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Review Article

Plant Breeding Challenges Posed by Genotype-Environment Interaction and Methods of Measurement

Wakuma Merga

Ethiopian Institute of Agricultural Research, Teppi Agricultural Research Center, Teppi, Ethiopia

Email address:
wakumerga@gmail.com

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Abstract: Plant breeders' ultimate goal in a crop improvement program is to generate varieties with high yield potential in order to sustain high agricultural productivity. In addition to great yield potential, a new cultivar should have stable performance and extensive adaptation over a wide range of settings in addition to great yield potential. The presence of genotype by environment interaction (GEI) interactions is of major concern to plant breeders, as large interactions can reduce selection gains and make identifying superior cultivars more difficult. It is also of major concern to crop breeders, as phenotypic responses to changes in the environment differ among genotypes. However, phenotypic response varies by location as it is influenced by biotic and a biotic factors as well as environmental factors. The importance of GEI cannot be overstated. It is critical for lowering genotype mean in various contexts. It is utilized as a test of genotype adaptability to the expression of specific phenotypes in diverse environments, and it is a continuous effort of plant breeders due to environmental variation across different locations and throughout time. The fundamental goal of multi-environment trials is to monitor genotype stability across environments, identify superior genotypes, and determine which location best mimics the target environment for production. GEI is critical for lowering genotype mean in various contexts. It aims to generate varieties that are resilient to climate change pressures and a variety of other stresses tolerance or resistance to key biotic stresses like drought, salinity, etc. as well as biotic ones like diseases and pests while also improving human skills.

Keywords: Adaptability, Genotype, Multi-environment Trail, Stability

1. Introduction

Genotype by environment interaction (GEI) is commonly documented in multi-environment agricultural plant experiments around the world, and it is very essential in plant breeding. Different genotypic performance across environments is always observed in multi-environment crop trials, resulting in dissimilarity and position shifts between genotypes [1]. It encompasses the majority of quantitative traits, such as grain yield, as well as aspects of economically viable traits. The importance of genotype by environment interaction and yield instability in agricultural plant development was addressed in the most current publication of the Plant Genome Project (PGP), a journal of the American Society for Plant Genetic Analysis and Synthetic Biology [2].

Genotype by environment interaction and yield instability have long been a source of disappointment for crop plant breeders and bio-statisticians, as they make it more difficult to choose superior genotype selections by reducing hereditary improvement. When selecting and advancing superior genotype choices to the breeding stage, it is vital to diminish genotype means values cross-location or environment [3].

Throughout the history of crop plant improvement and more recently through the established techniques of crop plant breeding, crop plant breeders have faced numerous obstacles in managing these interactions. Currently, crop breeders may manipulate genes that have been identified as being molecularly involved in genotype by environment interaction. Crop growth models that lead to separate morphologically distinct target videotapes, as promoted for many years [3], or genetically distinct target approaches as in emerging techniques can predict interactions that are understood at the morphological and physiological levels [4].

Calculation of potential combinations depends on a deeper thoughtful presentation of ancient time combinations, supported by thorough information on each part and the capability to significantly investigate that information. Crop plant breeders and geneticists are at present on the edge of bringing together that comprehensive information in a manner unimagined five continuations back. Three types of information are required to guide forecast models: genotypic, phenotypic, and environmental. The final neologism, among its similar environmental sense, is the complete extent of ecological distinctiveness. The price of collecting every one of the three types continues to rise: refusal, thanks to innovations in sequencing, and computerized field scoring of phenotype and weather conditions.

