.8987	0.6428	-0.757	0.0354
D-12401	1.1348	-1.206	-0.4558	-0.1883
D-12406	1.9853	-0.775	-0.0357	0.3553
ICBA-Q3	-0.9938	2.1037	0.5151	0.1705
ICBA-Q5	-0.0653	0.0124	0.9602	-0.5434
Titicaca	0.5172	-0.9006	1.1966	0.2712

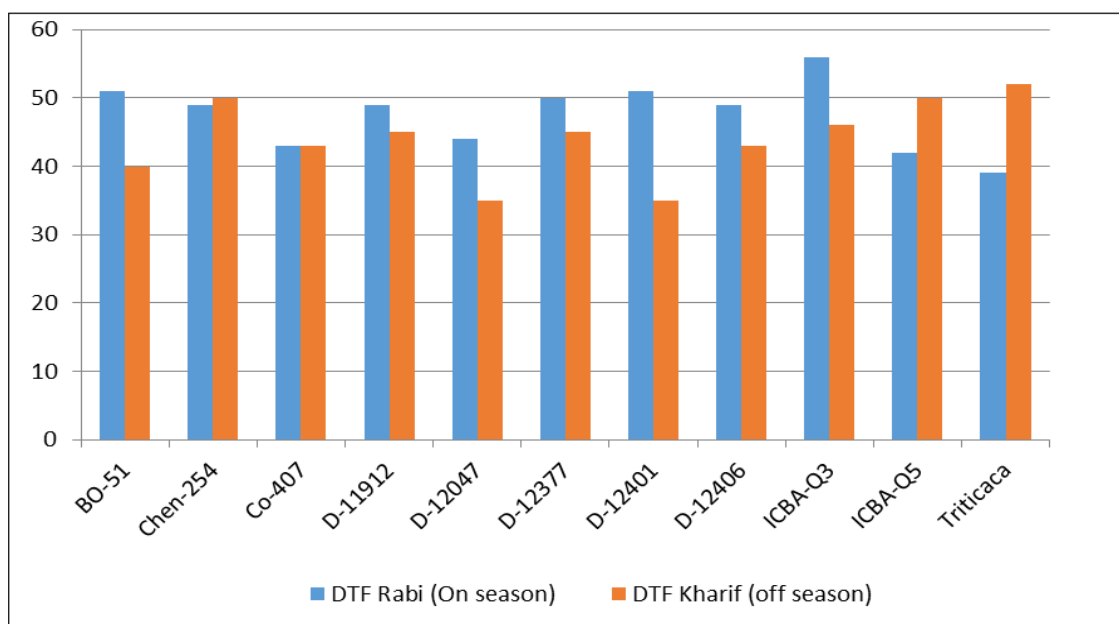


Fig. 3. Days to flowering (DTF, days) of quinoa genotypes grown during rabi and kharif seasons with significant differences among genotypes and seasons determined using least significant difference (LSD) at $p \leq 0.05$.

