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# Review on Breeding Cultivars for N-Low Stress Tolerance in Major Food Crops

**Lemi Yadesa**

Ethiopian Institute of Agricultural Research, Bako National Maize Research Center, Bako, Ethiopia

**Email address:**

lemikooyadi64@gmail.com

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**Abstract:** The growth and development of plants depend on nitrogen. Cereal crop development is greatly influenced by soil nitrogen content, and tropical soils have low nitrogen contents. Organic waste can trap nitrogen in the soil, making it unavailable to plants. On the other hand, low-input farming refers to systems that are maintained with less inputs, leading to a stressed system, typically caused by a scarcity of nitrogen and phosphate or a lack of water, which results in output losses. It is frequently related to and used as a synonym for organic farming in developed nations. A tolerant plant can no longer fend off or control the spread of a disease after it has taken hold. Finding ways to increase food production is therefore urgently needed, especially in the world's poorest areas. In contemporary improvement attempts, genotypic selection based on higher yield performance is typically carried out under optimal circumstances for each type of stress. To address these situations, breeding curricula that look at potential low-yielding varieties must be created. In these curricula, varieties with better stress tolerances such as delayed leaf senescence, improved nutrient economy, local environmental fitness, consistent yield, and disease resistance are chosen, increasing the sustainability of low-input systems. As a result, researchers from all around the world are putting in a lot of effort to create improved varieties and hybrids. Crop cultivars that are abiotic and biotic-tolerant can be created through introduction, selection, hybridization, and mutation techniques. Pedigree, modified bulk pedigree, and another culture method were used to produce a cultivar that can withstand salinity. In order to create superior genotypes by conventional breeding or biotechnological methods, a geneticist must comprehend the genetic foundation of biotic and a biotic tolerance in crop plants. Breeders must continuously update their knowledge and abilities to keep current due to the quick advancements in crop science and genetic technologies.

**Keywords:** Nitrogen, Organic, Economy, Performance

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## 1. Introduction

Nitrogen (N) is one of the most important components for crop development and growth, and it is widely employed in modern agriculture to increase yields. The global N-use efficiency (NUE) for grain production is around 33% [93]. Nitrogen is a critical component of plant growth and development. Maize development is greatly influenced by soil nitrogen levels, and tropical soils have low nitrogen levels [12]. Nitrogen stress causes a decrease in leaf chlorophyll, leaf area, and a faster rate of senescence, all of which lower photo-assimilates production in the leaf. Nitrogen is essential for the creation of leaf chlorophyll, which controls the plant's photosynthetic efficiency. This suggests that nitrogen is a factor in crop output [15].

Despite the importance of nitrogen to maize, its availability in the soil is influenced by a variety of circumstances, and it is not always available for plant uptake. For example, nitrogen can be trapped in soil organic matter, rendering it unavailable for plant usage [15]. Indeed, the cereal grain stores only about a third of the applied nitrogen [110]. Excessive N fertilization in intensive agricultural areas, notably major maize-producing regions, has resulted in substantial environmental problems due to reactive N from agriculture being enriched in the atmosphere, soil, and water [61]. Corn production depends on the efficiency of fertilizer capture and the ability to adjust to Low-N stress when there is a lack of nitrogen [111]. Improvement of N-use efficiency (NUE) and Low-N tolerance has become a desired breeding goal in crop production to lower the cost of N fertilization

and the detrimental impact of excessive N on the environment. As a result, increasing NUE and Low-N tolerance is critical for both agricultural sustainability and environmental benefits. The availability of enough genetic variability for the target traits is required when breeding for high NUE and Low-N stress tolerance.

Genetic variation or heterogeneity in N-utilization features among maize, wheat, rice, and spring barley accessions has been studied as a requirement for improving cereal crop NUE [28]. As reported by [47] a number of metrics have been established for evaluating NUE in crops [27]. When a large number of accessions must be examined, N-agronomic efficiency (NAE), which is defined as the efficiency of converting applied N to grain yield, is considerably more practical because no labor-intensive or time-consuming chemical analysis is necessary and no N is applied, respectively [27]. Currently, the goal of high NUE breeding is to maintain or increase productivity while using less nitrogen [47]. Tolerance refers to a plant's ability to operate effectively despite displaying the symptoms of a susceptible host. A tolerant plant lacks the ability to resist or slow the spread of a pathogen after it has established itself. A tolerant plant would be classified as vulnerable, just like a non-tolerant one, based on a visual assessment of symptoms. Despite the presence of disease symptoms, the performance of a tolerant plant would be comparable to that of plants that are not infected. Some people confuse tolerance with field resistance and other phrases that refer to the progression of an established infection. Others might rather not consider tolerance to be a type of resistance [91]. This overview's purpose is to look at crop breeding techniques that are appropriate for N-low perseverance.