As expected, having the information does not always translate into meaningful ways to investigate and comprehend it. on genotype by environment investigation in this matter is gathered to evaluate what apparatus crop plant breeders have, what challenges and opportunities are currently existing, a number of study thoughts, and some preliminary attempts at applying the prosperity of new information becoming accessible. The subject starts with four reviews. The first reflects on the narration of genotype by environment interaction analyses, providing references to the giants on whose shoulders we now stand [5]. The next gives an outstanding general idea and viewpoint for junior researchers concerning genotype by means of environmental analyses, giving them an instruction agenda of useful approaches by means of up-to-date but by now well-tested apparatus [6]. In the GGE biplot study, De Leon. [7] provide a working example of a practical collection implement in support of working crop breeding. Finally, Hayes et al. [8] provide an animal breeding viewpoint and put forward that animal and crop plant breeders are in the process of converging on general solutions to the investigation of genotype by environment interaction. Therefore, the objective of this article is to discuss the importance of genotype by environment interaction and yield instability in crop plant breeding and how they came to be predictable, mentioning in advance the variety of methods, which encompass working in search of a solution to them and putting, forward what developments may lie ahead in advance.

2. Effect of GEI in Plant Breeding

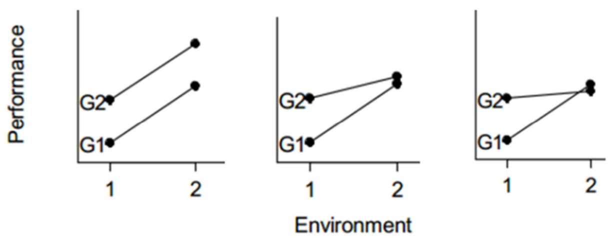
A genotype by environment interaction is defined as a change in the relative performance of crop plant characters of two or more genotypes evaluated in two or more agro-ecological environments. Genotype by environment Interaction consists of rank order variation for evaluated crop plants between environments and the comparative importance of inherent ecological and phenotypic inconsistency among agro-ecological zones.

Genotype by environment interactions are significant in the advancement and assessment of crop genotype varieties for the reason that they decrease the genotypic-stability values under diverse agro-ecological zones [9] In crop production Significant progress might be achieved by breeding crop varieties for stability in economically important traits [10]. Genotype by environment interactions are statistically detected as significantly different prototypes of responses between the verities in the agro-ecological zones and in nature, which occurs when the trait change between environments with the help of the genes [11, 12].

When genotype performance is shown alongside ecological gradient, the genotype by environment interaction is usually described as the gradient of the target line [12]. When the genotype performance rank continues in the same across agro - ecological zone, the performance line appears parallel and non-intersecting. Crossover of cultivar performance lines shows a shift in the position of the evaluated genotype across environmnts, with the best genotype being a location-specific genotype. Genotype by location influences practically every aspect of the crop improvement program's result selection process, including the identification of the best appropriate testing environments, property distribution within plant improvement programs, and genotype and breeding program selection [7].

The flexibility of genotypes in terms of the description of specific phenotypes in the diversified environmental effect is also evaluated by genotype by environment interaction [12]. The systematic basis concerned with physical flexibility, many investigators from other fields, and cultivars' ability to articulate multiple phenotypes when affected by diversified environments. Different groups of researchers have used to studying this phenomenon from the diverse approaches [7].

During cultivar, evaluation its performance depends on the genetic potential, the ecological location in which it is grown and their interaction [12]. To evaluate the wider and specific adaptation nature of cultivar information, studying adaptation of cultivars and similar performance over a variety of environments is very important. Discovering stable genotypes, which show a relatively small amount of genotype by cultivar interaction, is a very critical concern in locations where ecological variations are obvious. Genotype by location interaction occurs while the evaluated cultivar shows stable performance from one ecological zone to another ecological environment, which complicates the evaluation, selection, and recommendation of cultivars.



Figuer 1. *Interaction between two genotypes and two environments.*

Source: Ric Coe (r.coe@cgiar.org), Statistical Services Centre, University of Reading, UK and World Agroforestry Centre [13].

