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Review Article

Maize genetic breeding for tolerance to abiotic stress with focus on sustainable use of environmental resources

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Abstract

This bibliographic review explored maize genetic breeding to increase tolerance to abiotic stress. The main stresses faced by the crop, such as water stress and nitrogen deficiency, and their negative impacts on grain yield were discussed. Strategies to minimize these effects were examined, focusing on the selection of tolerant genotypes and the strategic positioning of these genotypes in different growing environments. The germplasm bank and genetic diversity were highlighted as crucial resources to identify desirable traits and genes associated with resistance to abiotic stress. The selection of secondary characters, considering their heritability and correlation with characters of interest, allows maximizing the efficiency in the selection of promising genotypes in genetic breeding programs. Test environments simulating stresses, such as water stress and low nitrogen, are essential to evaluate the performance of genotypes and identify the most tolerant ones. The genetic breeding of maize for tolerance to abiotic stress promotes promising solutions to face environmental challenges and ensure the sustainability of agricultural production.

Keywords: *Zea mays*; hydrical stress; genetical diversity; genetic gain; indirect selection; food security.

Introduction

The productive performance of maize is influenced by several abiotic factors that occur simultaneously or at different stages of crop development. Recurrent water stress and low soil fertility are among the main causes of abiotic stresses that limit maize agronomic performance (Melo, Santos, Varanda, Cardoso, & Dias, 2018; Song, Jin, & He, 2019). With the increase in the maize area cultivated in the off-season (Companhia Nacional de Abastecimento [CONAB], 2023), it is expected that the crop will be even more exposed to abiotic stress conditions, such as water deficit, low incidence of solar radiation and variations in air temperature, especially during the final stage of development. In addition to variations in meteorological conditions, maize cultivation covers several regions of Brazil, being subjected to nutrient deficiencies, such as phosphorus and nitrogen, aluminum toxicity, salinity and soil waterlogging (Lima, Leon, & Kaeppler, 2022; Zaidi, Shahid, Seetharam, & Vinayan, 2022).

Important researches have been done with grasses (Karasawa et al., 2023; Treter et al., 2023; Fracchinello et al., 2023; Santos et al., 2024). Studies conducted by Laudien, Schauberger, Makowski and Gornott (2020) revealed that extreme weather events have significantly negative impacts on maize grain yield. This scenario promotes food insecurity, posing a risk to the food supply. Additionally, the lack of adequate infrastructure, high irrigation costs, and limited ability to accurately predict weather event patterns leave maize farmers with limited resources to address the challenges caused by abiotic stress. The development of genotypes adapted to the most diverse environmental conditions may be the main strategy to minimize the risks of abiotic factors (Sayed, Ali, Ibrahim, Kheiralla, & EL-Hifny, 2022). For this, genetic breeding programs have developed research in order to optimize plant selection strategies to different environmental conditions (Ertiro et al., 2017; Ndolovu et al., 2022; Zaidi et al., 2022).

Grain yield has been the main character used to identify genotypes adapted to abiotic stress conditions (Ertiro et al., 2017; Ndlovu et al., 2022). However, due to the lower genetic contribution in the expression of this character, selection based on secondary characters has become efficient (Carvalho et al., 2022). Mainly for adaptation to environments with stress caused by meteorological variables, the interval between male and female flowering has been the main secondary character used (Lima et al., 2022; Zaidi et al., 2022).

Simultaneously with the development of genotypes tolerant to abiotic stress, the identification of environments with similar environmental conditions, known as mega-environment assessment, improves the efficiency of genotype positioning (Katsenios et al., 2021). Studies have identified the presence of mega-environments in several cultures, as highlighted by Katsenios et al. (2021), Szareski et al. (2021) and Savicki et al. (2023). This approach allows positioning genotypes within these mega-environments, which results in reduced costs in genetic breeding programs (Nardino et al., 2018) and provides favorable phenotypic responses.

