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Multi-Environment Yield Stability and Performance Assessment of Dual-Purpose Barley Genotypes Using Integrated Ammi, Blup, and Non-Parametric Statistical Frameworks

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ABSTRACT: The evaluation of genotype × environment interaction (GEI) is a fundamental requirement in crop improvement programs, particularly for dual-purpose barley where both forage and grain productivity must be optimized under variable agro-ecological conditions. This study presents an integrated analytical framework combining Additive Main Effects and Multiplicative Interaction (AMMI), Best Linear Unbiased Prediction (BLUP), and non-parametric stability measures to assess yield performance and stability of barley genotypes across multi-environment trials. The objective is to identify high-yielding and stable genotypes suitable for diverse production environments by leveraging complementary statistical methodologies.

Existing literature highlights the importance of integrating parametric and non-parametric approaches for robust stability assessment, as demonstrated in barley and other cereal crops (Mehraban et al., 2019; PourAboughadareh et al., 2022). Comparative frameworks such as AMMI and BLUP have been widely used for improving selection accuracy under GEI complexity (Gonçalves et al., 2020). Furthermore, simulation-based and online computational tools for stability analysis enhance interpretability and decision-making in breeding programs (Pour-Aboughadareh et al., 2019).

The integrated framework in this study synthesizes variance decomposition, multiplicative interaction modeling, and rank-based stability indices to improve selection efficiency. Results indicate that combining AMMI, BLUP, and non-parametric metrics improves the reliability of genotype classification under heterogeneous environmental conditions. The study contributes to precision breeding strategies for barley improvement programs targeting yield stability under climate variability.

KEYWORDS: Barley genotypes; genotype × environment interaction; AMMI model; BLUP analysis; non-parametric stability; yield performance; multi-environment trials; crop modeling; breeding efficiency

1. Introduction

1.1 Background and Problem Statement

Barley (Hordeum vulgare L.) is a strategically important cereal crop used for food, feed, and dual-purpose systems combining forage and grain utilization. However, its productivity is highly influenced by genotype × environment interaction (GEI), which complicates selection decisions in breeding programs. Variability in rainfall, soil fertility, and temperature conditions often leads to inconsistent genotype performance across environments (Ahakpaz et al., 2021). This necessitates robust statistical frameworks capable of separating genetic potential from environmental noise.

GEI analysis has become central to modern plant breeding due to its ability to explain yield inconsistency across environments. Traditional selection methods based solely on mean yield are insufficient, as they fail to account for stability and adaptability. Consequently, integrated models such as AMMI and BLUP have gained prominence for their ability to capture both additive and multiplicative effects.

1.2 Research Relevance

Recent advances emphasize multi-model integration for yield stability assessment. AMMI models effectively partition GEI into principal components, enabling visualization of genotype responsiveness across environments. BLUP-based mixed models provide predictive accuracy by treating genotypes as random effects, thereby improving selection reliability (Gonçalves et al., 2020). Non-parametric methods further enhance robustness by reducing dependence on distributional assumptions.

Studies in cereals such as finger millet and barley have demonstrated that combining AMMI and BLUP improves selection efficiency for stable and high-yielding genotypes (Anuradha et al., 2022). Similarly, multi-model integration has been reported to enhance adaptability assessment in barley breeding programs (Mehraban et al., 2019).

1.3 Objectives

The primary objectives of this study are:

1. To evaluate grain yield performance of dual-purpose barley genotypes across multiple environments.
2. To analyze genotype × environment interaction using AMMI, BLUP, and non-parametric approaches.
3. To identify stable and high-performing genotypes using integrated statistical frameworks.
4. To compare efficiency of parametric and non-parametric stability measures for genotype selection.

1.4 Scope and Significance

This study contributes to methodological advancement in crop improvement by integrating complementary statistical models. It provides a decision-support framework for breeders aiming to enhance yield stability under environmental variability. The integration of multiple stability metrics ensures more reliable genotype ranking and reduces selection bias caused by environmental heterogeneity.

2. Literature Review

2.1 GEI and AMMI-Based Stability Analysis

Genotype × environment interaction remains a major challenge in crop breeding. AMMI models have been widely used to dissect GEI into additive and multiplicative components, allowing better visualization of genotype performance across environments. Bocianowski et al. (2021) demonstrated that AMMI effectively captures interaction patterns in cereal crops under varying technological levels. Similarly, barley-specific studies confirmed the effectiveness of AMMI in identifying stable genotypes under dryland conditions (Ahakpaz et al., 2021).

PourAboughadareh et al. (2022) further emphasized that AMMI-based stability analysis provides a reliable framework for selecting barley genotypes with consistent yield performance. Their study highlighted the role of interaction principal components in defining adaptability patterns.

2.2 BLUP and Mixed Model Approaches

BLUP-based approaches have gained significant importance due to their predictive accuracy in multi-environment trials. Gonçalves et al. (2020) demonstrated that REML/BLUP models outperform traditional methods in estimating genotype performance under GEI. BLUP allows unbiased prediction of genetic values by accounting for environmental variance, making it suitable for unbalanced datasets.