The diagram above depicts the various genotypes and their locations (environments). In the first diagram, even if the genotypes' performances are different, there is no cross-over interaction; the genotypes' performances are similar, and the its performance line goes parallel to each other. In the center diagram, there is the performance of genotype one and genotype two is very different. The performance of genotype 2 is much greater than that of genotype 1 in the environment. Genotype 2 still showed great performance in both environments. The lines are no longer parallel. In the third graph, the interaction is stronger still, and we have G2 best in environment 1, but G1 best in environment 2, which is a little described as an over-cross interaction. The potential patterns of relations become increasingly difficult to recognize as the figure of genotype and environment increases, and we employ a variety of actions to begin to recognize them.

3. Variation and Its Alternatives

3.1. Genotypic Heterogeneity

During crop plant improvement programs, genotypic yield advance depends on genotypic diversity for a given character in plant population [8] The degree of inherited difference for crop plant improvement programs will enhance the progress of appropriate crop improving program in the direction of attain the greatest hereditary increase [14]. For instance, Jahufer and Casler [15] and Kai Luo et al. [14] studied and qualified the benefit of hereditary by means of sole characteristic assortment, associated answer to variety, and index assortment, based on predictable hereditary differences on behalf of a variety of physiological and quality characteristics in switch grass [12]. Forage grasses and legume crops have hereditary differences for key characters, including rye grass [14], white clover [14], and alfalfa grass [16].

During a crop plant-improving program, we have to consider variation components, and there are about three major components of hereditary variation: The first genetic variation component is additive genetic variation, which is passed down from generation to generation at a high rate. The next genetic variation component is dominant genetic material action, and the last variation component is epistasis hereditary components. In this case, one hereditary material masks the effect of another genetic material. All those components are used during plant breeding programs.

$$VP = VG + VE = VD + VH + VI + VE$$

where VP = total phenotypic variance, VG = genotypic variance, VD = additive gene, VH = dominance gene, and VI = epistasis, VI = i, j and 1 [12].

3.2. Differences in Phenotypic Characteristics

Selection of genotypes for a variety of yield-contributing characters in all the evaluated agro-ecological zones and growing seasons following a typical estimation scheme [17]. The clarification on potential yield and morphological traits was recorded as part of the experimental field evaluation.

The plant phenotypic component is determined not only by the crop plant hereditary component (genotype) and ecological elements (environmental component), but also by genotype by environment interaction, which is commonly represented by the linear model as P = G + E + GEI [12, 18]. As a result, crop cultivar performance evaluation trials in a plant development plan are typically conducted in a number of agro-ecological zones to reduce the possibility of discarding cultivars which may achieve sound in most, although not at all of the evaluated agro-ecological zones. Crop breeders are interested in determining how much of the selection progress made in one environment can be carried over to other environments [12].

3.3. Inheritance

It's the percentage of overall variance that may be attributed to average genetic effects. There are two types of heritability: genetic and environmental. 1. In a broad sense, heritability is definite as the portion of phenotypic variation related to genotypic variation, i.e., h2 = VG/VP X 100. 2. Narrow sense heredity is described as the proportion of phenotypic variance owing to additive genetic variance, i.e., h2 = VD/VP X 100 [19].

3.4. Phenotypic Plasticity

The ability of a genotype to produce a wide variety of phenotypes in various situations (even if it is the same genotype) A plant cannot move when confronted with changing environmental conditions, therefore it must cope with environmental heterogeneity by adapting to the new or changing environment. Plasticity is similar to changing gene expression and plant physiology in response to environmental stimuli [18]. Spite of the fact that the different effect of the environment on different plant genotypes has long been recognized and properly addressed in crop breeding programs, it remains a challenging subject to master it. Plant breeding research has shifted its attention away from the creation of molecular markers, which is no longer an issue, and toward high-throughput, automated phenotyping, thanks to technological breakthroughs in genotypic technologies. With these improvements, it should be simpler to figure out what is going on. As a result, we now have a better understanding of phenotypic plasticity [18].

