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SUSTAINABILITY INDEX AND MULTI-TRAIT STABILITY-BASED IDENTIFICATION OF CLIMATE-RESILIENT MAIZE HYBRIDS UNDER MULTI-ENVIRONMENT EVALUATION

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ABSTRACT

Climate variability has emerged as a major challenge to maize production in semi-arid agro-ecosystems, influencing genotype performance and yield stability across environments. Identification of hybrids combining high productivity with stable performance is therefore essential for sustainable maize production and climate-resilient agriculture. The present investigation was conducted during *Rabi*, 2023–24 at three representative maize-growing locations of Telangana, *viz.,* Maize Research Unit (MRU), ARI, Rajendranagar; Agricultural Research Station, Karimnagar and Agricultural Research Station, Tornala. Thirteen maize hybrids along with two standard checks were evaluated in a Randomized Block Design with two replications. Observations were recorded on yield and yield contributing characters. The Sustainability Index (SI) was employed to assess yield stability across environments, while multi-trait stability analysis based on the Ideotype Distance Index (IDI) was used to identify superior hybrids by integrating grain yield and associated agronomic traits. Considerable variation was observed among the hybrids for sustainability and stability parameters. Hybrid BH 419207 recorded the highest Sustainability Index (94.9%), followed by BH 417144 (88.9%) and BH 417177 (82.9%), indicating superior adaptability and resilience to environmental fluctuations. Multi-trait stability analysis further identified BH 419207 (IDI = 0.82), BH 417144 (IDI = 1.14) and BH 417177 (IDI = 1.48) as the most desirable hybrids. The combined application of Sustainability Index and multi-trait stability approaches effectively identified climate-resilient hybrids, and BH 419207, BH 417144 and BH 417177 are recommended for wider evaluation and potential cultivation in Telangana and similar agro-climatic regions.

Keywords: Maize, Sustainability Index, Climate resilience, Multi-trait selection, Grain yield

Maize (*Zea mays* L.) is one of the world's most important cereal crops and is widely recognized as the "Queen of Cereals" because of its high genetic yield potential, wide adaptability, and diverse end uses. Globally, maize is cultivated on approximately 205 million hectares, producing more than 1.2 billion tonnes annually, and serves as a major source of food, feed, and industrial raw materials, including starch, ethanol, and biofuel. In India, maize ranks third after rice and wheat, occupying about 14.4 million hectares with a production of nearly 43 million tonnes during 2024–25 and an average productivity exceeding 3.6 t ha^{-1}. Telangana is one of the major maize-producing states in southern India, where favourable agro-climatic conditions support extensive cultivation during both *Kharif* and *Rabi* seasons, contributing significantly to the feed and processing industries.

Despite substantial genetic improvement in maize productivity, sustaining high yields across diverse environments remains a major challenge because grain yield is strongly influenced by genotype × environment (G×E) interactions. Climate change, characterized by rising temperatures, erratic rainfall, and frequent extreme weather events, has further intensified environmental variability, thereby affecting crop performance and yield stability (Prasanna *et al*., 2021). Such interactions complicate varietal evaluation, as superior performance in one environment may not be consistently expressed under different agro-ecological conditions (Gauch and Zobel, 2019). Consequently, multi-environment testing has become an essential component of maize breeding programmes to identify hybrids with broad adaptation and stable performance (Crossa *et al.,* 2020; Yan *et al*., 2022).

Several statistical approaches have been developed to evaluate genotype stability and adaptability across environments. Among these, the Sustainability Index (SI) provides a simple and effective measure of the ability of genotypes to maintain high productivity under varying environmental conditions by integrating mean performance with yield variability (Hussain *et al*., 2018). In parallel, multi-trait selection approaches have gained considerable importance because grain yield is a complex trait

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governed by several interrelated agronomic characters. Multi-trait stability indices enable simultaneous evaluation of productivity, adaptability, and stability, thereby improving the efficiency of selecting superior genotypes for climate-resilient breeding programmes (Cai *et al*., 2019; Olivoto *et al.,* 2022).

