Genotype–Environment Interaction and Stability of Pepino Melon under Abiotic Stress: A Multi-Region Review of AMMI and GGE Approaches

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ABSTRACT

This review focuses on the adaptability of pepino melon across diverse environments, emphasising genotype-environment interactions and AMMI model analysis. It identifies significant variability in genotype performance depending on environmental conditions, highlighting specific genotypes with stable yield and adaptability. The AMMI model effectively captures interaction patterns and helps in the selection of resilient pepino melon varieties. These findings support targeted breeding for enhanced environmental suitability. This review synthesises research on pepino melon adaptability in different environments, genotype-environment interaction, and AMMI model analysis to address the complexity of genotype performance stability under variable agro-ecological conditions. The review aimed to evaluate adaptability across diverse environments, benchmark statistical models with an emphasis on AMMI, identify key phenotypic and genotypic traits associated with stability, compare genotype assessment methods, and analyse environmental stress impacts. Literature was selected based on multi-environment trials and advanced statistical analyses, focusing on studies from Mediterranean, South American, North African, and Asian regions, employing AMMI, GGE biplot, and related models. Findings reveal that AMMI and GGE biplot effectively partition genotype, environment, and interaction effects, identifying stable genotypes with consistent yield and quality traits, however, limitations exist in handling data heterogeneity and environmental covariates. Phenotypic traits, such as yield components, soluble solids, and physiological parameters, correlate strongly with adaptability, while molecular insights into stress tolerance remain under-integrated with GEI modelling. Abiotic stresses, including drought, salinity, and temperature, significantly modulate genotype responses, yet combined stress effects and their genetic bases are insufficiently explored. Comparative analyses indicate no consensus on optimal stability assessment methods, highlighting the need for integrated multi-trait and multi environment approaches. Collectively, these findings underscore the necessity for comprehensive models combining phenotypic, molecular, and environmental data to enhance breeding strategies for resilient *P. melon* cultivars across diverse agro-ecological zones.

1. Introduction

Research on Pepino melon adaptability in different environments, genotype-environment interaction (GEI), and AMMI model analysis has emerged as a critical area of inquiry due to the increasing need to optimize crop performance under variable climatic and agronomic conditions (Prohens *et al.*, 2005; Neto *et al.*, 2025). The cultivation of pepino melon (*Solanum muricatum*) and related melon species has expanded from traditional Andean regions to Mediterranean and semi-arid zones, driven by their nutritional and economic value (Walters *et al*., 2021). Over the past two decades, studies have evolved from germplasm screening and breeding efforts to advanced statistical modelling of genotype performance across environments (Adiredjo, 2024). This research is significant given the challenges posed by climate change, soil salinity, and water scarcity, which affect yield stability and fruit quality (Yang *et al*., 2023). For instance, genotype-environment interactions have been shown to complicate selection processes, with implications for food security and sustainable agriculture.

The specific problem addressed is the complexity of GEI in pepino melon and related cucurbit crops, which hinders the identification of genotypes with broad adaptability and stability (Dhakare & More, 2008). Despite advances in breeding and phenotypic evaluations, there remains a knowledge gap in effectively quantifying and interpreting GEI using robust statistical models such as the AMMI (Additive Main Effects and Multiplicative Interaction) model. Moreover, controversies exist regarding the best analytical approaches to dissect GEI, with some studies favoring mixed models and BLUP-based methods, while others emphasize biplot analyses and multivariate techniques (Firew *et al*., 2019; Assis, 2020; Rahmati *et al*., 2024).

The consequences of this gap include suboptimal cultivar recommendations and limited genetic gains under diverse environmental conditions (Mandalapu *et al*., 2025).

The conceptual framework integrates the definitions of genotype-environment interaction, adaptability, and stability, with the AMMI model serving as a key analytical tool to partition and interpret GEI effects(Assis, 2020) . Adaptability refers to the capacity of genotypes to perform well across environments, while stability denotes consistency of performance. The AMMI model combines analysis of variance with singular value decomposition to capture main effects and interaction patterns, facilitating genotype selection (Rahmati *et al*., 2024). This framework underpins the systematic evaluation of pepino melon genotypes to enhance breeding strategies.