3.5. Environmental Parameters

Envirotypes (environment + types) are environmental factors that affect crop yield advancement. The technique of determining and measuring all environmental elements is known as envirotyping [20]. The notion was first introduced as "etyping" at worldwide meeting conference, followed by more detailed scientific articles [20]. The term "envirotyping" is used to indicate a group of approaches used to differentiate agriro-ecological zones throughout several envirotyping trials, and the agro-ecological types that often repeat found in the objective population of environment [21].

Environmental phenotyping differs from traditional environmental phenotyping in three ways. To begin with, environmental phenotyping will assess all agro-ecological elements with the purpose of influence crop yield. Expansions of yield have to prioritize intended for all companies, now the most important. Environmental entomology will next targated on particular field plots and individual plants, allowing environmental data to be collected and compared to genotypic and phenotypic data. Third, crop management and companion organisms was included as environmental elements such that their effects on crop plants can be investigated [20].

Environmental influences, whether micro or macro, inorganic or organic, internally or externally, can all play a role. The inside and outside environment has effect on plant growth and yield [12]. Water, waste products, and small molecules with internal hydrostatic pressure or pressure are all controlled by vacuoles, which are essentially encapsulated in plants. Maintaining turgid, temperature, and an acidic pH changes in pH, osmotic pressure, and temperature generated by material exchange and signal transduction with the external environment, among other things, have a considerable effect on internal environments. Ion transmembrane transport, metabolic pathway regulation, cytoskeleton remodeling, and gene expression regulation are all examples of how plants respond fully to specific external environmental factors with a variety of receptors, signal transductions and responses [20, 22].

The four types of external environmental factors comprise climate, soil factors, biotic factors, and crop management or cropping system. Temperature, radiation, precipitation or availability of water, and wind always have an impact on where and how a plant can develop, while other factors can influence how it grows. For instance, companion species some organisms affect or stress plants, such as diseases and pests while others, are beneficial. Crop management, which is a different environmental component, comprises intercropping, rotating, and agronomic methods [20].

4. Methods of Measuring GEI

Breeders have identified the adverse consequences of cultivar by environment interaction in collection, selection, and variety development, and have worked to develop breeding procedures and techniques to avoid these consequences of optimizing the benefits of interaction [7, 21, 23]. Cultivars are commonly chosen for use in specific situations. In stress experiments, the GEI was used to emphasize the impact of specific sources of biotic stress on genotype performance and to better understand the effect of environmental disruption on phenotypes. All most all of studies on the effect of the environment on performance should discover and create cultivars based on multi-environmental field-testing that replicates target production conditions [7]. These multi-site studies produce two-way tables of means for different cultivars in different environments.

To analyze the data from such two-way tables, models that combine the effects of genotype and environment, as well as partition the remaining variation into the effect of the interaction between environments and genotypes and the residual experimental error, could be used [12]. When compared to GEI, this provides an idea of the extent of variance attributed to the genotype's main effect, but it limited in situation of information about the relations nature. Natalia de Leon et al [7] and others [24] classified GEI depending on the slope of the regression of genotype performance across an ecological slope, base much of the descriptive information within the area of plant breeding on studies. In the most basic models, the quality gradient is determined by the average performance of all genotypes in that environment. Using the approach, researchers can evaluate the performance of the genotypes under study in untested situations.

The significance of GEI is that it allows multidimensional environmental characterizations to be included in statistical models. The additive main effects and multiplicative interaction (AMMI) model [7] was one of the first to have used this method. GEI is calculated as the measure of a genotype's specific sensitivity to a latent (unobservable) environmental variable and its influence in this context. The variation described by the products of the resulting genotype responses to ecological factors is improved using a principal component technique [7]. In the development of modeling approaches, GEI variation and the combined effect of the genotypic main effect and the phenotypic main effect plus the genotypic main effect have always been considered. The GGE model, also known as "genotype major effects and GEI," appears to be a set of approaches [7, 25].