## 2. Literature Review

### 2.1. Effects of High and Low Nitrogen Inputs on Crop Plant Responses

Large-acreage monocultures dependent on heavy machinery, high-yielding cultivars, synthetic and natural fertilizers, regular pesticide applications, and irrigation are all examples of high-input systems. To achieve consistent consistency, the most effective individual plants are picked in consecutive generations [39]. In today's improvement projects, genotypic selection based on higher yield performance is usually done under ideal conditions. This approach of artificial selection yields a crop that is consistently homogeneous and has limited genetic variability. Due to a lack of natural genetic variety, genotypes selected for high performance in high-input settings are unlikely to sustain those same high yields under stress conditions [84]. Low-input farming can be characterized as systems that are managed with less inputs, resulting in a system that is stressed, usually due to nitrogen and phosphorus deficits or insufficient water availability, resulting in yield losses. It is frequently connected with and used as a synonym for organic farming, particularly in developed countries [84].

Agriculturists with little resources account for half of the world's population, providing up to 20% of the world's food supply [106]. Despite the large number of these resource-poor farmers, contemporary breeding efforts have not benefited them as much as they might. Improved varieties are being created in settings that are not typical of marginal environments [1].

Current low-input varieties have largely been generated utilizing local germplasm, enhancing (G×E) interaction, adaptability, and crop performance [124]. It has been demonstrated that selecting varieties while under low-input or stress situations is the most efficient approach to boost yields [85]. Breeding programs that examine potential varieties more suited to low-yielding conditions must be developed, in which varieties with more advantageous adaptations in stress conditions, such as delayed leaf senescence, improved nutrient economy, local environmental fitness, consistent yield, and disease resistance, are selected, resulting in increased sustainability of low-input systems. As the human population grows, so does the need to shift current agriculture's high-input model to low-input. Breeding under low-yielding and changing stress situations is more difficult than breeding for homogeneous, regulated, high-yielding systems, but it is essential to feed the world's rising population while preserving global resources [39]. When phenotypic selection becomes unreliable, the use of genetic markers has been suggested as a viable option for breeding variants with improved genotypes [43].

### 2.2. Crop Development Through Increased Nitrogen Usage Efficiency and the Selection of N-Low Tolerant Crops

The application of organic breeding with low N improvements of landraces, notably key cereal food crops, is known as low N breeding (Maize, Wheat & Rice). The availability of enough genetic variability for the target traits is required when breeding for high NUE and Low-N stress tolerance. Genetic heterogeneity in N-utilization features among maize, wheat, rice, and spring barley accessions has been explored as a necessity for improving cereal crop NUE [27]. The most environmentally friendly and cost-effective way to reduce N fertilizer overuse without compromising productivity and grain quality is to use genetic interventions to develop more (NUE) crop plants, which would require less N fertilizers with no yield losses [65]. NUE are complicated features that necessitate the genetic identification of genes/QTL involved in enhanced nitrogen uptake, distribution, and accumulation in many sections of the plant. Markers associated with the genes have been found and can be utilized for marker-assisted selection (MAS) to choose genotypes to perform better in low-nitrogen environments [122].

NUE is the product of absorption efficiency (amount of absorbed N/quantity of accessible N) and utilization efficiency (yield/absorbed N), or N-uptake efficiency, which is calculated by dividing the total amount of N in above-ground plants at harvest by the amount of available N in the soil. There is genetic heterogeneity for both N absorption

efficiency and N utilization efficiency in a significant number of crops [30]. The Low-N tolerance index (LNTI) is defined as a reduction in grain yield under Low-N stress compared to that under optimal conditions in the same experiment, and is calculated as  $(1 - (\text{GLN}/\text{GOP}) \times 100 \text{ percent})$ , where GLN = grain yield under Low-N conditions and GOP = grain yield under optimal conditions [131].

