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STABILITY OF YIELD IN RESPONSE TO INTEGRATED NUTRIENT MANAGEMENT TECHNIQUES IN QUINOA (*Chenopodium quinoa* WILLD.)

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ABSTRACT

The best treatment combination giving stable yield over the locations for quinoa cultivation in various conditions is crucial for their acceptance by farmers. Moreover, climate change presents novel problems to integrated nutrient management practices, particularly in cereal like quinoa (*Chenopodium quinoa* Willd.), regarding their adaptability to adverse settings. In order to stabilize productivity throughout seasons and geographical areas, In the present study eight statistical methods were employed to determine the optimal combination of inorganic fertilizers. and two bio-inoculants in quinoa tested over three locations during 2021-24. Thre statistical measures namely, Wricke's ecovalence (*Wi2),* geometric adaptability index (*GAI*), sustainability index (*SI*) and deviation from regression (S_d^2) values were determined to be the most suitable and identical in identifying the best treatment over the locations. Based on the mean seed yield, B:C ratio and the three statistical measures, treatment T_5 - 50% RDF+50% N through Farn yard manure (Yield 21.20 q/ha, B:C ratio 2.73), followed by T_7 - 50% RDF + 50% N from *Azadirachta indica* cake (Yield 20.54 q/ha, B:C ratio 0.93) and T_8 - 50% RDF+50% N through FYM + Seed treatment (Azotobactor + PSB) [Yield 20.97 q/ha, B:C ratio 3.03]. Based on the mean seed yield treatment T_2 75% RDF+50% N through Farm yard manure (Farm Yard Manure) was the elevated yield was inconsistent between regions. The inoculants Azotobactor and Phosphate-solubilizing bacteria increased and stabilized the yield over locations as compared to other treatment. Overall, application T_8 - 50% RDF+50% N through FYM + Seed treatment (Azotobactor + Phosphate-solubilizing bacteria) is recommended as a stable and suitable strategies to improve the yield and economic return in Indian situation.

***Key word*:** Environment interaction, Statistical measures, Sustainability index, General Adaptability index, Integrated nutrient management, Bio-inoculants, quinoa

Introduction

Quinoa (*Chenopodium quinoa* Willd.), referred to as the 'Mother of all grains,' is a promising pseudocereal native to the Andean region of South America. Quinoa (Chenopodium quinoa Willd.) is an annual herbaceous plant in the Amaranthaceae family, formerly categorized under the Chenopodiaceae family, native to the Pacific slopes of the Andes in South America. It was cultivated and employed by the Inca nobility since 5,000 B.C. The principal quinoa-producing countries are Bolivia, Peru, Ecuador, and Chile (Coral *et al*., 2014). This crop is presently cultivated in South America, the United States, China, Europe, Canada, and India. Quinoa is successfully grown in the Hyderabad and Ananthapuram districts of

Andhra Pradesh, India. It grows naturally in the Himalayan regions of India. Quinoa is cultivated on 440 hectares in India, producing an average of 1,053 tonnes (Srinivasa Rao, 2015). It is cultivated worldwide on 126,000 hectares, yielding 103,000 tonnes. Bolivia is the predominant producer of quinoa in South America, representing 46 percent of global output, succeeded by Peru at 42 percent and the United States at 6.3 percent (FAOSTAT, 2013). Bolivia, Peru, and Ecuador are the major global producers of quinoa. Rajasthan, Andhra Pradesh, and Uttarakhand are becoming the primary producers of quinoa in India. The The UN General Assembly designated 2013 as "The International Year of Quinoa" to recognize the historic traditions of Andean cultures (Bavec and Bavec, 2006). There is currently increased interest in quinoa production because its seeds possess high-quality protein with a balanced amino acid profile relative to most cereal grains. Quinoa grains are a valuable source of dietary fiber, vitamins, minerals, and natural antioxidants. The Food and Agricultural Organization (FAO) has observed that quinoa exhibits a superior amino acid profile relative to other cereals. The protein in quinoa is comparable in quality to that present in cow's milk (Angeli *et al.*, 2020)