A number of mixed model applications for examining GEI have also been developed, essentially for multi-environment studies involving a high number of genotypes [12]. In this scenario, genotypes can be considered of as random effects, and their potential heterogeneity of variances or co-variances could also be taken as a sign of genotypic sensitivity to specific changing environment.

4.1. Interaction of Genotype and Environment

During investigating GEI the maximum consequence *occurred* on the location (environment), even though it has little bearing on what to choose. Because most of the selected activities undertaken under the conventional technique performed at on-stations, which are ideal production environments, the interaction between selection environments and targeted production settings has been a main difficulty in most country. Many statistical techniques account with all phenotypic variation across environments, which can contribute to genotype inconsistency. This GEI Interaction undertaking was both a challenge and an opportunity. Variations in the experimental location, along with variations in the growing season in each agro-ecological, may threaten varietal stability [26]. Specific adaptations can make the difference between a success and a failure. There is an excellent variety as well as a superior variety. Some environmental variables like soil type, fertility, as well as plant density are predictable, while others like rainfall, temperature, humidity are not predictable.

4.2. Adaptability and Stability

Stability refers to a genotype's ability to adapt or adjust itself to a variety of environments, and it has been used to discover genotypes that remain unaffected by changes in the environment, whereas adaptability refers to a genotype's ability to thrive in any particular environment [27]. Yield stability is important for crop variety selection as well as breeding efforts. Yield stability is an interesting characteristic of today's plant breeding programs because the considerable yearly variability in mean yield, particularly in arid and semi-arid environments. It is considered more adaptable or stable if a variety or genotype has a high mean yield but a low variance. If a variety or genotype has a high mean yield value but a low degree of variability in yielding capacity when grown in a variety of environments, it is considered more adaptable or stable..

Biometrical approaches have been designed to evaluate stability, including univariate and multivariate, and the concept of stability has been estimated in them [27]. The regression approach, which would based on regressing individual genotype's mean value on the environment's environmental index or marginal, is the majority of that frequently employed [12, 27, 28] presented a good approach for measuring stability, which has been later refined by Chandrakanth et al. [27]. They also evaluated the stability index in silkworm breeds in three environments that used the approach proposed by Eberhart and Russell [24]. This strategy is being implemented within a variety of situations [27, 29].

During selection program yield per se or one or more of the morphological components of yield should be used as a criterion in breeding programs aimed at increasing yielding capacity. Therefore, It's also important to have an effective understanding of the characteristics that have a considerable relationship with yield, because the characters have to considered as indirect selection criteria to enhance the mean performance of the new population varieties [27]. Any attempt to improve these characteristics needs an understanding of the relationships between both the targeted traits and other traits. Different statistical techniques such as correlation, regression, path, factor, and cluster analyses can be applied to study the interrelationships among yield and other characteristics [27, 30]. Correlation estimates are one of them, and while they are significant for determining the components of a complicated characteristic like yield, they do not really offer anything-clear understanding of the proportional importance of each component concept's direct and indirect effects on the desirable characteristic [27, 31].

Path coefficient analysis is a standardized partial regression analysis that tends to be effective in identifying among causal factors of correlation coefficients [27]. It is a multivariate technique similar to principal component analysis, however with the introduction of a multiplicative model for the main trait of interest. [27].

Yield and yield components are a dynamic quantitative variable with several ecological factors, hence selecting genotypes based on their performance in a single environment is not the best approach to develop varieties [32]. Plants must be selected for yield stability rather than average performance over a number of environments [33]. Prior to suggestion, genotype selection for stability and responsiveness is vital for a crop plant like rice, which is produced in a range of agro-ecological conditions.

The AMMI method has been widely used in constancy and adaptableness evaluations of plants. since it (i) provide an early assessment of the model and is very well for data analysis with several environmental factors, ii) allows greater progression of the GEI and summarizes the relationships and patterns among both genotypes and environments, and iii) increases the accuracy of trait estimates [34].

