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GENETIC ADAPTATION PATHWAYS AND ENVIRONMENTAL ZONING CLASSIFICATION MODELS—A REVIEW

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SUMMARY

This study aimed to develop special paths for genetic-environmental interference and classify them based on their economic yield. As for genetic composition, the appropriate environment is the basic condition in developing superior cultivars through breeding programs. Genetic variation helps in distinguishing genetic compositions under different environments and maintaining their economic yield for long and short terms. Flexible genetic variation enables the genotypes to adapt to the changing environment and develop genes for resistance to various stress factors while stabilizing their production. Based on this, the classification of environments depended on their productive capacity into ideal, very suitable, suitable, and weak, depending upon the crop goals. Therefore, this study aimed to determine the percentage of genotypes' contribution to ideal, appropriate, and specialized environments and their patterns of environmental distribution. The genetic-environmental interactions also reached either a positive or negative interpretation, depending on the genotypes' response to the existing environment, as per plastic models and diagrams that facilitate the classification process.

Keywords: Genotypes, breeding programs, genetic pathways, environmental variations, environmental classification, genotype-by-environment interactions

Key findings: The results confirmed that knowledge of genotype-by-environment interactions is the key factor in developing plant cultivars resilient and adaptable to climate change.

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INTRODUCTION

Crop improvement is crucial for sustainable productivity and meeting global food demands in the face of various challenges, such as climate change, shrinking arable lands, and increasing population growth (Zhao *et al*., 2017; Méndez-Vallejo *et al*., 2023). Therefore, exploiting genetic diversity for a suitable environment is the cornerstone of any breeding program (Cooper *et al*., 2023). It is a fact that heterogeneity of crop patterns allows them to grow in varied environmental conditions (Yang *et al*., 2023). By comparing the performance of genetic combinations under different environmental conditions, the considerable differences were evident in their performance (Blum, 2013). Genotypes of different plants show different reactions according to the variation of environmental conditions, as these plants may achieve prominent growth and productivity in certain environments that are beneficially suited to their genetic and physiological needs. However, their migration to other environments varies in their climatic factors, with a significant reduction in their performance (Bulekova *et al*., 2025).

Crop breeding programs are constantly seeking to classify crops according to their productivity, quality, and ability to tolerate the biotic and abiotic stresses by selecting the appropriate crop for each environment (Zandalinas *et al*., 2018). Genetic variation also has a profound impact on genetic diversity and specialized environments by selecting and distributing the desired crops to the environments and not neglecting other cultivars, especially wild ones and those adapted to existing environmental conditions (Cooper *et al*., 2016).

Geographical distribution of genotypes indicates how different genotypes of plants are present and distributed within specific geographical areas based on their adaptation to dominant environmental conditions, i.e., climate, soil, and biological factors. But domestication of new genotypes may cause the restructuring of this distribution. This process enhances the emergence of new farming communities and different production patterns, changing the prevalence map of genotypes previously cultivated in specific environments or at the level of a single environment. The introduction of new varieties may also improve the diversity of agricultural systems and cause the transfer of some genotypes to new environments where they had no previous cultivation (Gao *et al*., 2023). This also depends on the available genetic diversity in the selected genetic compositions and the extent of their genetic base (Espeland and Kettenring, 2018), such as cultivars comprising pure lines and cultivars with external breeding. Moreover, this includes heterozygous cultivars resulting from quantitative selection (Maphosa *et al*., 2020), synthetic cultivars, compound cultivars, and wild types, with these genetic patterns characterized by a wide degree of adaptation under diverse environmental conditions (Thornton *et al*., 2014).

Genotypes developed from a single lineage, which are genetically associated and possess a narrow genetic base, have specific and consistent traits that are readily traceable across generations. It also involves varieties that contain specific genetic lines or are sourced from genetic structures, which have succeeded in their development with the aim of reinforcing desirable characteristics. These genotypes resulted from different hybridization programs, whether crossbreeding or intersibling hybridization, in addition to patterns resulting from the self-replication of specific lines. These strategies lead to increasing the strength of hybrids, enhancing genetic variation within the breed, and aiding in the development of varieties with stable and unique performance under specific environmental conditions. This improves the effectiveness of plant breeding and genetic enhancement programs (Hamdan *et al*., 2025). Combinations of a single seed and genetically modified plant (Oguz *et al*., 2022) and the genetic loss increase at the level of individual genes or a specific genetic group, especially in local strains with low genetic diversity. Furthermore, genetic erosion occurs as a result of a decreased genetic variability in the plant community due to internal mating and genetic drift (Takahashi *et al*., 2018).