### **2.3. Nitrogen-Use Efficiency and Crop Response and Physiological Processes**

Roots play a range of roles in plant productivity, including water and nutrient intake, developing symbiotic relationships with various microorganisms in the rhizosphere, anchoring the plant to the soil, and acting as storage organs. From the cellular to the whole-plant level, the varied interactions of a root with its environment are determined by its organization and structure. The use of subsequent marker assisted selection to find genes linked with root development and N uptake is a significant breeding strategy. Once root phenotypic diversity and root gene sequence diversity have been identified, gene-based association mapping can be used to find quantitative trait polymorphisms (QTPs) that have a causal genetic effect on root traits. For QTP discovery, ancestral recombination in unrelated maize inbred lines and linkage disequilibrium at candidate gene loci are used in association mapping [129]. QTPs discovered through association studies could be used as diagnostic functional markers, which can help with germplasm selection [4]. Other root qualities were substantially linked with root DW, suggesting that direct selection based on root DW may be adequate to improve other root traits [21]. Maize lines with a long and enlarged root system are desirable for breeding drought tolerance and fertilizer usage efficiency, as well as identifying the genetic areas that influence these traits. Variability in root characteristics has been documented in a small number of maize lines at various stages of plant growth, according to studies [78].

Drought tolerant genotypes have low shoot dry weight, a robust root system, and a high root to shoot ratio during the seedling stage, according to maize studies [114]. Because a fibrous roots system allows for better and faster plant development before drought, as well as speeding up water extraction and progressively capable under drought conditions during the seedling stage; because the root system will be revealed to more soil volume and thus boost nutrient uptake due to nature's plasticity; so because root system will be exposed to more soil volume and thus increase nutrient absorption; since the root system will be given access to more soil volume and thus increase nutrient uptake; so the root system will be exposed to more soil volume [62].

### **2.4. Association Between Root Architectural System and Signs of N-Stress**

The response of crop plants to abiotic stressors is largely determined by root system architecture (RSA). Roots are the first to detect abiotic challenges because they grow

underground, and they adapt their genetic program for post-embryonic development to survive the stress. The soil, which is a complex system with intrinsic features, abiotic and biotic interactions, provides water and nutrients to plant roots. When changes in the plant's nutritional condition and external nutrient supply are sensed and integrated into the intrinsic root development program over time, RSA is modulated. Variations in the number, extension, positioning, and development direction of distinct root system components determine the degree of root plasticity [89]. Alteration in RSA affect above-ground biomass growth and development by affecting carbon allocation to shoots and/or initiating signaling pathways involving hormones, proteins, and RNAs, among other things. When confronted to abiotic stress, roots indirectly modulate leaf stomatal conductance and influence leaf blade posture and photosynthetic rate [130]. Even if breeding for root features is difficult, marker-assisted selection may be particularly useful for pyramiding numerous phenotypes linked with major effects of quantitative trait loci (QTL) in wheat, such as root angle, root length, root weight, and root-to-shoot ratio [7].

In wheat, direct selection for root system architecture features (length, biomass, density, and lateral root dispersion) has been linked to increased water and nutrient uptake. Lower canopy temperatures could be interpreted as an indication of enhanced root absorption capability, but higher stomata conductance would provide a similar signal [96]. [118] found that the core break approach can directly identify the variance in deep root traits to speed up selection on a variety of genotypes (cultivars, near-isogenic lines, and recombinant inbred lines) in Australia. Crown roots collected from the field were excavated and scored visually. The total plant depth and root system total length were shown to be highly associated in maize results [112]. Because crops with deeper roots have better access to stored water and nutrients like nitrogen, a soluble nutrient that tends to seep into the deeper layers of the soil, rooting depth is one of the most often studied features [117]. Because nitrate is easily leached from the soil profile, the major root qualities to optimize for improved N capture are rooting depth and rooting density, particularly for postanthesis N uptake [41]. Further advances in root architecture could focus on root proliferation at depth in wheat, and a deeper relative distribution of roots could be part of an ideotype to increase N capture [25]. The total root biomass, total root length, and root surface area are all increased by lateral roots. Greater nutrition and water intake is linked to increased lateral root density [107].

In soils when N is scarce, maize lines with long and few lateral roots yield 30% more than those with many short lateral roots, according to recent research. Root systems with fewer lateral roots lower metabolic costs associated with maintaining a complex root architecture, allowing more resources to be allocated to deeper roots for N access [126]. Many crops, such as maize, have a variety of roots, including cluster, brace, and crown roots, each with its own parent root in the node from which it grows. Depending on the environmental conditions, plants with these root systems can

generate steep primary roots and shallow adventitious roots for a more effective exploration of their surrounds. Hydro patterning is a phenomenon that occurs in the roots of various plant species, in which lateral roots grow from the side of the root that is in contact with the moist soil [119].