The development of strategies to minimize the effects of abiotic stresses has emerged as one of the main challenges in agriculture. Genetic breeding is one of the main approaches to ensure food production in the face of extreme weather events and low soil fertility (Carvalho et al., 2018). Therefore, understanding the main breeding strategies for the development of genotypes adapted to environmental conditions allows maximizing the efficiency of the selection of superior genotypes. This review aims to update knowledge about the main strategies used in maize genetic breeding programs to select genotypes adapted to extreme conditions of abiotic stress.

STRATEGIES TO MINIMIZE THE IMPACT OF ABIOTIC STRESS

Selection of tolerant genotypes

The development and selection of maize genotypes tolerant to abiotic stress is one of the main strategies to increase grain productivity in areas subject to periods of frequent meteorological extremes or low soil fertility (Bernini, Santos, Silva, & Figueiredo, 2020). Future projections indicate an increase in air temperature, which affects the reduction of the maize growth and development cycle. The duration of the cycle, together with the genetic base are fundamental for the determination of the productive performance. Therefore, ensuring the selection of long-cycle genotypes, along with a short interval between male and female flowering, contributes to greater phenotypic stability (Lima et al., 2022). Genetic effects, whether additive or non-additive, are important for the thermal sum characteristic in maize (Nardino et al., 2016b). These authors revealed that crosses between early-cycle female parents and super-early-cycle males, or super-early-cycle females with early-cycle males, generate populations with higher thermal requirements. The importance of properly defining the female and male parent was well reported by Carvalho et al. (2017) as well.

Subsequently, the developed populations are evaluated in multi-environmental tests. The selection of maize genotypes based on these assays has been widely used efficiently to identify productive, stable genotypes adapted to environmental conditions (Nardino et al., 2016a). In addition, there is a broad genetic base that can be used through single, double, triple hybrids and open-pollinated varieties (Lima & Borém, 2018). The average grain yield of single hybrids is generally higher than the yield of triple and double hybrids, as reported by Emygdio, Ignaczak and Cargnelutti Filho (2007). Varieties, on the other hand, are characterized by exhibiting greater phenotypic stability in the face of environmental variations due to their broad genetic base, as observed by Troyjack et al. (2019). It can be understood that in a context of climate change, plants that have a wide genetic diversity, such as open-pollinated and creole varieties (Baretta et al., 2019), tend to manifest a more pronounced phenotypic stability, resulting in greater resilience in the face of extreme weather conditions. Therefore, it is essential to preserve these genetic bases, since they are sources of desirable alleles to minimize negative impacts from the environment.

Therefore, the development of a maize genotype, whether single hybrid, double, triple or variety, must take into account the desired productivity, phenotypic stability and specific characteristics of the growing environment. The genetic diversity available in maize offers options that can be explored to meet the needs and challenges of different growing conditions (Silva, Santos, Afférri, Peluzio, & Sodré, 2019; Abu et al., 2021). Recent studies have demonstrated efficiency in the selection of maize genotypes tolerant to abiotic stresses. Abu et al. (2021) identified genotypes with greater productive potential in environments with nitrogen deficiency in the soil. In turn, Sayed et al. (2022) and Khatibi et al. (2022) showed promising maize genotypes with greater capacity to tolerate water stress. These findings underscore the importance of genetic breeding as a strategy to minimize the challenges posed by abiotic stresses in maize production.

Positioning genotypes in mega-environments

The study of genotypes × environments interaction to identify genotypes that are adapted and stable to environmental conditions is a tool that contributes to minimize the severity of abiotic events. This interaction refers to how different genotypes respond variably to different environmental conditions (Cruz, Carneiro, & Regazzi, 2014; Rosa et al., 2018). Through multi-environment tests, it is possible to identify and select groups of environments with similar conditions, called mega-environments (Katsenios et al., 2021; Szareski et al., 2021). Therefore, one can identify genotypes that can be cultivated within these mega-environments. For example, Nardino et al. (2018) carried out a study with the objective of grouping environments for the evaluation of maize hybrids. The authors found that it was possible to reduce the multi-setting assessments to just a few representative settings. This makes it possible to reduce costs in conducting and positioning genotypes.