Plant population with a narrow genetic base entails exposure to a complete loss in productivity once its growth environment changes, even relatively (Hultgren *et al*., 2025). Environmental conditions and their impact on field crops have reached classification into controllable elements, such as soil type, planting date, plant density, and fertilizer quantities, and uncontrollable elements like rainfall, temperature, and relative humidity (Egea-Gilabert *et al*., 2021). On this basis, an overlap has emerged between the genetic compositions and existing environmental conditions, as well as between the genetic compositions and applied treatments.

A considerable overlap also existed between genetic compositions and crop seasons, as the breeders could not predict by developing models for successive years. There may be the genetic-environmental interactions; however, it does not change the behavior of genetic compositions. Meanwhile, genetic-environmental interference may affect the performance of crop genotypes and their genetic compositions (Des *et al*., 2013; Lu *et al*., 2021). Therefore, the following study aimed to provide an overview of the crop genotypes' ability owing to genetic variations and their adaptation to varied climatic conditions. Likewise, it looked at the resulting effects of the environmental distribution by classifying them and identifying the paths of genetic-environmental interaction.

Environmental triangle for genotypes' distribution

The triangle about the environmental distribution of the genotypes enunciated that in the performance of genotypes, the distribution of stability and variations can occur across the small triangle of environments, as per their adaptation (Figure 1). Most genotypes appeared to be adapted to the most suitable and optimal environments, located at the base of the triangle of environments, which represents the first environment (E1). It was the highest for all the genotypes (G1, G2, G3, G4, G5, G6, and G7), being identified as an optimum environment possessing all the growth and production elements, separating from the group and placed in the second environment (E2). However, the number of adapted genotypes (G1, G2, G3, G4, and G5) decreased in the third environment (E3), except for genotype G5.

The genotypes placed in the middle of the environmental triangle for the third and fourth environments (E3 and E4) in sequence reached environments with special environmental conditions, wherein certain genetic compositions (G1, G2, and G3) showed adaptability and suitability only for these environments. These environments (E1, E2, and E3) sat near the head of the environmental triangle (top of the environmental pyramid). Here, a specific species sustained a specific environment assignment, especially the two genetic compositions (G1 and G2), with the genetic composition (G1) found as the most stable and adapted species to all environments and the most specialized species for the seventh environment (E7).

By moving from optimum to special environments (environments with limited growth and less suitability), adaptation occurred for some genetic compositions, as their certain characteristics changed; some genetic compositions may stabilize from the optimum environments and reach environments with hard environmental conditions. The few genetic compositions stabilize, however, becoming identified as the most adapted genotypes to new environments, being located at the top of the environmental triangle. The absence of particular traits in one genotype and their presence in another emerged as mostly responsible for the adaptation of the genotype to a specific environment. Therefore, the genotypes' ability to adapt and change the growth traits may be due to the presence and absence of specific genes responsible for expression and stability in growth and production traits across the diverse environments (Przybylska *et al*., 2025).

Environments responsible for stable crop yields

These environments are classifiable into:

Table 1. Average plant yield (g) in optimum environment.

VXE	Cultivars					
E	V1	V2	V3	V4	∑X	X̄E
E1	10	30	15	40	95	23.75
E2	39	37	40	36	152	38
E3	20	10	30	39	99	24.75
E4	40	20	15	35	110	27.5
∑V	109	97	100	150	390	114
X̄V	27.25	24.25	25	37.5	114	28.5

Table 2. Average plant yield (g) in the specific environment.

VXE	Cultivars				X∑	X̄E
E	V1	V2	V3	V4		
E1	10	30	15	25	80	20
E2	30	15	20	40	105	26.25
E3	20	10	30	30	90	22.5
E4	40	20	15	20	95	23.75
V∑	100	75	70	115	370	=92.5X∑
X̄V	25	18.75	17.5	28.75	Total X̄= 23.12	

Optimum environment (OE)

The optimum environment can offer the best growth and productivity conditions per unit area for all cultivated cultivars, compared with other environments that achieve yields below and equivalent to the general average. The number of cultivars that can grow and exhibit the highest productivity increases as the environmental conditions become balanced and accommodate a wide range of quantitative and qualitative genetic diversity (Al-Jaf *et al*., 2025).

Productivity may also be high and stable across the most cultivated cultivars (Table 1). The environment E2 was recognizably the best in productivity for all cultivated cultivars, achieving the highest yields for most cultivars (39, 37, 40, and 36 g), respectively, compared with the genotypes' yield obtained in other environments. This means the inability to produce those specific formulations under the different environments (E1, E3, and E4) compared to the environment E2 (Des *et al.*, 2013; Zandalinas *et al*., 2018).