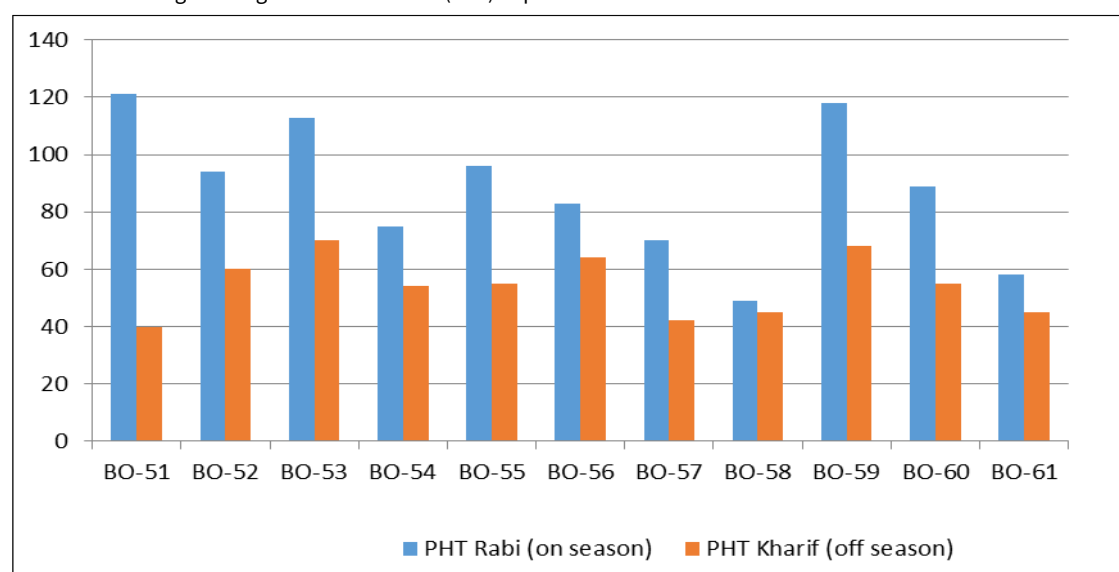


Fig. 4. Plant height (PHT, cm) variation among quinoa genotypes across rabi and kharif seasons with significant differences among genotypes and seasons determined using least significant difference (LSD) at $p \leq 0.05$.

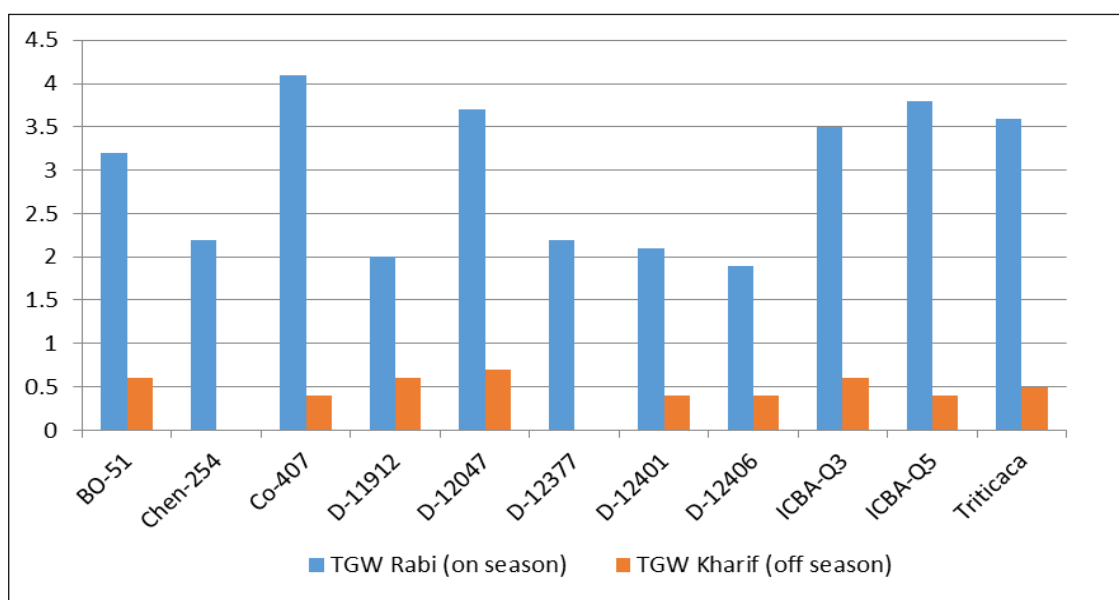


Fig. 5. Comparison of thousand grain weight (TGW, g) of quinoa genotypes between seasons with significant differences among genotypes and seasons determined using least significant difference (LSD) at $p \leq 0.05$.