4.3. Experiments in Multiple Environments

Multi-environmental trials (METs) have to considered a fundamental category of agro-ecological sampling for the professional gathering of similar agro-ecological data, as they involve numerous cultivar evaluated in numerous locations, for several years in multiple environment with multiple replications. Weather, climatic, and soil data, as well as Crop management records, including fertilization, disease, pest, as well as weed management, were rigorously collected to categorize the conditions most suited for commercialization of the verified cultivers.

Multi-environment trials are used to evaluate the yield stability of genetic materials in variety of environments. Sometimes, in multiple cultivar grown in conditions will recurrently demonstrate considerable mean yield changes. It's special effects are known as GEI, and they are regulated by various environmental factors [35].

The GEI reduces the genetic advantage in crop improvement program by decreasing the correlation among phenotypic and genotypic characteristics [36]. As a result, GEI must be leveraged by selecting a superior genotype for each specific target environment or by selecting a genotype that is widely adaptable and stable over a broad range of environments [35].

Regression coefficient sum of squared deviations from regression [24], stability variance, coefficient of determination, coefficient of variability are some methods used to analyze data from (MET). A GGE is an additive multiplicative interaction [35]. GGE biplot is another way for displaying the GEI pattern of multi-environment experimental data graphically, and it has a number of advantages [25, 35]. It is a powerful principal component analysis (PCA)-based approach for comprehensively exploring MET data. It enables for visual correlation analysis of test environments, genotypes, and GxE interactions. It is a vital technique for mega-environment analysis (for instance, with "which-won-where" pattern), in which particular cultivar can be suggested for particular mega-environments [35, 37].

Whether or not stability is genetic, the parameter measures something other than a genetic characteristic, it is not hereditary, and hence selection for that parameter is meaningless. Stability indices are genetically determined and subsequently hereditary, according to several authors [35]. If the characteristic is heritable, the next stage in genetic research is to identify the genes that control it on the chromosome.

The chromosomal location of the genes influencing quantitative variables like yield and yield stability must be determined in order to understand the genetics of variation. Various methods have been explored to identify the genes, which monitor quantitative traits, with cytogenetic methods being the most widely utilized. Because of its phenotypic stability's complex, there is little understanding on the chromosomal location of the genes influencing response. [35].

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4.4. Agro-ecological Zones

Defining the environment necessitates the selection of a project area [39]. Geographic Information System (GIS) tools can be used to establish crop production zones with similar agro - ecologies. In MET, the environment is used. For picking environments that represent the project area, data from other sources (for example, climatic data) is useful. To assist in determining target-breeding conditions, more work is needed to link information from GIS with actual performance data.

5. Conclusion

GEI and yield instability have long been a source of dissatisfaction for breeders and biostatisticians in crop improving programs that are conducted over locations, as they make it more difficult to select superior genotypes by decreasing heritability. However, the flexibility of genotypes in terms of the description of specific phenotypes in diversified environmental conditions can be evaluated by GEI. Discovering stable genotypes, which show a relatively small amount of genotype by cultivar interaction, is a very important concern in locations where ecological variations are obvious. Genotype stability occurs when the evaluated cultivar shows stable performance from one ecological zone to other ecological environments, while yield instability complicates the evaluation, selection, and recommendation of cultivars across locations. So while improving cultivars, we have to consider three hereditary variation components. The first genetic variation component we have to consider is additive genetic variation. The next is dominant genetic material, and the last genetic variation component we have to consider is epistasis hereditary components. To analyze the complicated yield instability, we should use models that combine the effects of the genotype and environment, as well as partition the remaining variation into the effects of the interaction between environments and genotypes and error. The additive main effects and multiplicative interaction (AMMI) of the GGE model are wildly used in stability and adaptability evaluations and to enter prate data gathered from multi-environment trials. So when we conduct multi-environment agricultural experiments, we have to consider appropriate stability measuring techniques to suggest superior genotypes across locations.

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