Integrated Nutrient management in cereals crops is a wide approach that not only boosts efficiency but also protects soil fertility, the environment, and economic sustainability. Improper use of chemical fertilizers has caused nutritional imbalance in the soil, instability in productivity and hidden hunger, besides depletion of nutritional quality of the pulse crops (Bairwa *et al*., 2009). The recent concept of integrated nutrient management avoids depletion of soil, organic matter and plant nutrients, besides, suppression of some insect pests and diseases (Gaur 2001). Looking at the availability of the organic manures and existing gap between the demand and supply of quinoa, organic farming could not be taken as a complete substitute for inorganic fertilizers and pesticides. Rather, organic sources can be used as a supplement or partial replacement of chemical fertilizer. Alternatively, the application of bio-inoculants can enhance the efficacy of either the complete or partial dosage of required inorganic fertilizers to achieve affordable yields, ensure sustainability and stability in production, and preserve soil health and an environmentally friendly ecosystem.

Thus, a strategy for judicious use of nutrient resources is the need of the hour. The improved agronomic practices are developed based on multi-environment trials. A fertilizer dose can be recommended when it gives relatively more stable yield across the environments. The bio-fertilizers are cost effective, but are greatly influenced by the environment due to their biological nature. Therefore, balanced use of inorganic fertilizers and bio-fertilizers are important for integrated nutrient management.

Application of 100 % RDF + Bio fertilizers (M4) along with 25% N through poultry manure in quinoa showed greater levels of yield and economic performance and can be recommended for higher plant vigour yield and yield attributes (Veerababu *et al.*, 2021).

Stability indices may help in identifying the widely adapted fertilizer dose and bio-fertilizer. The data regarding the interaction between bio-fertilizers, fertilizers, and the environment is quite scarce in India.

In recent times, numerous farmers have expressed interest in growing this crop because of its nutrient density and ability to adapt to various climates. Owing to the lack of studies on this crop in India, the project aims to standardize nutrition management approaches for quinoa. Simultaneously, increased reliance on chemical fertilizers is adversely affecting soil health. Consequently, the sustainable farming practice of Integrated Nutrient Management (INM) is essential, and this crop shows positive responses to the use of organic and biofertilizers.

Nutritional composition of quinoa varieties is affected by both environmental and climatic factors in various agroecological regions (Gonzalez *et al.*, 2012).

A study was performed to evaluate the effects of Integrated Nutrient Management approaches on growth and yield of quinoa (*Chenopodium quinoa* Willd.) under the National Network on Potential Crops (Raiger *et al.*, 2022).

Keeping this in view, the present research was conducted to (*i*) to evaluate the degree of fertilizer × location interaction in different combinations of inorganic fertilizer doses with bio-inoculants, (*ii*) identify the best treatment combination giving stable yield over the locations, and (*iii*) study relationship and similarities among different statistical parameters utilized to evaluate the stability.

Materials and Methods

The study's data was derived from quinoa (Him Shakti) yield trials using 10 combinations of inorganic fertilizers and bio-inoculants (Table 1), conducted over three years (2021-2024) at three distinct locations in India. The sites were UBKV, Cooch Behar (latitude 26°19' N, longitude 89°27' E, altitude 48 m, sandy soil texture); UAS, Bengaluru (latitude 18°58' N, longitude 77°38' E, altitude 914 m, clay soil texture); SDAU, SK Nagar (latitude 26.7672° N, longitude 83.0361° E, altitude 68 m, primarily

Table 1: Treatment and combination of different fertilizer doses.

Treat-ment	Details of fertilizer doses and combination	Mean Grain yield (q/ha)	B:C Ratio
T_1	100% RDF (60-40-40 NPK/ha)	**20.28**	2.23
T_2	75% RDF+50% N through Farm yard manure (FYM)	**21.39**	2.42
T_3	75% RDF+25% N through Vermi compost (VC)	**20.58**	1.85
T_4	75% RDF+25% N through *A.indica* cake (AC)	**21.37**	1.45
T_5	50% RDF+50% N through Farn yard manure (FYM)	**21.20**	**2.71**
T_6	50% RDF+50% N through Vermi compost (VC)	**20.72**	1.48
T_7	50% RDF+50% N through *A.indica* cake (AC)	**20.54**	0.92
T_8	50% RDF+50% N through FYM+Seed treatment (Azotobactor+PSB)	**20.97**	**3.03**
T_9	50% RDF+50% N through VC+Seed treatment (Azotobactor+PSB)	**20.25**	1.86
T_{10}	50% RDF+50% N through *A.indica* cake(AC)+Seed treatment (Azotobactor+PSB)	**20.28**	1.07
*RDF in quinoa is N:P:K @ 20:40;20 kg/ha			