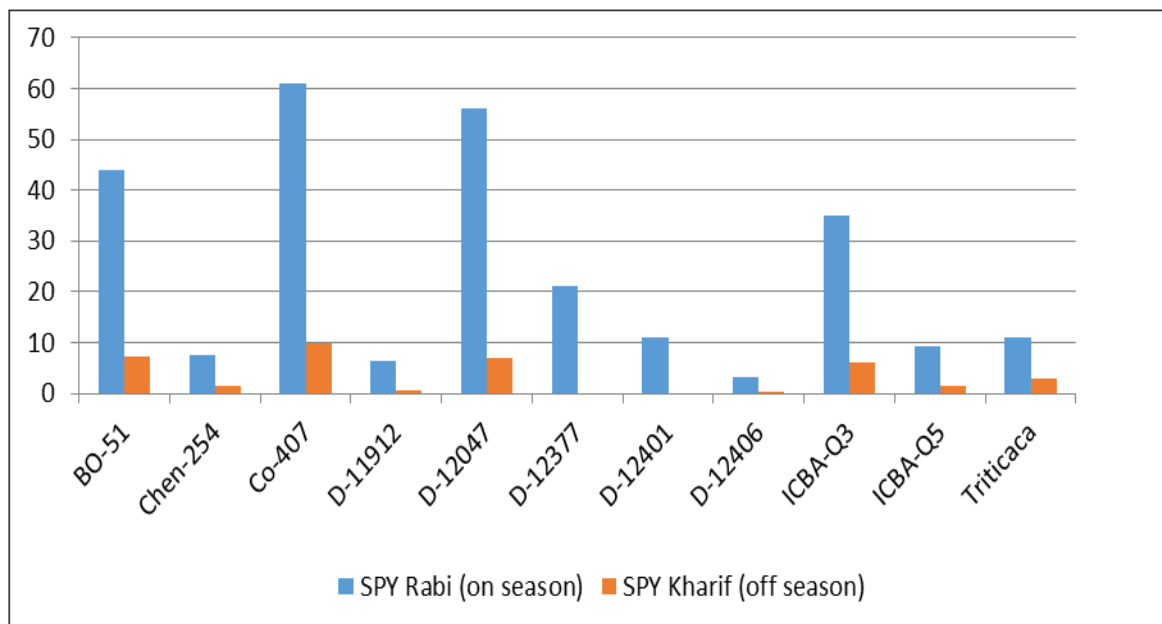


Fig. 6. Single plant yield (SPY, g plant⁻¹) variation among quinoa genotypes under rabi and kharif conditions with significant differences among genotypes and seasons determined using least significant difference (LSD) at $p \leq 0.05$.



Fig. 7. Comparison of grain weight of quinoa genotype BO-51 under rabi and kharif seasons.