Specific environment (SE)

In specific environments, the number of adaptable cultivars decreases, keeping only certain cultivars tolerant to specific environmental conditions, such as salinity, drought, freezing, and extreme heat. Here, productivity generally declines, and some cultivars often maintain the highest and acceptable levels of economic production if the genetically improved and inbreeding cultivars are designed to withstand specific conditions. This trend was toward a decline in the number of cultivars with decreased productivity (Palmgren and Shabala 2024).

The results further revealed the environments E2 and E4 were remarkably the best in the production of the cultivars V3 and V1 (40 g) versus the rest of the environments that showed lower productivity for all cultivars (Table 2). This means these genotypes have certain special adaptations suitable for increasing their productivity and were not preferable for cultivation in other environments, except after ensuring those environments have the same environmental conditions.

Accordingly, adopting the general average productivity of the environments and cultivars is least preferable, as it does not provide a clear position of the cultivar in its own environment. However, it depends rather on determining an environment for each genotype or a cultivar for each environment independently or the specific adaptation. Past studies also revealed most of the developed hybrids proved suitable for certain environments, compared with synthetic

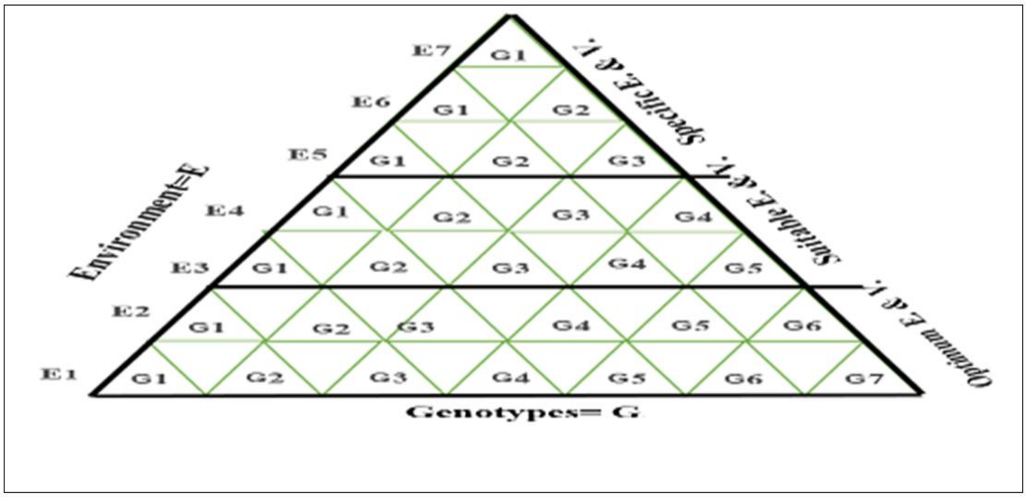

Figure 1. Mujahid's environmental model or environmental triangle for the distribution of genotypes.

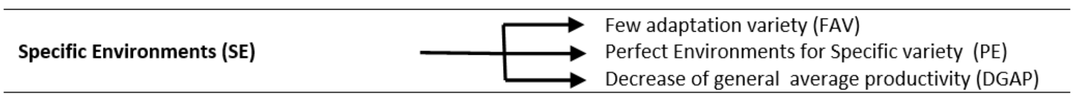

Figure 2. Mujahid's paths to classification and adaptation to specific environments.

cultivars that were more flexible and adaptable to production under different environments (Blum, 2013; Hamdan *et al.*, 2025).

Models of environmental classification

The environment classification could rely on the productivity of each genotype and their position in the proposed schematic figure into five main environments (Figure 1):

Optimum environment types

General optimum environment (GOE)

The said environment occurred suitable for the growth and production of all the genotypes, achieving a production (≥ 100%) higher than the average production, as it possesses ideal and highly suitable environmental conditions for growth and production of any genotype. These environments were few in possessing the same growth requirements during the stages of growth, reproduction, and production (Semahegn, 2026).

Specific optimum environments (SpOE)

The said environment proved suitable for the growth and production of any specific genotype, achieving a production (≥ 100%) higher than the average production in any other environment. These environments possess the conditions found highly suitable for the growth and production of specific genotypes (Figure 2).

Suitable optimum environment (SuOE)

This environment was recognizably suitable for the growth of any genetic combination that achieves a productivity ranging between 80% and 99% of its average productivity. These environments represent most cultivated crops, particularly with genetic combinations introduced for acclimatization purposes, and possess suitable environmental conditions. These environments received classification as optimum, suitable, semi-suitable, average, and semi-poor.