alluvial soil). A randomized block design (RBD) was employed at each location with three replications. The dimensions of the plot were 4.0 × 3.6 m², with a row-to-row spacing of 30 cm and a plant-to-plant spacing of 10 cm at all sites. The grain yield for every treatment was assessed during harvest at every location. Yield data from eight situations, encompassing three locations over a span of two years, was employed for the stability research. This stability in production is quite significant, particularly amid climate change unpredictability. These findings indicate that this Andean crop can thrive in various environments; however, social and cultural factors are essential when considering its potential adoption as a staple food in new agricultural systems globally. (Bazile *et al.*, 2016).

For original data sets, treatment (*T*), environment (*E*), treatment × environment interaction (*TE*) Variances were determined through a combined analysis of variance (ANOVA). Significance testing was conducted using F-tests.

The interaction sum of squares between treatments and environments was separated into two components. One part represented the heterogeneity of linear regression coefficient (*bi*) and the second part represented the pooled deviation from individual regression line (S_{di}^2) as per the method proposed by Eberthart and Russell (1966) to evaluate the cultivar's reaction to environmental variations. Here, the response to environmental changes in treatment was estimated as under:

$$b_i = 1 + \frac{\sum_j \left(X_{ij} - \bar{X}i. - \bar{X}.j + \bar{X}..\right)\left(\bar{X}.j - \bar{X}..\right)}{\sum_j \left(\bar{X}.j - \bar{X}..\right)^2}$$

$$S_{di}^2 = \frac{1}{s-2}\left[\sum_j \left(X_{ij} - \bar{X}i. - \bar{X}.j + \bar{X}..\right)^2 - (bi-1)^2 \sum_j \left(\bar{X}.j - \bar{X}..\right)^2\right] - \bar{S}_e^2$$

Where,

X_{ij} is seed yield of quinoa for i[th] treatment in j[th] environment, $\bar{X}i.$ is the mean seed yield for i[th] treatment, $\bar{X}.j$ is the mean yield of j[th] environment, $\bar{X}..$ is the grand mean, $\bar{S}_e^2$ is the error variance and *s* is the number of environments.

The effectiveness of fertilizer applications was categorized according to the magnitude of regression coefficient (b_i). The treatments with high yield and regression coefficient (>1) were considered suitable for favourable environments, the treatments with regression coefficient <1 and high yield were deemed appropriate for adverse conditions and the treatments with regression coefficient equal to 1 and having high yield were adapted to all environments. The treatments with minimum deviation from regression (S_{di}^2 being almost equal to 0) were most stable.

The environmental variance acts as an important indicator for evaluating the notion of statistical stability (Lin *et al.*, 1986) and was determined for each fertilizer treatment throughout the test environments. A treatment exhibiting minimal variance across varied environments was regarded as stable. This measure was calculated as follows:

$$S_{ti}^2 = \frac{\sum_j \left(X_{ij} - \bar{X}i.\right)^2}{\left(s-1\right)}$$

Where,

X_{ij} is the grain seed yield of i[th] treatment in j[th] environment, $\bar{X}i.$ is the mean seed yield of i[th] treatment and *s* is the number of environments.

The superiority index (*PI*) measures the adaptability or suitability of treatment across various environments. It uses the treatment with the highest seed yield in each environment as a benchmark for calculations. The treatment that shows the greatest yield difference relative

to the reference treatment would possess the highest P_i value (Lin and Binns 1988), however, the stable therapy will possess a reduced P_i value.

$$P_i = \frac{\sum_j \left(X_{ij} - M_e\right)^2}{2s}$$

Where,

X_{ij} is the seed yield of the i^{th} treatment in j^{th} environment, M_e is the seed yield of the treatment with maximum yield at j^{th} environment and s is the number of environments.