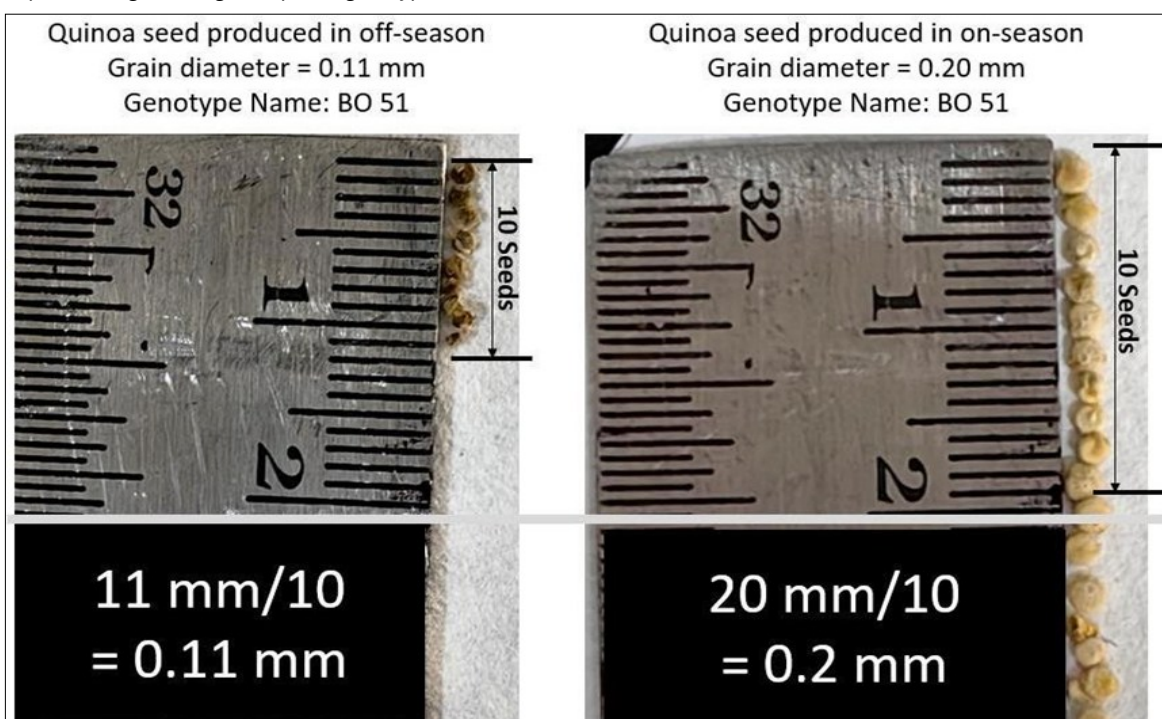


Fig. 8. Grain diameter variation of quinoa genotype BO-51 under rabi and kharif conditions.

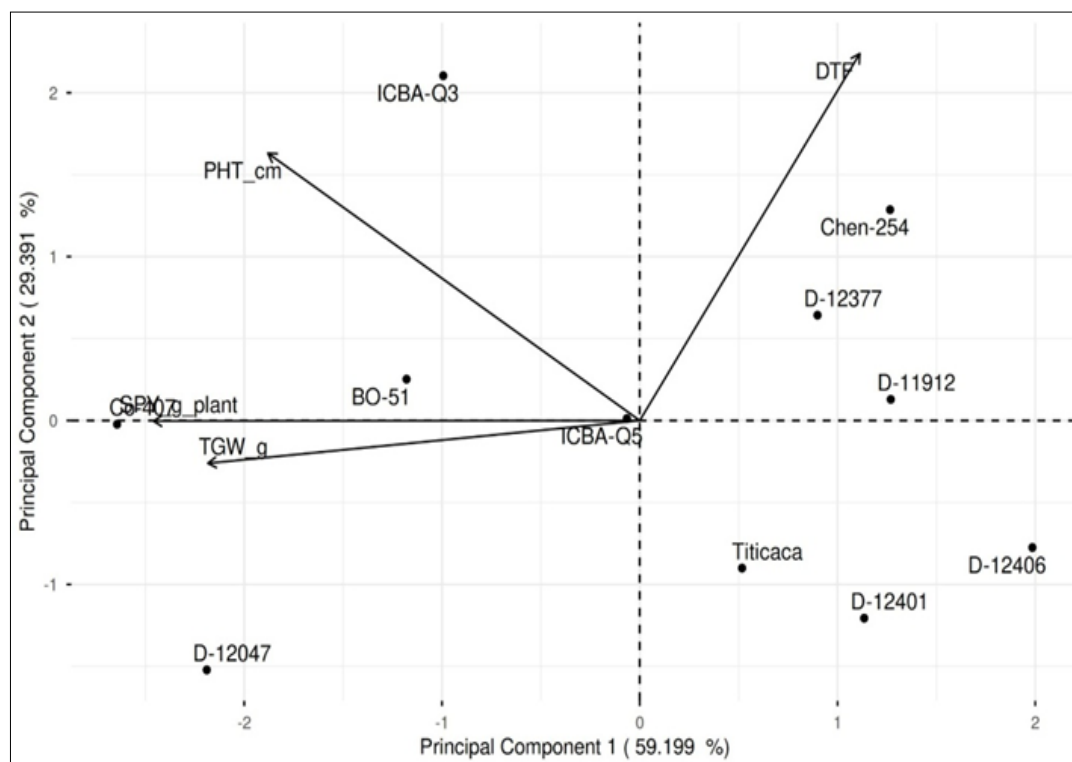


Fig 9: Principal component analysis (PCA) biplot showing association of quinoa genotypes with yield and morphological Traits.