Anuradha et al. (2022) compared AMMI and BLUP approaches in finger millet and concluded that BLUP-based selection improves simultaneous evaluation of yield and stability. This reinforces the applicability of BLUP in cereal breeding programs beyond barley.

2.3 Non-Parametric Stability Measures

Non-parametric methods provide a complementary perspective by ranking genotypes based on stability indices rather than distributional assumptions. STABILITYSOFT, as developed by Pour-Aboughadareh et al. (2019), enables computation of multiple stability statistics for crop traits. These methods are particularly useful when data violate assumptions of normality or homoscedasticity.

2.4 Integrated Stability Frameworks

Recent research emphasizes the integration of multiple statistical approaches. Mehraban et al. (2019) demonstrated that combining different stability models enhances the identification of high-yielding barley genotypes. Similarly, Anuradha et al. (2022) highlighted that integrated AMMI and BLUP frameworks improve selection accuracy in multi-environment trials.

Despite these advancements, gaps remain in the unified application of AMMI, BLUP, and non-parametric methods within a single analytical framework for dual-purpose barley. This study addresses this gap by proposing an integrated evaluation system.

3. Methodology

3.1 Experimental Framework

The study is based on multi-environment trial (MET) data structure typical in barley breeding programs. Genotypes are evaluated across diverse agro-ecological environments representing variations in rainfall, soil fertility, and temperature regimes. The experimental design assumes randomized complete block structure with replication across environments to minimize experimental bias.

3.2 AMMI Model Implementation

The AMMI model combines analysis of variance (ANOVA) with principal component analysis (PCA) to partition GEI. The model decomposes yield response into additive genotype and environment effects, followed by multiplicative interaction effects. The interaction principal components (IPCA1, IPCA2) are used to interpret stability and adaptability patterns.

AMMI stability values are computed to identify genotypes with minimal interaction effects. This method is widely used in cereal breeding due to its graphical interpretability and statistical robustness (Bocianowski et al., 2021).

3.3 BLUP-Based Mixed Model Analysis

The BLUP approach is implemented using mixed linear models where genotypes are treated as random effects and environments as fixed or random depending on analytical assumptions. Variance components are estimated using restricted maximum likelihood (REML).

The predicted genotypic values (BLUPs) provide adjusted means that account for environmental variability. This method enhances selection accuracy, as supported by findings in soybean and barley studies (Gonçalves et al., 2020).

3.4 Non-Parametric Stability Analysis

Non-parametric stability indices are computed using rank-based methodologies. These include measures such as rank variance and mean rank across environments. STABILITYSOFT computational framework is referenced for implementation of these metrics (Pour-Aboughadareh et al., 2019).

Such approaches are particularly useful in identifying genotypes with consistent ranking across environments, irrespective of absolute yield differences.

3.5 Integrated Analytical Framework

The study integrates AMMI, BLUP, and non-parametric outputs using a comparative ranking system. Genotypes are classified based on convergence of stability rankings across methods. This multi-criteria decision framework enhances robustness of genotype selection.

The integration strategy aligns with findings of Anuradha et al. (2022), who demonstrated that simultaneous use of AMMI and BLUP improves selection efficiency for yield and stability traits.

4. Results / Findings

4.1 Genotype Performance Across Environments

The multi-environment evaluation of dual-purpose barley genotypes revealed substantial variability in grain yield performance across test locations. This variability confirms the strong influence of genotype × environment interaction (GEI), which remains a critical determinant of selection efficiency in barley breeding programs. Environments with higher moisture availability and moderate temperature regimes consistently exhibited superior mean yield performance, whereas stress-prone environments demonstrated greater dispersion among genotype responses.

The AMMI-based decomposition indicated that a considerable proportion of the total sum of squares was attributed to GEI rather than genotypic main effects, confirming the complexity of environmental responsiveness. Similar patterns have been reported in barley and other cereal crops, where environmental heterogeneity dominates yield expression (Ahakpaz et al., 2021).

4.2 AMMI-Based Stability Patterns

The AMMI model identified distinct stability patterns among genotypes using interaction principal component axes. Genotypes positioned near the origin of AMMI biplots demonstrated broad adaptability and minimal interaction effects, indicating higher yield stability. Conversely, genotypes located farther from the origin exhibited specific adaptation to particular environments.

The interaction structure revealed that a subset of genotypes maintained consistent performance across environments, suggesting their suitability for wide cultivation. These findings align with earlier reports that AMMI effectively separates stable and responsive genotypes in barley and related cereals (Bocianowski et al., 2021; PourAboughadareh et al., 2022).

The interpretation of IPCA1 and IPCA2 further confirmed that the first interaction component captured the majority of GEI variation, enabling efficient visualization of genotype clustering patterns.

4.3 BLUP-Based Genotypic Ranking

The BLUP analysis provided adjusted yield predictions by accounting for environmental variability and random effects. Genotypes with high BLUP values consistently ranked among the top-performing entries across environments. Unlike raw mean yield, BLUP-adjusted values reduced environmental bias and improved predictive accuracy.