Root hairs are another potential route for increasing N capture, and two genes for root hair elongation have been discovered in maize, RTH1 and RTH3 [57]. Root architecture and function are likely to be multigene, making selection even more challenging (Hall and Richards, 2013). Single cell projections develop from root epidermal cells to form root hairs. Because root hairs make up such a big percentage of the overall root surface area, it is no surprise that they account for nearly half of the plant's water absorption. When wild-type *Arabidopsis* plants were compared to a root hairless mutant, the relevance of root hairs for water uptake was established. The root hairless mutants are more susceptible to drought, salt, and heat stress because of their diminished ability to absorb water [109]. The size of a plant's root system is an important factor that influences resource intake from the soil, and it should be compared to the size of the aboveground plant parts. For various species, the importance of a deep and strong root system for increased output has been described [115].

### **2.5. Selecting N-Low Tolerant Crop Plants Using Best Breeding Techniques**

The type of reproduction of the species, whether self-pollinating, cross-pollinating, or asexual, should be considered when selecting any breeding method for any crop. The cultivar type is linked to the trait's genetic regulation. It can be difficult to breed a species for more than one robust characteristic at a time since individual plants react so differently to similar abiotic stress conditions, but that is exactly what plant breeders are aiming for. Drought resistance is bred in the same way as yield and other income levels. For self-pollinated crops, pedigree and bulk methods might be utilized, whereas recurrent selection could be used for cross-pollinated crops. However, if the goal is to transfer a few drought-resistant features to a high-yielding genotype, back crossing is the approach to use. Biparental mating (half-sib and full-sib) on the other hand, retains a broad genetic foundation while also allowing for the evolution of the desired drought resistant genotype [125]. Drought-tolerant crop cultivars can be created through a variety of methods, including introduction, selection, hybridization, and mutations. Pedigree, modified bulk pedigree, and another culture technique were used to generate a salinity tolerant cultivar. Genetic modification for effective stress tolerance in plants is difficult due to the complex features of abiotic stress occurrences in plants [116]. [26] Have all discussed breeding methods for drought tolerance. Breeding for abiotic stress is an important approach to counteract yield loss. Scientists from all around the world are working hard to develop varieties and hybrids with better heterotic in stress-prone conditions. The most promising, less resource-intensive, economically viable, and socially acceptable solution is to

develop crop varieties with built-in salt, drought, and heat tolerance.

### **2.6. Low-Nitrogen Breeding Strategy**

Many smallholder farmers are unable to afford inorganic N sources due to its high cost, or are unable to acquire it due to its scarcity, or do not believe the returns from N use are sufficient to justify its cost. Furthermore, for these farmers, producing organic N sources (manure) is inefficient. Breeding for maize genotypes with high yield potential and high N efficiency is an excellent way for smallholder farmers to save money on fertilizer [82]. The performance of maize genotypes varies with soil fertility levels and the plant's N consumption efficiency, according to the findings [97]. Commercial maize varieties intended for greater yield in the tropics are chosen under ideal N fertility conditions, which may not suit the needs of resource-constrained farmers who cannot buy inorganic fertilizer. As a result, maize varieties that are resistant to N stress are needed. The most significant impediment to building tolerance to N stress is successful selection. It is critical for a breeder to have access to the right germplasm. The ability to appropriately estimate tolerance to N under relevant conditions to the target area and the intensity of selection comes next. To accomplish this, better understanding of the crop's behavior in Low-N environments, the ability to impose appropriate levels of stress, a set of secondary traits related to yield under N stress, the use of appropriate experimental designs, and proper germplasm selection and breeding strategy are all required [15].

Improvement of genotypes for Low-N tolerance requires less breeding stress than improvement for drought tolerance because N stress affects plant growth more evenly than drought stress [15]. As a result, evaluating genotypes under a single level of severe N deficit is sufficient to assess tolerance to Low-N stress for variable levels of soil N deficit. According to [9], genotypes with drought tolerance also show significant tolerance to low soil N stress. According to [14], using recurrent selection to improve drought tolerance leads to correlated improvement in Low-N tolerance. A strategy for reducing the impact of N stress on maize productivity is to select cultivars that use available N more effectively due to their increased capacity for uptake as well as grain production [67].