The purpose of this systematic review is to synthesise current knowledge on pepino melon adaptability across environments, elucidate the role of genotype-environment interactions, and critically assess the application of the AMMI model in this context (Kaur, 2016). By addressing the identified gaps, this review aims to provide breeders and researchers with comprehensive insights to improve genotype selection and crop resilience. The value-added lies in consolidating diverse methodological approaches and empirical findings to guide future research and practical applications.

The review methodology involves a comprehensive literature survey of peer-reviewed studies focusing on pepino melon and related cucurbits, emphasising multi-environment trials and statistical analyses of GEI (Neto *et al*., 2025). Inclusion criteria prioritize studies employing AMMI and related models, while exclusion criteria omit non-empirical reports. Analytical frameworks include comparative evaluation of model performance and genotype stability metrics. Findings are organised to reflect adaptability, interaction effects, and modelling approaches (Aragão *et al*., 2015).

1.1 Statement of Purpose

The objective of this report is to examine the existing research on "pepino melon adaptability in different environments, genotype-environment interaction, AMMI model analysis" in order to synthesise current knowledge on the genetic and environmental factors influencing pepino melon performance. This review is important because understanding genotype-environment interactions is critical for breeding programs aimed at improving yield stability and fruit quality across diverse cultivation conditions. By analysing the application of the AMMI model and related statistical approaches, the report aims to elucidate how different genotypes respond to environmental variability, identify key traits associated with adaptability, and highlight methodological advances in stability analysis. Ultimately, this synthesis will support the development of more resilient pepino melon cultivars suited to varying agro-ecological zones.

1.2 Specific Objectives

- To evaluate current knowledge on pepino melon adaptability across diverse environmental conditions and cultivation systems.

- Benchmarking of existing statistical models, particularly the AMMI model, for analysing genotype-environment interactions in melon crops.
- Identification and synthesis of phenotypic and genotypic traits contributing to stability and adaptability in pepino melon.
- To compare the effectiveness of different genotype stability and adaptability assessment methods applied to melon breeding.
- To deconstruct the influence of environmental stressors on pepino melon performance and genotype-environment interaction patterns.

2. Methodology of Literature Selection

More specific search statements at Google Scholar, PubMed research gate like website and by systematically expanding a broad research question into several targeted queries,

- Pepino melon adaptability in different environments, genotype-environment interaction, AMMI model analysis
- Impact of environmental stress on pepino melon adaptability and genotype environment interaction analysis
- Physiological responses of melon genotypes to environmental stressors and their adaptability mechanisms
- Screening Papers: The multiple paper reviewed with the applied Inclusion & Exclusion Criteria to retrieve a focused set of candidate papers for our always-expanding database of 190 research papers. During this process found 88 papers relevant to the review title.
- Relevance scoring and sorting: Impose a relevance ranking so that the most pertinent studies rise to the top of our final papers table. We found 190 papers that were relevant to the research study. Out of 190 papers, 50 were highly relevant.

2.1 Genotype Stability Indices

Over 20 studies quantified genotype stability using indices like HMRPGV, regression coefficients, and AMMI stability values, identifying genotypes with consistent yield and quality across environments (Silva *et al.*, 2019 ; Gupta *et al.*, 2024). Several studies emphasized the importance of multi-trait stability indices to select genotypes combining yield and quality traits (Pramanik *et al.*, 2024). Stability assessments often revealed both broadly adapted and specifically adapted genotypes, highlighting the complexity of breeding for diverse environments (Dehghani *et al.*, 2016).

2.2 AMMI Model Performance

AMMI was widely used to partition genotype, environment, and interaction effects, explaining 10-70% of GEI variance depending on the crop and study design (Mandalapu *et al.*, 2025). Bayesian and weighted AMMI models improved inference and robustness in GEI analysis, especially under data heterogeneity (Silva *et al.*, 2020; Assis, 2020). AMMI combined with GGE biplot provided complementary insights into genotype stability and mega-environment delineation (Malosetti *et al.*, 2013).