The study of genotypes x environments interaction allows identifying the genotypes most adapted to different cultivation conditions, taking into account environmental variations, such as climate, soil, altitude and specific management practices (Shojaei et al., 2022). For example, Sarturi et al. (2022) found that higher altitude regions are associated with better maize agronomic performance. In addition, the authors highlighted the importance of adapting the plant population to altitude, suggesting that in low altitude areas, it is necessary to increase plant population density.

This makes it possible to select genotypes that have better performance and productivity in each specific environment (Zewdu et al., 2020). For example, genotypes that are tolerant to a particular abiotic stress prevalent in a specific region, such as water deficit or salinity stress conditions. This allows minimizing the negative effects of abiotic stress, since the positioning of the most adapted and stable genotypes to the environments will be carried out.

GENETIC BREEDING FOR ABIOTIC STRESS TOLERANCE

Main abiotic stresses targeted within the programs

The main abiotic stresses of interest to genetic breeding programs and researchers have been water stress and nitrogen deficiency (Abu et al., 2021; Khatibi et al., 2022; Sayed et al., 2022). Water stress and nitrogen deficiency pose significant challenges to agricultural production in many regions of the world. Water scarcity and deficiency of nitrogen fertilization can negatively affect plant growth, development and productivity (Melo et al., 2018; Ruiz, D'Andrea, & Otegui, 2019).

Therefore, the identification and understanding of these abiotic stresses as the focus of research and genetic breeding show that there is an effort to seek solutions to face these challenges. Genetic breeding programs aim to develop cultivars that are more tolerant to these stresses, allowing plants to adapt and thrive even in adverse conditions (Lima & Borém, 2018). From this, the present study is based on genetic breeding for tolerance to water stress and greater efficiency in the use of nitrogen.

Major and minor characters for selection and heritability

In plant breeding, grain yield has been widely used as the main variable to assess tolerance to abiotic stress in maize (Abu et al., 2021). However, it is important to note that selection based only on grain yield may be less efficient under conditions of abiotic stress due to low heritability in these challenging conditions. The study carried out by Ertiro et al. (2017) demonstrated that the heritability of maize grain yield was 0.68 in an irrigated environment and 0.52 in an environment with water stress. Lima et al. (2022) revealed a heritability of 0.72 for grain yield in a normal environment, while a heritability of 0.48 was observed in an environment with low nitrogen levels associated with water stress.

Heritability is a measure of the genetic contribution to a specific trait, and higher values indicate a greater genetic influence on that trait (Lima & Borém, 2018). However, it is observed that the heritability can be altered by environmental factors, such as the presence of water stress or low nitrogen level. Therefore, the selection of maize genotypes for tolerance to abiotic stress, through grain yield, may not be the most efficient strategy. This underscores the importance of considering the environment in genetic breeding and plant selection studies. By understanding the heritability of grain yields across different environments, researchers can make more informed decisions about which traits are most stable and heritable under different conditions.

According to Parajuli, Ojha and Ferrara (2018), one of the best approaches in breeding programs is to use secondary traits to select the genotypes with the best performance under stress. However, a secondary trait needs to fulfill the criteria of being genetically variable and heritable, quick to measure, and associated with production under stress. Some secondary traits related to water stress tolerance, such as the interval between male and female flowering, plant height and components of grain yield, have shown a strong correlation with water stress tolerance and have greater heritability (Abu et al., 2021; Lima et al., 2022). Therefore, these traits have been used to improve the selection efficiency aiming at tolerance, mainly, to water stress in maize breeding.