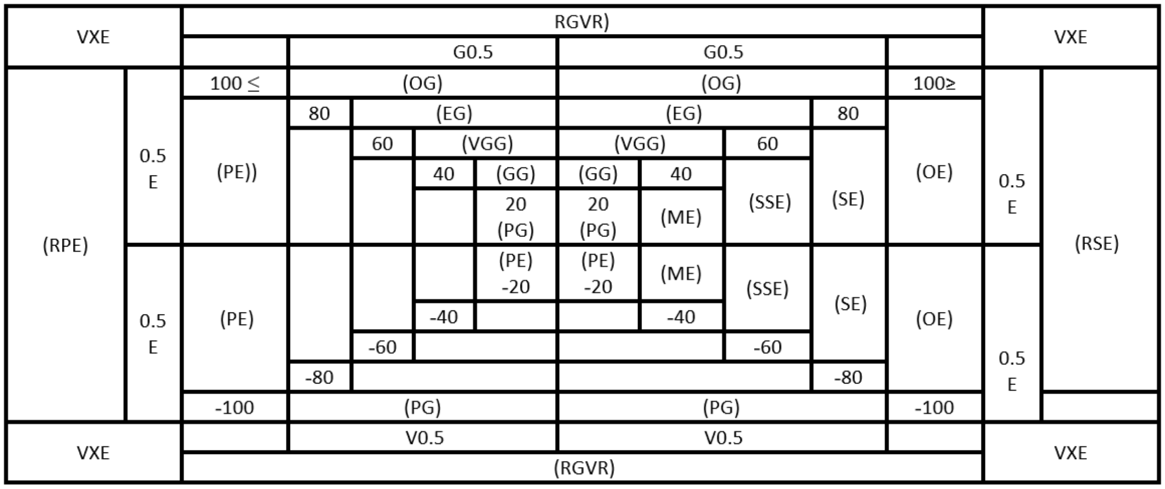

Figure 3. Mujahid's model for classifying environments and the location of species for each environment based on genotypes productivity average. * Variety= (V), Ratio of Good Variety Responsible= (RGVR), Optimum Genotypes= (OG), Excellent Genotypes= (EG), Very Good Genotype= (VGG), Good Genotype= (GG), Poor Genotype= (PG), Ratio of Poor Genotype Responsible= (RPGR).* Environment= (E), Optimum Environments= (OE), Suitable Environment= (SE), Semi Suitable Environment= (SSE), Mid Environment= (ME), Poor Environment= (PE), and Ratio Suitable Environment= (RSE).

Suitable environment (SE)

This was the most suitable environment for the growth of any genetic combination that achieves a productivity ranging between 60% and 79% of its overall productivity. These environments gain considerable effects from environmental stresses to such a degree that production can succeed with a good economic return (Figure 3).

Moderate environment (ME)

The said environment emerged as suitable for the growth of any genetic composition that achieves a productivity ranging between 40% and 59% of its average productivity. These environments usually undergo exposure to environmental stresses, such as salinity, high and low temperatures, and drought, to a higher degree than other environments, but below the critical threshold of impact on growth and productivity. Their environments also obtained recognition as economically feasible, but to a lesser extent (Figure 3).

Poor environment (PE)

With this environment, the genetic combination achieves a productivity of less than 39% of its overall productivity. These environments have extreme and higher conditions of heat, drought, and salinity than the critical threshold for crop growth and productivity, resulting in production falling below economic feasibility. However, these environments can be useful after improving their properties, reclaiming them, and changing their climatic growth conditions (Figure 3).

Classification of genetic-environment interactions

Genetic-environmental influences can entail division into four interactions:

Homogeneous environment interactions (HoEI)

In genotype-by-environment interaction effects, the performance of the genotype

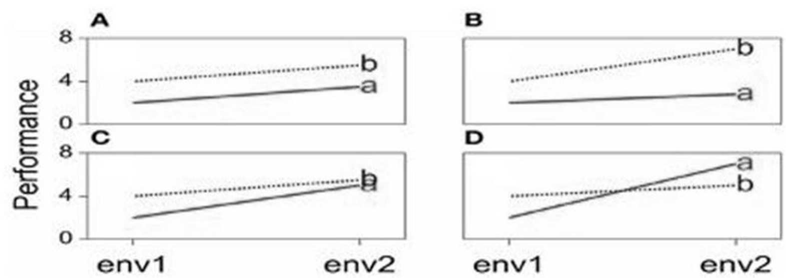

Figure 4. Performance of two genotypes A and B in two different environments (Environ. 1 and Environ. 2).

acquires effects from multiple environments. If it deviates from the general average, it is unstable, while if it approaches the origin and general average, then it indicates the stability of the genotype (Figure 3).