When compared to other beneficial molecular and physiological traits, genetic control is the most powerful. Improvements in root structure, such as length and thickness, as well as density, by increasing the production of root hairs and adventitious roots, are effective ways to improve crops' ability to acquire and absorb soil nutrients [33]. Shifting breeding and selection methods toward Low-N conditions and making better use of local natural genetic variability, varieties that are best suited genetically and able to respond appropriately when exposed to stress conditions can improve the management of valuable, finite resources, as well as potentially reduce the energy used to produce sufficient quality food for people all over the world [29].

### **2.7. Methodology of Reaction Breeding Under Duress for N-Low**

Breeders are primarily concerned with selection for increased grain yield when breeding for improved genotypes, but selection for grain yield under stress conditions may introduce some bias because heritability, which determines genetic advance under selection, changes with stress pattern and severity [15]. Similarly, [22] discovered that using grain yield alone as a measure of genotype improvement for stress tolerance is inefficient, but using secondary traits that are highly correlated with grain and have a high heritability will help to increase selection efficiency.

Secondary traits are advantageous because they improve the ability to identify genotypes with genetic potential to withstand drought and/or Low-N stresses. This is made possible because the heritability of some secondary traits remains high even under stressed conditions, which grain yields cannot tolerate [13]. [15] Identified some secondary traits that, in addition to grain yield, can guide selection for drought and Low-N tolerance. Some of these traits, such as anthesis-silking interval, leaf senescence, and ears per plant, are shared by drought and Low-N stresses. Secondary traits, in general, can be used to create a selection index for improving maize genotypes for drought and/or Low-N stress.

### **2.8. Selection of N-Low Tolerance Cultivars Using a Gene Action Approach**

Simply put, it refers to how genes (hereditary units) work to determine a character's phenotypic expression. Gene action can be additive or non-additive. Breeders prefer additive gene action to non-additive gene action because it is responsible for character transfer from parents to offspring. Many genetic studies have reported gene action controlling yield in terms of tolerance to drought and Low-N stresses, but these reports have been inconsistent. To name a few, [19] found that non-additive gene action dominated hybrid maize grain yield under low N and additive gene action dominated under high N. On the contrary, [18] found that additive gene action predominated in Low-N conditions and non-additive gene action predominated in High-N conditions. [51] found non-additive gene action to be dominant for hybrid maize grain yield under drought, but [44] found additive gene action to be dominant for grain yield under drought in their studies. The variations in general and specific combining abilities are used to deduce gene action [103]. GCA mean square expresses additive variance, whereas SCA mean square expresses non-additive variance, which includes dominance as well as all forms of epistasis interaction components, assuming epistasis exists.

Heterotic in hybrids may be caused by epistasis as well as the dominance effect of the genes. As a result, the failure of wide crosses to show heterosis may be largely attributed to the epistasis interaction of the Gene action in breeding for low N-tolerance genes [48]. [48] Defined epistasis simply as a condition in which one gene masks the effect of another gene on expression. Selecting varieties that perform well

under suboptimal N conditions is one strategy for increasing maize productivity. This can be accomplished by increasing the utilization of available N, either by having a high N-uptake capacity or by making better use of absorbed N in grain production [67]. Cultivars that are less responsive to applied N have been identified, and they sometimes outperform N-responsive hybrids or cultivars at low N levels [113].

The development of maize genotypes with high and stable yields under drought conditions is critical, as access to drought-adapted genotypes may be the only option available to many small-scale farmers. As a result, at the International Institute of Tropical Agriculture, improved tolerance to drought stress and suboptimal N conditions are important breeding goals (IITA). In the Guinea savannas, studies are being conducted independently to identify or develop maize genotypes that are tolerant to drought or low soil N. Although [10] discovered that drought-tolerant genotypes performed well under N-deficient conditions, no information is available on whether genotypes developed in West African savannas for tolerance to one of the stresses are also tolerant to others. Such information would be useful for future strategies in the development of stress-tolerant cultivars for West and Central African savannas.

### **2.9. The Importance of Combining Ability Assessments Crops That Are N-low Tolerant Are Selected Using This Method**

To expedite and increase selection efficiency for low N environments, a better understanding of the genetic basis for maize development and production under low N conditions is essential [13]. The value of inbred lines for hybrid maize breeding is determined by their capacity to combine. The principles of general and specialized combining ability were established by [105]. General combining ability (GCA) was defined by [54] as the mean performance of a line in all of its crosses, given as a deviation from the mean of all crosses. It is the average contribution an inbred makes to hybrid performance in a series of hybrid combinations when compared to other inbred in the same series of hybrid combinations, and specific combining ability (SCA) is the contribution of an inbred to hybrid performance in a cross with a specific other inbred when compared to its contributions in a variety of other inbred crosses. SCA is also defined as two inbred lines' capacity to complement each other and create improved hybrid performance.