The Wricke's (1962) ecovalence is normally used for genotype interaction assessment. However, it was utilized here for assessing the interaction between fertilizer treatment and environment as follows:

$$W_i^2 = \sum_j \left(X_{ij} - \bar{X}i. - \bar{X}.j + \bar{X}..\right)^2$$

Where,

X_{ij} is the observed yield of i^{th} treatment in j^{th} environment (average value across replications), $\bar{X}i.$ and $\bar{X}.j$ correspond to mean of i^{th} treatment j^{th} environment respectively, and is the grand mean. Greatest stability is when $W_i^2 = 0$.

Coefficient of variance stability parameter, as usual, is measured by use of following formula.

$$CV_i = \frac{\sqrt{\sum \left(Xij - Xi.\right)^2 / n}}{\bar{X}i.} \times 100$$

The approach with low CV and high average yields was considered the most preferable.

In the case of geometric adaptability index, the geometric mean serves to assess the adaptability and appropriateness of the treatments (Mohammadi and Amri 2008) and is calculated as below:

$$GAI_i = \sqrt[s]{(X_{i1})(X_{i2}).....(X_{is})}$$

Where,

X_{ij} seed yield of i^{th} treatment and j^{th} environment and s is number of environments. The treatments featuring elevated GAI will be preferable.

The sustainability indices were calculated using the formula below (Gangwar *et al.*, 2004). It indicates that treatment with a high SI will be favorable.

$$SI = \frac{\bar{X}i. - \sigma n}{M_e} \times 100$$

Where,

Table 2: Analyzed variance collectively for seed yield across 10 fertilizer treatments assessed through six sites.

Source	d.f.	MS
Treatment (T)	9	1.20
Environment	5	127.73**
Treatment X Envion.	45	5.26**
Env+Treatment X Env	50	17.51
Env. (linear)	1	638.65**
G×E (linear)	9	15.77**
Pooled deviation	40	2.37
Pooled Error	108	2.31
Average Error	108	0.69
* P < 0.05; ** P < 0.01		

$\bar{X}i.$ is the average performance of i^{th} treatment across the locations, σn is the standard deviation and M_e best performance of the i^{th} treatment across environments.

The relationship among these statistical parameters was estimated using Spearman's rank correlation (Spearman 1904). To understand the relationship among these measures, three categories have been proposed. In Category-I are those measures which are positively and significantly correlated with mean seed yield, in category-II are those which are positively and non-significantly correlated with seed yield and in category-III are those which are negatively correlated with mean seed yield.

Results and Discussion

Joint variance analysis for seed yield across different environments has been presented in Table 2. The differences caused by environmental factors, fertilizer applications, and their interactions were very significant ($P \leq 0.01$). The overall mean seed yield of the treatments in various places throughout three years (Table 3) also showed that there were wide variations in yield over locations and years and thus, the treatment × environment interactions were evident. Under such situations, it becomes difficult to identify the most suitable treatment just founded on the average performance and therefore, estimation of stability parameters becomes essential.

The notable genotype × environment interaction suggests that the grain yield of genotypes varies from one environment to another because of differences in climatic and soil factors (Jokarfard *et al.*, 2024).

However, based on the mean performance (Table 4) treatments T_2, T_4, T_5, T_8 and T_6 were better than treatments T_3, T_7 and T_{10}, T_1 and T_9.

The use of various manure sources, whether individually or combined with fertilizer and biofertilizers, notably influenced the growth and yield of quinoa. Using

Table 3: Mean seed yield of 10 treatments at four sites across three years.

S. No.	Location	Year	Mean Grain yield (q/ha)
1	Bengaluru	2021-22	15.09
2	S.K. Nagar		21.90
3	Cooch Behar		18.90
4	Bengaluru	2022-23	20.06
5	S.K. Nagar		25.10
6	S.K. Nagar	2023-24	23.51
Mean Grain yield (q/ha)			**20.76**

a treatment of 50 percent nitrogen dose (ND) and 50 percent N from vermicompost (VC), along with seed treatment (Azotobacter + PSB), resulted in significantly higher grain yield and stover yield compared to the application of 100 percent fertilizer dose (Bindu *et al.*, 2024).