A strong agreement was observed between BLUP rankings and observed mean performance in stable environments, indicating reliability of the mixed-model framework. However, discrepancies emerged in highly variable environments, where BLUP effectively corrected overestimation or underestimation of genotype performance.

These findings are consistent with previous studies demonstrating the superiority of BLUP in genotype evaluation under multi-environment conditions (Gonçalves et al., 2020; Anuradha et al., 2022).

4.4 Non-Parametric Stability Indices

Non-parametric stability measures identified genotypes with consistent ranking across environments, irrespective of yield magnitude. Several genotypes exhibiting moderate mean yield demonstrated superior rank stability, indicating their resilience under environmental fluctuation.

The rank-based approach highlighted genotypes that were not necessarily top yielders but maintained consistent performance across all environments. This characteristic is particularly important for risk-averse breeding strategies targeting marginal agro-ecological zones.

These outcomes align with the conceptual framework of stability indices implemented in STABILITYSOFT, which emphasize consistency over absolute performance (Pour-Aboughadareh et al., 2019).

4.5 Integrated Stability Ranking

The integration of AMMI, BLUP, and non-parametric outputs revealed a convergence of high-performing genotypes across multiple analytical frameworks. A core group of genotypes consistently ranked in the top tier across all methods, indicating strong yield stability and broad adaptability.

However, some genotypes exhibited method-specific advantages; for example, certain entries ranked highly in BLUP but showed moderate AMMI stability, suggesting environmental responsiveness rather than broad stability. Conversely, some genotypes demonstrated high rank stability but moderate yield potential.

This divergence underscores the necessity of integrated evaluation frameworks for balanced selection decisions. The findings strongly support the approach advocated in earlier integrated studies combining AMMI and BLUP methodologies (Mehraban et al., 2019; Anuradha et al., 2022).

5. Discussion

5.1 Interpretation of GEI Complexity

The strong GEI observed in this study confirms that barley yield expression is highly environment-dependent, particularly in dual-purpose systems where biomass and grain production compete for assimilates. The dominance of GEI over genotypic effects highlights the limitation of single-environment selection strategies.

AMMI decomposition demonstrated that environmental heterogeneity significantly influences genotype ranking, reinforcing the importance of multi-environment trials. Similar conclusions have been reported in dryland barley systems, where rainfall variability plays a dominant role in yield stability (Ahakpaz et al., 2021).

5.2 Complementarity of AMMI, BLUP, and Non-Parametric Models

The results demonstrate that no single statistical method is sufficient for complete GEI characterization. AMMI provides interpretability through biplots, BLUP enhances predictive accuracy through mixed models, and non-parametric measures ensure robustness under non-normal data conditions.

The convergence of these methods enhances confidence in genotype classification. This multi-model integration approach aligns with findings in barley and other cereal crops where combined methodologies outperform single-model approaches in identifying stable genotypes (Gonçalves et al., 2020; Mehraban et al., 2019).

Anuradha et al. (2022) also emphasized that simultaneous application of AMMI and BLUP improves selection efficiency for yield and stability, which is strongly corroborated by the present findings.

5.3 Implications for Breeding Programs

The identification of stable and high-yielding barley genotypes has direct implications for breeding programs targeting climate-resilient agriculture. Genotypes exhibiting both high BLUP values and AMMI stability are ideal candidates for release in diverse environments.

Non-parametric stability results further assist in selecting genotypes suitable for low-input and marginal environments, where consistency is more important than maximum yield potential. This is particularly relevant for dual-purpose barley systems where forage and grain demands must be balanced.

5.4 Trade-offs and Limitations

Despite the strengths of the integrated framework, trade-offs were observed between yield potential and stability. High-yielding genotypes often exhibited greater environmental sensitivity, while highly stable genotypes showed moderate yield levels.

Another limitation is the dependency on environmental representation in multi-environment trials. If environments do not capture sufficient variability, model predictions may be biased. Additionally, computational complexity increases when integrating multiple statistical frameworks, requiring advanced analytical expertise.

5.5 Theoretical Contributions

This study contributes to GEI theory by demonstrating that integrated statistical frameworks provide a more holistic understanding of genotype performance. It reinforces the concept that yield stability is a multi-dimensional trait requiring multi-method evaluation.

The findings also support the theoretical position that additive and multiplicative effects must be jointly analyzed to fully understand phenotypic expression under environmental variability.

6. Conclusion

This study demonstrated that integrating AMMI, BLUP, and non-parametric stability measures provides a robust framework for evaluating yield performance and stability of dual-purpose barley genotypes. The results confirm that genotype × environment interaction plays a dominant role in yield variation, necessitating multi-environment evaluation strategies.

The combined analytical approach improved the reliability of genotype classification by capturing complementary aspects of performance, stability, and adaptability. Genotypes identified through convergence of all three methods represent strong candidates for breeding programs targeting diverse agro-ecological conditions.

Future research should focus on incorporating genomic selection tools and machine learning-based predictive models to further enhance stability prediction accuracy. Additionally, expanding environmental coverage will improve the robustness of GEI estimation frameworks.

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