2.3 Phenotypic Trait Variation

Key traits influencing adaptability included yield components, soluble solids content, fruit size, photosynthetic parameters, and antioxidant enzyme activities (Sharma *et al.*, 2020; Weng *et al.*, 2022). Morphological and physiological traits such as root architecture, leaf water content, and stomatal conductance were critical under nutrient and water stress (Hussein and Selim, 2020 ; Li *et* *al*., 2022).Molecular traits like gene expression of transporters and miRNAs also contributed to phenotypic variation under stress (Ansari *et al*., 2024).

2.4 Environmental Stress Impact

Abiotic stresses, including drought, salinity, high temperature, and combined stresses, significantly affected genotype performance and interaction patterns (Hussein & Selim, 2020; Yang *et al*., 2023; Weng *et al*., 2022). Stress tolerance was linked to physiological adaptations such as osmolyte accumulation, antioxidant enzyme activity, and ion homeostasis (Akrami & Arzani, 2018; Wang *et al*., 2013). Some studies highlighted the complexity of combined stresses and the non-additive nature of plant responses (Villalba-Vermell *et al*., 2024).

2.5 Comparative Methodological Effectiveness

Mixed models, AMMI, GGE biplot, and multi-trait stability indices were benchmarked, with AMMI and GGE often used in tandem for robust GEI analysis (Olaniyi *et al*., 2013). Novel approaches like Bayesian AMMI, Tucker3, and Procrustes analysis provided enhanced capabilities for multi-trait and multi-environment data (Silva *et al*., 2020; Kirch *et al*., 2024). Physiological and molecular analyses complemented statistical models, offering deeper insights into genotype adaptation mechanisms (Ansari *et al*., 2024; Tiwari, 2019).

3. Overall Synthesis and Conclusion

The body of literature on pepino melon demonstrates that genotype-environment interaction (GEI) plays a pivotal role in shaping yield stability, fruit quality, and adaptability across diverse agro-ecological zones. Multi-environment trials employing advanced statistical models—most notably the AMMI and GGE biplot approaches—have been instrumental in dissecting these interactions, revealing both simple and complex patterns of GEI that influence breeding decisions. These models quantify and visualize genotype stability and adaptability, enabling identification of broadly adapted genotypes as well as those specifically suited to particular environments or stress conditions. The integration of Bayesian and weighted AMMI variants and the use of multi-trait stability indices further refine the robustness and precision of GEI analysis, though challenges persist in handling data heterogeneity and outliers.

Phenotypic traits, including yield components, soluble solids content, fruit size, and physiological traits such as stomatal conductance and antioxidant enzyme activity, emerge as key indicators of adaptability. Complementing these are molecular insights derived from gene expression and transcriptomic studies, which elucidate underlying mechanisms of stress tolerance, particularly for drought, salinity, and high-temperature humidity stresses. Such physiological and molecular traits provide a biological basis for the observed GEI patterns, although comprehensive integration of omics data with GEI models remains limited. Environmental stressors are shown to exert significant effects on genotype performance, and while individual stresses have been extensively studied, combined stress effects and their regulatory complexities—such as miRNA-mediated responses—are less well understood and warrant further exploration.

Methodologically, the literature underscores the comparative effectiveness of combining AMMI and GGE biplot analyses, often alongside mixed models and novel multivariate techniques like Tucker3 and Bayesian approaches, to achieve a more nuanced understanding of genotype stability and adaptability. Despite no universal consensus on the optimal stability assessment method, these tools collectively enhance decision-making in breeding programs. However, existing studies often differ in environmental scope, trait focus, and experimental rigor, limiting direct comparability and generalization. There is a clear need for standardized protocols integrating physiological, molecular, and statistical analyses to better predict genotype performance under fluctuating field conditions.

In sum, the current research landscape affirms that successful pepino melon breeding for adaptability hinges on a multidisciplinary approach combining thorough Multi-environment phenotyping, advanced GEI modelling, and mechanistic insights into stress physiology and genetics. Advancing the integration of genomic and environmental data into predictive models promises to accelerate the development of resilient, high-yielding pepino melon cultivars tailored to diverse and changing environments.

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