GCA impacts can be utilized to assess trait gene action. GCA effects suggest largely additive gene action in statistical terms. Specific combining ability is linked to non-additive genetic effects that are unpredictable and transient, making statistical models difficult to forecast [37]. A strong GCA effect in a parent for a given trait implies the presence of additive gene effects for that trait in that parent. When parents with strong GCA effects are crossed, it is expected that a substantial proportion of progenies will have high values for the trait in question, aiding selection for that trait [38]. Under low N environments, the effects of GCA can be

utilized to select superior genotypes. High GCA effects in the presence of poor N tolerance could indicate the presence of the desired trait.

When it comes to identifying the optimal parents or parental combinations for a hybridization program, combining ability analysis is critical [108]. To measure the breeding value of the parents and the genetics of the traits under transfer, a variety of biometrical techniques are available. GCA and SCA effects, as well as their consequences in breeding, are estimated using diallel analysis [11, 50]. [50] Proposed a method for estimating the general and specific combining abilities of lines and hybrids in diallel mating systems. Another approach used frequently is line x tester analysis [64]. Several experiments were conducted to evaluate genotype performance and gene action in traits under optimal nitrogen and controlled low-nitrogen stress, as well as optimum moisture and managed drought stress [20]. However, the majority of this research only looked at one type of stress at a time. Multiple stressors, particularly drought and poor soil nitrogen, occur concurrently or at different periods within the same growing season in SSA under farmers' management settings.

Breeders in SSA have long recognized the necessity to combine drought and low nitrogen tolerance in maize cultivars. [75] Examined diallel crossings of maize inbred lines under optimal moisture and nitrogen, moisture stress, and low-nitrogen environments to find inbred lines with high GCA. Different gene actions were also documented in the control of grain yield under various management settings, according to the scientists. [82] Tested drought tolerant hybrids with various doses of drought-tolerant parents and found that most hybrids containing at least one drought-tolerant parent yielded more under low-nitrogen stress. [19] found that additive gene effects are important for grain output under drought, non-additive gene effects are important under low nitrogen, and both additive and non-additive gene effects are important under optimal moisture and nitrogen conditions. [31] discovered additive gene action for grain yield during drought, while both additive and non-additive gene actions are active under ideal conditions.

Although previous studies have used lines created through the pedigree breeding process, the purpose of this research is to find new lines and hybrids that perform well under drought and low nitrogen conditions while also yielding well under optimal conditions. The Drought Tolerant Maize for Africa (DTMA), Water Efficient Maize for Africa (WEMA), and Improved Maize for African Soil (IMAS) initiatives utilized new lines and tests produced in SSA utilizing traditional pedigree breeding, double haploid technology, and molecular breeding [20].

### **2.10. The Heterosis Analysis Approach Has Been Proposed as a Tool for Developing N-Low Tolerant Crops**

Heterosis refers to an offspring's improved performance (size and growth rate) over the parental genotypes. Increased grain production, shorter blooming period, and other characteristics of heterosis in crop plants can be observed

[34]. Crossbreeding results in improved size, vigor, productivity, and developmental rate, as well as resistance to pests and diseases and tolerance to climatic stressors, according to [100]. Based on the hybrid performance standard, heterosis can be classified into two types: mid-parent heterosis and better parent heterosis. [37] Claim that mid-parent heterosis explains a hybrid's performance in comparison to the parental lines' mid-performance.

Better parent heterosis, also known as heterobeltiosis, describes how a hybrid performs in comparison to its better parent. In order to fulfill rising demand, hybrid maize output has increased over the world due to heterosis. In four locations, [8] tested several extra-early inbred and single cross genotypes under drought stress, Low-N, and ideal circumstances. As drought intensity and N-low tolerance grow, the difference in grain yields between the single cross hybrids and their parental inbred increases, demonstrating heterosis. Inbred lines yield less than hybrids, according to [2], since hybrid genotypes have a higher level of heterosis for yield. Hybrids can produce up to three times the yield of their mother inbred lines, although superior hybrid genotypes are not necessarily genotyping with high heterosis from the farmer's perspective [34].