Although maize hybrids are routinely evaluated in multi-location trials, comprehensive information on their sustainability and multi-trait stability under the diverse agro-climatic conditions of Telangana remains limited. Therefore, the present study was conducted to evaluate 13 maize hybrids along with two commercial checks across three contrasting environments during *Rabi* 2023–24 using the Sustainability Index and multi-trait stability approaches. The objective was to identify high-yielding, stable, and climate-resilient maize hybrids with broad adaptation, thereby providing valuable genetic resources for sustainable maize production and future hybrid breeding programmes under semi-arid environments.

MATERIAL AND METHODS

The present experiment was conducted during *Rabi,* 2023–24 at three representative maize-growing environments of Telangana, *viz.,* Maize Research Unit (MRU), ARI, Rajendranagar; Agricultural Research Station (ARS), Karimnagar and Agricultural Research Station (ARS), Tornala. These locations represent diverse agro-climatic conditions with variations in soil type, rainfall distribution and temperature regime. Thirteen maize hybrids were evaluated along with two standard checks. The experiment was laid out in a Randomized Block Design (RBD) with two replications at each location following the procedures outlined by Gomez and Gomez (1984). Each entry was planted in two rows of 4 m length by following a spacing of 60 cm between rows and 20 cm between plants. All the recommended agronomic package of practices were followed to raise a good crop. Data on quantitative characters *i.e.* plant height, ear height, and shelling percentage were recorded on five randomly selected competitive plants in each replication while, grain yield (kg/ha) were recorded on a plot basis. Sustainability Index (SI) was computed following the approach described by Hussain *et al.* (2018) and recently employed by Riaz *et al.* (2023) for evaluating crop adaptability under variable environmental conditions. To facilitate simultaneous evaluation for yield and yield contributing characters, a multi-trait stability framework was employed. All measured traits were standardized using Z-score transformation to eliminate scale differences among variables, as suggested by Olivoto *et al.* (2019).

RESULTS AND DISCUSSION

Yield stability is a critical requirement for maize cultivation under climate-variable environments. The Sustainability Index (SI) analysis revealed substantial differences among hybrids (Table 1). The SI values ranged from 52.6 to 94.9 %, indicating considerable variation in the ability of hybrids to maintain stable productivity across locations. Hybrid BH 419207 recorded the highest SI value (94.9%), followed by BH 417144 (88.9%) and BH 417177 (82.9%), indicating superior adaptability and resilience to environmental fluctuations. These hybrids maintained consistently higher grain yields across environments with minimal variation, suggesting the presence of favourable adaptive mechanisms.

Higher SI values are generally associated with greater yield buffering capacity under variable environmental conditions (Hussain *et al.,* 2018). Similar findings were reported by Riaz *et al.* (2023), who observed that genotypes possessing high sustainability indices exhibited superior adaptability and stable productivity across diverse environments. Likewise, Cairns *et al.* (2021) emphasized that climate-resilient maize hybrids capable of maintaining stable yields under stress-prone conditions are essential for sustainable crop production.

In contrast, hybrids BH 419500, KMH 23-2 and BH 418456 exhibited comparatively lower SI values, suggesting greater sensitivity to environmental variability. Lower sustainability indices indicate larger fluctuations in grain yield across environments and consequently reduced adaptability (Woyann *et al.,* 2022). The simultaneous occurrence of high grain yield and high SI values in BH 419207, BH 417144 and BH 417177 demonstrates that productivity and stability can be effectively combined through appropriate breeding strategies. Similar observations were reported by Prasanna *et al.* (2021), who highlighted the importance of identifying maize hybrids possessing both high yield potential and environmental resilience.