As per the statistical parameter b_i, the treatments T_2, T_4 and T_5 with high yield and regression coefficient (b_i) higher than 1 were most suitable to favorable environments, whereas treatment T_7, with moderate seed yield and $b_i \approx 1.0$ could be considered as suitable for all the environments. Treatments T_8 with $b_i < 1$ and good seed yield were well adapted to poor environments. The treatments T_7 and T_5 with higher mean seed yield and regression coefficient being equivalent to 1 had low deviation from regression also. Therefore, these treatments had good combination of yield and stability. This indicated that the combination of PSB and *Rhizobium* either with 50% RDF+50% N through *A.indica* cake (AC) (T_7) or 50% RDF+50% N through Farn yard manure (FYM) (T_5) is important to get higher and stable yields in quinoa. The treatment T_1 (100% RDF (60-40-40 NPK/ha) also gave higher average seed yield over locations but because of having higher values of b_i (1.79) and S_{di}^2 (21.53**) was not stable in its performance.

According to environmental variance S_{ti}^2, T_{10} followed by T_8, T_9, T_6 had lower variances across the environments and therefore were considered as stable in performance, whereas T_1 followed by T_2, T_5, T_3 showed higher variances (Table 4) and thus were not stable in their performance. Similarly, treatments T_5, T_7, T_3 and T_6 had lower Wi^2 values and were stable in performance, whereas treatments T_9, T_1, T_2 T_8 and T_{10} had higher Wi^2 values and were unstable. Based on coefficient variance parameters (*CV*), the treatments T_{10}, T_8, T_9 and T_6 were considered to be stable as they had low values, whereas treatments T_1, T_2, T_4 and T_3 showed higher coefficient of variances and were considered to be unstable.

A per *Pi* values, the treatments T_8, T_{10}, T_6, T_9 and T_7 were considered stable as they had lower *Pi* values (Table 4).

As per *GAI* parameters, the treatments T_4, T_8, T_5 and T_2 were the best for yield stability, whereas the treatments T_1, T_9, T_3 and T_4 were poor in this respect (Table 4). Further, the treatments T_8, T_{10}, T_6 and T_9 also showed better sustainability as against the treatments T_1, T_2 and T_3 which showed poor sustainability indices (Table 4).

The association of various statistical measures with average seed yields. The average seed yield had a significant positive correlation with Wi2, GAI, Sdi2 (Category I), a non-significant positive correlation with Sti2, PI, CV, and bi, SI (Category II), and no significant negative correlations were noted (Category III) has been

Table 4: Mean seed yield and stability values as per different statistical measures of 10 fertilizer treatments tested in 6 environments in quinoa.

Treatments code	Mean Grain yield (tonnes/ha)	*Sti2*	*PI*	*Wi2*	*GAI*	*CV*	bi	*Sdi2*	*SI*
T1	20.28	45.19	49.75	61.31	19.31	33.16	1.79	21.53**	48.16
T2	21.39	30.52	33.28	21.89	20.74	25.83	1.52	4.41	57.06
T3	20.58	20.72	32.21	10.91	20.16	22.12	1.23	7.65*	58.40
T4	21.37	22.58	28.71	11.81	20.91	22.24	1.29	6.38	60.24
T5	21.20	17.04	17.75	3.14	20.83	19.48	1.14	1.85	66.12
T6	20.72	9.21	5.67	11.74	20.51	14.65	0.77	8.32*	78.13
T7	20.54	14.46	14.41	6.59	20.24	18.51	1.01	6.58	67.95
T8	20.97	5.30	3.20	18.88	20.85	10.98	0.56	6.51	83.41
T9	20.25	6.49	5.86	74.13	20.11	12.58	0.17	30.53**	77.76
T10	20.28	3.54	3.99	16.28	20.21	9.27	0.51	1.01	81.69
Correlation with average Grain yield	1	0.284	0.37	0.639*	0.928**	0.284	0.232	0.770**	0.37
* Significant at P < 0.05; ** Significant at P < 0.01 and bold values indicate stability of the treatment									

indicated in Table 4. The parameters in category I are ideal for identifying the most effective agronomical treatments, and thus, any of these three (Wi2, GAI, and Sdi2) can effectively be employed to determine the optimal stable treatment.