## **3. Breeding Methods**

### **3.1. To Find N-Low Tolerant Crops, Researchers Used Heritability Analysis**

Gomez and Kalamani [46] found that biological yield per plant, plant height, and number of panicles per plant has significant heritability and genetic progress, indicating that those traits should be considered during rice selection for drought and N-low tolerance. For low  $\text{Na}^+/\text{K}^+$  ratio in  $9 \times 9$  diallel in rice, [49] observed substantial environmental impacts with low narrow-sense heritability estimates. [52] Found a high magnitude of narrow sense heritability for the  $\text{Na}^+/\text{K}^+$  ratio and grain yield in both alkali and saline soils.

Recent research at IRRI has revealed that grain output under drought has a moderate to high heritability [66]. [127] reported high broad sense heritability for chlorophyll an and b in wheat.  $\text{Ca}^{2+}$ ,  $\text{K}^+$ ,  $\text{Na}^+$ ,  $\text{K}^+/\text{Na}^+$ ,  $\text{Ca}^{2+}/\text{Na}^+$ , and stress tolerance index all had high narrow-sense heritability values, showing the relevance of additive effects in their genetic regulation in Brassica naps [96]. If narrow sense heritability is low, early generation population sizes should be big; replications and locations should be expanded over years if possible to screen the proper genotypes; and selection should be done in later generations.

### **3.2. Estimating N-Low Tolerant Crops Using Conventional Breeding Methods**

A variety of factors influence the selection of an appropriate breeding program for the creation of tolerant cultivars to a specific abiotic stress, including screening procedures, sources and mechanisms of tolerance, gene action and heredity, and their link to agronomic qualities. The timing, duration, and

intensity of the stress are three critical aspects of drought characterization for successful stress tolerance breeding. Using traditional breeding procedures, drought-tolerant lines of crops such as peanut, common bean, safflower, chickpea, wheat, tall fescue, soybean, wheatgrass, barley, and maize have been created. Identifying traits that correlate well with drought N-low tolerance is one issue with this technique. Long ago, cycles of recurrent selection were reported as a strategy for breeding cross-pollinating species for salt tolerance [31]. To assist out-crossing in a self-pollinating species, the same technique would necessitate the introduction of male sterile lines [92]. These methods rely on the overall trait's heritability, which has been demonstrated in wild grasses [6], sorghum [73], maize [74], and tomato [74].

### **3.3. Method for Identifying Best N-Low Tolerant Cultivars (Selection and Introduction)**

The analysis of genetic variation via the collection and evaluation of accessible germplasm is the first step in breeding for any trait. If a locality or species lacks the desired variability, alien germplasm can be introduced. In all breeding tactics, this traditional approach is still highly useful. Using selection and introduction methods, a few salinity-tolerant cultivars have been generated around the world. The first step in improving the rain fed lowland ecosystem's varietal diversity was to purify landraces via pure line selection [77]. Selection of superior lineages within local landraces was the start of such breeding efforts. These could be tall, photoperiod-sensitive cultivars with varied levels of submergence tolerance [76].

### **3.4. MAS Supplements Diallel Selective Mating System**

The small genetic background in the resulting progenies is the main bottleneck in self-pollinated crop breeding, as breeders can only exercise parental control on two individuals for a single cross, three and four way crosses, and four at most for a double cross. IRRI is using a diallel selective mating system (DSMS), which is a modified version of Jensen's DSMS, to strengthen parental control, broaden the genetic base, and break up linkage blocks. This redesigned DSMS will be used to produce numerous abiotic stress tolerance genotypes with greater adaptability in the future. It is a recurrent selection method in which only the desirable alleles (selected genotypes) are advanced for selective inters mating. This system is based on "recurrent selection of the desired genotypes" and "intense crossing among the selected genotypes," with the goal of increasing the likelihood of obtaining the intended recombinant genotypes. The main goals of this long-term breeding strategy are to develop genetic materials with multiple abiotic stress tolerance, break up the very tight linkage blocks common in self-pollinated crops like rice, and maximize the chances that only the desired gene frequencies are forwarded to subsequent generations, tap germplasm donors available at IRRI from various geographical niches, and enable large-scale validation and use of marker aided selection (MAS) in

combinative breeding. Submergence prone coastal saline soils, inland salt impacted soils, N-low tolerance and drought, Fe toxic soils, and Zn deficient soils are the target regions for the materials generated [101]. For salinity (SALTOL locus) and submergence (SUB 1 locus) tolerance, this method uses marker assisted selection (MAS), while phenotypic selection is used for other variables [102].