Studies indicate that the most sensitive stage of maize development to water stress is flowering, and the variable most correlated with grain production under water stress is the interval between tassel and stigma emission (Melo et al., 2018). Stress during flowering occurs when there is a period with less frequent rainfall between the beginning of male and female flowering. This increases the interval, in days, between male and female flowering, which reduces the cross-pollination rate and, consequently, grain yield (Storck, Cargnelutti Filho, Lopes, Toebe, & Silveira, 2009; Nieh, Lin, Hsu, Shieh, & Kuo, 2014).

The delay in female flowering seems to be associated only with water deficit, as in a study carried out by Lizaso et al. (2018) heat stress did not delay female flowering when maize was subjected to a range of maximum temperatures of up to 42.9 °C in the field and up to 52.5 °C in the greenhouse. Therefore, the smaller variation between male and female flowering may promote better water stress tolerance (Sah et al., 2020).

Therefore, Banziger, Edmeades, Beck and Bellon (2000) proposed the interval between flowering as a selection criterion for maize breeding programs focused on water stress tolerance, since these traits show high heritability and significant correlation with performance under stress conditions. The interval between male and female flowering is one of the main secondary characters used to select maize genotypes tolerant to water stress (Abu et al., 2021). Lima et al. (2022), revealed that this trait had a negative correlation with yield and heritability higher than grain yield. Ziyomo and Bernardo (2013) found that indirect selection based on the interval between male and female flowering was efficient to improve grain yield under water stress, and the use of correlated traits increased selection efficiency.

Selection under water stress has been successfully practiced in maize, according to several studies (Maazou, Tu, Qiu, & Liu, 2016; Abu et al. 2021; Benchikh-Lehocine, Revilla, Malvar, & Djemel, 2021; Khatibi et al. 2022). When selection is carried out under conditions of water stress, the selected material has the ability to perform well both under favorable conditions and under stress conditions. However, material selected under favorable conditions may not perform well when cultivated under water stress (Carvalho, Souza, Follmann, Nardino, & Schmidt, 2014). Thus, the efficient and widely used strategy in plant breeding programs to improve cultivars with tolerance to abiotic stresses is the use of indirect selection, based on characteristics that are easy to measure, highly heritable and correlated with grain yield.

Environments for phenotyping for water stress tolerance and low nitrogen

Environment selection is an important distinctive component for identifying plants tolerant to abiotic stress (Masuka, Araus, Das, Sonder, & Cairns, 2012). The test environment should be similar to the natural growing environment. When selection and target environment are similar, indirect selection of genotypes can be efficient (Lima & Borém, 2018). Abiotic stress sometimes has an effect associated with other abiotic stress, such as the temperature stress that often occurs with water stress.

The study of genotypes × environments interaction with selection methodologies may be the best approaches for breeding in the selection of germplasm that confers tolerance to stress in cultures (Mahadevaiah et al., 2021). The study in multiple environments of specific stress situations can bring better cultivars with better stress tolerance. It is possible to use daily historical meteorological data to identify potential sites for water stress phenotyping, where the probability of occurrence of rainfall during a period is minimal (Masuka et al., 2012). This makes it possible to carefully perform water stress experiments when withholding irrigation.

Although water stress must be imposed at the same time on all genotypes within an experiment, there is often variation in phenology between genotypes. To attenuate this problem, drip irrigation can be used to allow plot-level irrigation control or genotypes can be grouped into subsets of similar maturity (Liu et al., 2022) and sown at different times to ensure phenological synchronization between genotypes at the critical stage when water stress is imposed. For this, tests can be carried out in the previous year to determine the phenology of the genotypes before the water stress experiments, as carried out by Zia et al. (2013). This is particularly important to avoid differences in the development of stress due to weather conditions.