tolerance, suggests that photothermal limits still constrain its cultivation, aligning with observations from high-latitude studies (10,13). Suitability analysis based on spatial distribution maps highlights the importance of quinoa beyond its domestication centre, (the Andes), under conditions of supplemented irrigation. Variations among weighting schemes (1, 2 and 3) emphasize the differential influence of relative humidity and temperature on suitability across regions such as Asia, Africa, Europe and Australia. Notably, assigning zero weight to rainfall resulted in increased predicted suitability, suggesting that quinoa can be successfully cultivated in arid regions, including the Middle East and North Africa, provided irrigation is available. These findings are consistent with previous reports highlighting quinoa's potential in water-limited environments of South Asia and the Middle East (14,15). However, the requirement for supplemental irrigation in desert ecologies, as indicated by weightage scheme 3, reinforces earlier evidence that extreme aridity without irrigation adversely affects crop establishment and yield (12). Overall, quinoa holds considerable promise for integration into existing cropping systems across Asia and Africa, particularly in marginal and water-scarce environments. However, its successful expansion will depend not only on agronomic interventions but also on the development of region-specific, high-performing varieties adapted to local agro-climatic conditions.

The morphological variations among *quinoa* accessions grown during rabi and kharif seasons highlights the species' phenotypic plasticity in response to seasonal climatic variability. Superior growth and reproductive development observed during the rabi season imply that quinoa adapts well to the reduced humidity and lower temperatures that are typical of subtropical climates. Extended vegetative and floral development reduced biotic and abiotic stress and optimal photosynthetic efficiency are likely supported by these conditions (16). In contrast, the reduced growth observed during the kharif season characterized by shorter plant heights, narrower leaves and poor inflorescence development

reflects unfavourable physiological response of quinoa to environmental stressors such as elevated temperatures, erratic rainfall and increased pests and disease pressure. Accelerated or impaired reproductive development under these conditions may be associated with stress-induced flowering, a common drought-escape strategy in annual crops (17). Across the evaluated accessions, plants grown during the rabi season consistently showed superior vegetative growth, inflorescence development, thousand grain weight (TGW) and single plant yield (SPY) compared to those grown in kharif, consistent with findings from winter-sown quinoa studies in India and the Mediterranean region (18,19). The drastic reduction in TGW and SPY under kharif conditions, including complete seed failure in some accessions, indicates that elevated temperatures combined with high monsoonal humidity during flowering and grain filling is particularly detrimental, as also reported under tropical and coastal environments (20,21).

Analysis of variance (ANOVA) revealed highly significant seasonal effects along with substantial genotypic effects, implying that macro-environmental factors predominate phenotypic expression under the tested conditions (22,23). Nevertheless, accession-specific plasticity was evident in certain genotypes; D-12047 and Co-407 showed relatively high thousand grain weight, BO-51 and ICBA-Q5 exhibited stable performance across seasons, whereas D-12377 performed poorly in kharif. This supports classification of genotypes as stable, plastic, or sensitive for targeted breeding in multi-environment quinoa studies (24). Overall, presence of significant genetic variability along with strong genotype $\times$ environment interaction underscores the scope for selection and breeding of quinoa genotypes with improved yield and adaptability. Genotypes such as Co-407, D-12047 and BO-51 can be considered promising candidates for further evaluation and incorporation into breeding programs targeting both stability and high productivity (25).

Conclusion

The study confirms that rabi season is far more productive than kharif for cultivation of quinoa in Indian Subcontinent, though the noted differences in accessions provide a useful starting point for further evaluation in multi-environment experiments. Further, the pronounced seasonal variability and significant genotype × environment interactions observed in this study highlights the need for caution against the indiscriminate promotion of quinoa across diverse seasons and agro-ecological regions solely based on its global reputation as a climate-resilient crop (26,27). Therefore, policy and extension efforts should prioritize region-specific adaptive research focusing on genotype selection and agronomy management practices. These efforts should be complemented by participatory on-farm trials in suitable environments, prior to recommending quinoa as a large-scale diversification option in non-traditional growing regions (28).

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Authors' contributions

PV contributed to the conceptualisation of the study. LM, DS and AS carried out phenotypic characterisation. Data analysis and interpretation were performed by PV, SS, SY and MT. The original draft of the manuscript was prepared by PV and LM. Review and editing were undertaken by PV, SY, KT, AS, MT, RK, SPS, CM, VSG, LM and PV supervised the study. All authors have read and approved the final version of manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

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