According to these parameters, the optimal stable treatment for the current case is T_5 50% RDF+50% N via Farm yard manure (FYM), succeeded by T_7 50% RDF + 50% N via *A.indica* cake (AC) and T_8 50% RDF+50% N via FYM + Seed treatment (Azotobactor + PSB). The treatment T_2 75% RDF+50% N using Farm yard manure (FYM) produced a high average seed yield, but it lacked stability across different environments. Therefore, it was evident that the inoculation of Azotobacter + PSB was crucial for achieving higher and consistent yields across different environments in quinoa. Utilization of a treatment combining 50 percent nitrogen dose (ND) + 50 percent N via vermicompost (VC) + seed treatment (Azotobacter + PSB) significantly impacts grain yield and straw yield compared to the application of a complete 100 percent fertilizer dose (Bindu *et al.*, 2024).

Pulses have shown that treating with these two bio-agents enhances seed yield and various growth factors in chickpea (Saini *et al.*, 2004, Rudresh *et al.*, 2005) and greengram (Ghosh and Joseph, 2008).

A comparable outcome was observed in the significantly increased grain and stover yield of grain amaranth in the treatment combining 50% ND + 50% N via vermicompost plus seed treatment (Azotobacter + PSB), attributed to the ample availability of nutrients from both organic and inorganic sources, alongside effective microbes in biofertilizers, fostering a positive environment for plant growth that improves growth and yield metrics (Neeraja and Patel, 2015).

Performance of treatments with seed yield and B:C ratio

Yield and yield parameters were determined to be significant due to integrated nutrient management. Among different integrated nutrient managements, grain yield (21.39 q/ha) were significantly higher in T_2 - 75% RDF+50% N through Farm yard manure (FYM) which was at par with T_8 - 50% RDF+50% N through FYM + Seed treatment (Azotobactor + PSB) (20.97 q/ha) and T_4- 75% RDF+25% N through *A.indica* cake (AC) (21.37 q/ha). However highest B:C ratio (3.03) was found with T8 - 50% RDF+50% N through FYM + Seed treatment (Azotobactor + PSB). Economic analysis is at utmost importance in agriculture as it indicates the net return, cost incurred and benefit to cost benefit ratio (B:C) of the agronomic practice. Maximum benefit in terms of net return of quinoa was achieved by T_8 - 50% RDF+50% N through FYM + Seed treatment (Azotobactor + PSB) which is attributed to higher seed yield and comparatively lower cost of nutrients compared to other treatments. Lowest net return under organic fertilization treatment could be due to higher cost of nutrients compared with mineral fertilizers and also comparatively lower seed yield. Further, compared to control, the organic treatment had lower net return and cost benefit ratio (B:C) which is justified by the fact that quinoa can be grown on low fertility soil and need lesser nutrients compared with other crops (Jogendra *et al.*, 2024). Cumulative effect of treatment combination was exhibited in terms of highest yield potential along with highest net return and B:C ratio over control (Singh *et al.*, 2024). INM is a holistic method that integrates a variety of fertilizer sources to promote long-term crop production and soil health management, and it offers a feasible solution to the difficulties produced by traditional agricultural practices (Saini *et al.*, 2025). Seed and stalk yield of quinoa was significantly higher with 100% RDF+ Biofertilizers than rest of the treatments and was on par with the 125% RDF. From economics point of view 100% RDF+ Biofertilizers found to be more remunerative (Veerababu *et al.*, 2021). Soil major nutrients like nitrogen, phosphorus and potassium had a higher significant effect with the application of 50% nitrogen dose (ND) + 50% N through vermicompost (VC) + seed treatment (Azotobacter + PSB) in comparison to application of 100% fertilizer dose (Bindu *et al.*, 2024).

Conclusion

Considering the outcomes achieved in present investigation, it is determined that application of balanced inorganic fertilizers along with bio fertilizer (Vermi compost, PSB and Azotobacter) significantly enhanced the growth, yield in quinoa. This treatment combination may be recommended for quinoa after carrying multilocation trial in India. Further, the cultivation of quinoa must be encouraged since it has strong potential as an effective nutritional food and feed crop, and has excellent features for adaptation in marginal lands under harsh environmental conditions of the India.

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