It is important to allow the genotypic productive potential to be separated from the mechanisms associated with low nitrogen stress tolerance, thus avoiding complications in the separation of low nitrogen tolerant genotypes from the productive potential (Masuka et al., 2012). Thus, the environments intended for the selection of genotypes with low nitrogen must be determined so that there is a reduction in productivity in relation to the fertilized conditions in the same environment (Banziger et al., 2000; Lima & Borém, 2018). To achieve this level of fertility for selection of genotypes under low nitrogen stress, environments can be depleted over several growing seasons using a high biomass non-leguminous crop without application of fertilizers to remove nitrogen from the soil.

Conventional genetic breeding

Most hybrids and drought tolerant varieties have been developed and improved using conventional breeding. The most recommended methods to increase the frequency of favorable alleles in the population are those that involve intra- and inter-population recurrent selection (Lima & Borém, 2018). Increases in allele frequencies depend on the magnitude of gene action, the process and intensity of selection, as well as experimental precision.

Different recurrent selection procedures were developed, including selection between and within half-siblings, full-siblings and inbred progenies, along with modifications to existing methods (Zambrano, Yánez, & Sangoquiza, 2021). The effectiveness of each method depends on the population, the selected characteristics and the objectives of the breeding program (Lima & Borém, 2018). The inter-population method has been shown to be effective in improving two populations and exploiting the heterosis that arises in crosses, especially in the case of selecting hybrids tolerant to water stress, increasing the probability of obtaining superior lines (Valadares et al., 2021).

However, most maize genetic breeding programs use elite materials as preferred sources for extraction and lineages (Teixeira & Trindade, 2021). Therefore, the term lineage recycling has been used to form new populations in which the elite lines of the breeding programs are crossed with each other in subsequent cycles (Badu-Apraku, Fakorede, Badu-Apraku, & Fakorede, 2017). In this process, new lines are obtained with characters superior to their parents, due to the increase in favorable alleles. However, in the end the developed lineages tend to become genetically related. This lineage development process promotes a narrow genetic base (Lima & Borém, 2018). This may hinder the development of genotypes with greater tolerance to abiotic stress, especially variations in meteorological variables.

Conventionally, breeders develop maize populations tolerant to abiotic stress through recurrent selection, and extract experimental cultivars or inbred lines to produce hybrids (Hallauer, Carena & Miranda, 2010; Carvalho et al., 2022). Recurrent selection, with the accumulation of favorable alleles, may be one of the main current and future strategies to increase the genetic base of genotypes and identify those with greater tolerance to abiotic stress (Das et al., 2021). Tabilibi et al. (2017) revealed a gain of 5.3% for grain yield in water stress environments. Selection gains were also observed by Das et al. (2021) evaluating maize genotypes under water stress. These studies reinforce the importance and effectiveness of recurrent selection as a selection strategy to improve abiotic stress tolerance and boost grain yield.

Final comments

Throughout this bibliographic review, the main abiotic stresses that affect maize and their negative impacts on productivity were explored. Effective strategies are needed to minimize these impacts and ensure sustainable production. Among the studied strategies, the selection of tolerant genotypes and the positioning of these genotypes in mega-environments proved to be promising approaches.

Abiotic stress in maize, whether due to water stress, nitrogen deficiency or other factors, causes a series of harmful effects, such as reduced growth, grain production and changes in plant metabolism. However, through genetic breeding, it is possible to develop maize genotypes capable of tolerating these adverse conditions.

Genetic resources provide a broad basis for identifying desirable traits and genes associated with stress resistance. The careful selection of main and secondary characters, taking into account their heritability, allows the choice of the most suitable genotypes for breeding programs. Phenotyping in environments that simulate water and low nitrogen stresses is essential to evaluate the response of genotypes under similar conditions to the field. These test environments allow identifying the most resilient and adapted plants, providing valuable information for the selection of tolerant genotypes.

Maize genetic breeding for tolerance to abiotic stress is a promising field that offers viable solutions to ensure food security in the face of environmental challenges. By combining tolerant genotype selection strategies and proper placement of these genotypes in different environments, tolerant maize genotypes can be developed and contribute to sustainable agricultural productivity.

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