Heterogeneous environmental interactions (HeEI)

This interaction describes the variations in the performance of a group of genotypes grown in multiple environments and multiple seasons, with the influence of different stress factors, leading to different paths than the general average (Mullualem *et al*., 2024).

Complex interactions (CI)

The complex interaction indicates genotypes and how their performance receives impact from various environmental factors. Many environmental stresses like heat, drought, salinity, and others also affect the growth and productivity of plants directly and indirectly. These environmental changes work with the plant's genetic makeup to determine how distinctively each genotype responds (Zakir, 2018).

Predictive interaction environments (PIE)

In this case, the genotypes' performance does not show any kind of interference within the ranges of the study factors, as the genotypes were not close at certain points, do not intersect, and are almost parallel. However, by looking at the chart analysis, an imaginary interference can be evident with study factors' effect on the performance of the genotypes. The independence of environmental influence from genetic influence and their interaction (GE) can be demonstrated by testing several genotypes (b and a) in two different environments (E1 and E2) in several directions (Figures 4 A, B, C, and D). Figures 4 A and B showed the absence of interaction (GE) for the two genotypes (a and b), while the interaction in Figure 4C was at the highest average for the two classes (a and b) in environment E2. Figure 4D provided the highest interaction effect and revealed that the genotype was better than the genotype b in environment (E2); however, it emerged with a lower performance in environment E1.

Classification of genetic variations based on heritability

Genetic variations can be classifiable as non-genetic variations. If a change occurs in vegetative tissues, the inheritance of new traits only appears through vegetative propagation. In nature, changes may occur in the offspring that were different from the traits observed in the parental genotypes. Since most of these traits are not inherited, which also do not appear in the offspring when grown under natural conditions, the non-inherited traits can seemingly be temporary acclimatization (Campbell *et al*., 2022). The lack of inheritance of these traits could be due to the unaffected genetic content of the parental genotypes and their offspring. A plant may re-establish its growth paths and regain its growth traits in response to the stresses in its existing

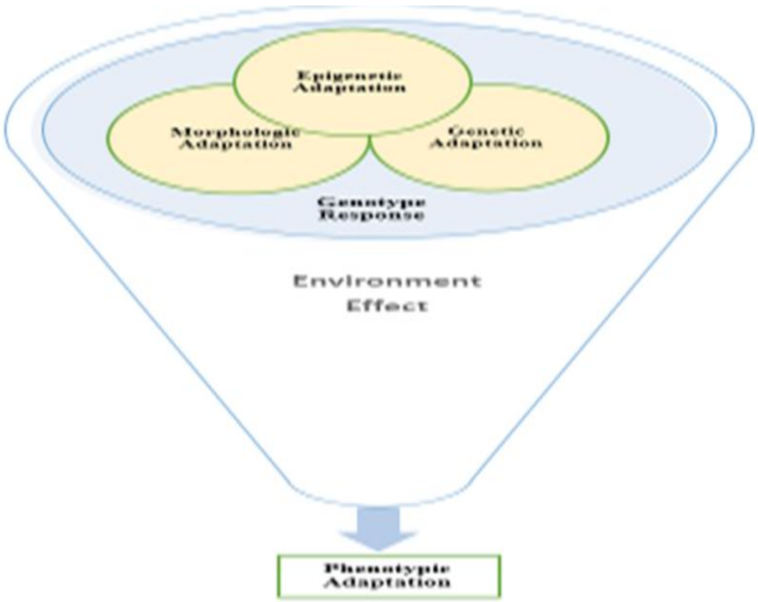

Figure 5. Mujahid's model (Ice Cream adaptation) effect of genetic, phenotypic, and epigenetic adaptation on the phenotypic adaptation of the genotype.

environment (Cheong, 2021). This means it adapts in any way that increases its ability to survive and adapts to its surrounding environments in an inherited manner under the natural environment. This is where epigenetic variation occurs. But often, a plant changes its genetic expression to be more durable to withstand harsh environmental conditions. Over time, it adds a new, stable, and resistant appearance that helps it withstand those conditions, whether specific or random, which is called as inherited genetic variation (Figure 5, Ice Cream Adaptation Model).

CONCLUSIONS

The genotype-by-environment interaction (GEI), with a significant impact on the genotype adaptation, may cause the presence of gene-gene interaction, leading to genotypes being arranged differently across diverse environments. Selection efficiency decreases when the relationship between phenotype and promising genotype decreases. GMOs can entail adoption by targeting high-yielding environments, resulting in crop responses when growing conditions improve.

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