Table 1. Sustainability Index (SI) of maize hybrids evaluated across three locations during *Rabi,* 2023–24

Sl. No.	Hybrid	Grain Yield (kg ha^{-1})	Sustainability Index (%)	Rank
1	BH 419207	12889	94.9	I
2	BH 417144	12122	88.9	II
3	BH 417177	11339	82.9	III
4	BH 418103	10728	79.6	IV
5	RMH 3456(Check)	9813	75.4	V
6	BH 417189	9786	74.8	VI
7	KMH 23-1	9607	72.3	VII
8	BH 419505	9572	71.9	VIII
9	KMH 23-4	9373	69.5	IX
10	KMH 23-3	9173	67.8	X
11	DHM 117(Check)	9149	66.9	XI
12	BH 419215	8608	61.4	XII
13	BH 418456	8213	57.8	XIII
14	KMH 23-2	7991	54.2	XIV
15	BH 419500	7958	52.6	XV

Multi-trait stability analysis

Selection based solely on grain yield may overlook important agronomic attributes contributing to overall adaptation. Therefore, a multi-trait stability framework integrating grain yield, shelling percentage, plant height and ear height was employed to identify superior hybrids. The Ideotype Distance Index (IDI) effectively discriminated among hybrids, with lower IDI values indicating closer resemblance to an ideal genotype possessing superior productivity and desirable agronomic characteristics (Table 2). Hybrid BH 419207 recorded the lowest IDI value (0.82) and ranked first, followed by BH 417144 (1.14) and BH 417177 (1.48). The consistency of rankings obtained through both Sustainability Index and IDI analysis confirms the robustness of these hybrids and their suitability for cultivation across diverse environments. These hybrids combined high grain yield with favourable plant architecture and yield-contributing traits, thereby enhancing their overall desirability. The superiority of BH 419207, BH 417144 and BH 417177 corroborates the findings of Olivoto *et al.* (2019), who demonstrated that multi-trait indices are more effective than single-trait approaches in identifying superior genotypes. Similarly, Olivoto *et al.* (2022) reported that the Multi-Trait Stability Index enables simultaneous selection for productivity, stability and agronomic desirability, thereby improving breeding efficiency. Woyann *et al.* (2022) also observed that integration of multiple traits into genotype evaluation significantly enhances the precision of hybrid selection under multi-environment trials. Intermediate performers such as BH 418103 and RMH 3456 exhibited acceptable adaptation but were inferior to the top-ranked hybrids. Hybrids with higher IDI values, including KMH 23-2 and BH 419500, deviated substantially from the ideotype and therefore exhibited lower overall desirability. Similar trends were observed by Vaezi *et al.* (2023), who reported that genotypes with larger ideotype distances generally possess reduced adaptability and stability across environments.

Implications for climate-resilient maize breeding

Climate change is expected to increase environmental variability and production risks in maize-growing regions. Under such circumstances, hybrids capable of maintaining stable performance across environments become increasingly important. The present study identified BH 419207, BH 417144 and BH 417177 as highly productive and stable hybrids across diverse environments. Their superior performance suggests the presence of adaptive traits enabling efficient resource utilization, enhanced stress tolerance and stable grain production. Prasanna *et al.* (2021) emphasized that the development and deployment of climate-resilient maize hybrids constitute a key strategy for ensuring food and nutritional security under changing climatic conditions. Similarly, Crossa *et al.* (2020) highlighted the importance of integrating productivity and stability parameters for identifying broadly adapted genotypes suitable for future climate scenarios. The superior performance of BH 419207, BH 417144 and BH 417177 indicates their potential for enhancing maize productivity in Telangana and similar semi-arid agro-ecologies

CONCLUSION

The evaluation of 15 maize hybrids across three environments during *Rabi,* 2023–24 revealed significant variation for grain yield and associated traits. Hybrid BH 419207 recorded the highest grain yield (12,889 kg ha^{-1}), highest Sustainability Index (94.9%) and lowest Ideotype Distance Index (0.82), indicating superior productivity and stability. Hybrids BH 417144 and BH 417177 also demonstrated excellent performance across environments. The study confirmed that the integration of Sustainability Index and multi-trait stability analysis provides a comprehensive and reliable approach for identifying climate-resilient maize hybrids. Based on overall performance, BH 419207, BH 417144 and BH 417177 are recommended for wider evaluation and potential cultivation in Telangana and similar agro-climatic region.

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