### **3.5. Method of the Back Cross**

Backcrossing is a type of recurrent hybridization in which a gene for a desirable trait is added to a desirable variety. The backcross method of breeding is excellent for transferring drought tolerance features to a high yielding cultivar [35]. However, due to a lack of understanding of the physiological and genetic basis of drought tolerance in high yielding genotypes, transferring drought tolerance in high yielding genotypes is difficult. A thorough breeding method for N-low tolerance, drought resistance, and high yield potential has been proposed, utilizing the recurrent selection procedure [90]. The number of backcrosses required is determined by the donor's relative performance in comparison to the recurrent parent. Backcrossing may be advantageous if one parent contains more loci with favorable alleles than the other, if the parents are diverse, or if the level of dominance is high, according to [32]. In Australia [40] successfully transferred a key gene for Al tolerance from the Carazinho wheat variety to the Egret wheat variety. [23] also proposed that relevant drought-resistance traits be selectively incorporated into cultivars with superior yielding ability under ideal conditions, making them more adapted to poor environments. The International Rice Research Institute (IRRI) is now using this breeding approach to improve rice drought resistance [69]. In a big backcross breeding program using three recurrent parents and 203 donor lines with tolerance to numerous abiotic stresses in rice, a large number of introgression lines with increased abiotic stress tolerance were generated [3].

### **3.6. Marker-Assisted Selection Molecular Approaches**

Nitrogen boosts rice grain yield by improving other yield-related characteristics such as panicle number, thousand grain weight, and spikelet fertility [36]. Furthermore, a nitrogen deficiency causes plant growth to slow down, resulting in lower yields [128]. Tolerance to low nitrogen stress is a key quality for long-term rice production. Roots are essential for a variety of tasks, including water uptake and nutrient efficiency, physiological function, anchoring, and mechanical support, and they serve as the primary contact between plants and numerous biotic and abiotic challenges in the soil environment [104]. The root's response to nitrogen deprivation appears to be highly dependent on the current environment, plant species, and individual differences across cereal crops [56]. In rice breeding programs, root characteristics such as length, total number, root and shoot dry weight, and total dry weight are significant [63].

Quantitative gene-induced phenotypic variations might vary depending on diverse allelic combinations, potentially leading to continual variation in important features. These multigene traits are studied via quantitative trait loci (QTL) mapping. QTL analysis has the advantage of allowing researchers to look at a large number of genetic components and interactions between loci at once. This is particularly relevant for growth-related components, which are primarily influenced by a large number of genes [94]. QTLs can only be expressed in one condition, but when the conditions change, they have an impact. Natural variations have the potential to identify genetic material with improved nutrient uptake and utilization efficiency, and QTL analyses using natural variation have already revealed genes involved in nutrient deficit [95]. In another study, some QTLs for LN tolerance were mapped from a recombinant inbred line (RIL) population of 'Shenzhen 97'/Minguk 63' at seedling stage, and locations of a few QTLs parallel to the loci of genes responsible for N assembling and allocation, such as NADH-GOGAT, GS, and GDH2 were discovered [70].

Root morphological and physiological features are controlled by QTLs. Root length, weight, total number, thickness, and density of primary, adventitious, and lateral roots are all part of the root architecture system [86]. A root architecture system study, on the other hand, is difficult to conduct in soil conditions. To get over these limitations, a number of research have been carried out to look into root architecture by growing rice seedlings in a hydroponic environment using a variety of mapping populations [88]. QTLs for root length discovered in hydroponic experiments have been found to be useful for increasing grain yield in fields [87]. Under normal and stressed field conditions, a similar technique was used to identify QTLs responsible for better root architecture [98]. The current study, which aims to characterize the genetic basis of root architecture and development in rice seedlings at various N levels, will aid in the classification of rice lines with superior root architecture and development systems, as well as the breeding of rice germplasm with Low-N tolerance using molecular assisted markers.

Because screening for NUE components is complex and time consuming, NUE enhancement is an increase in grain production obtained through traditional plant breeding procedures. The linkage of roots with AMF, as well as root architecture and its interaction with N supply [72], are crucial from the enhancement of NUE. However, phenotyping wheat roots in the field is a difficult task [79].

### 3.7. Plants Transgenic for NUE in Cereal Crops

Amino acid biosynthesis, translocation, nitrogen remobilization and senescence, signaling and N regulatory proteins, and C/N storage proteins were among the 25 genes involved in the transgenic processes. The genes for main N metabolism were included in this transgenic (NR, GS and genes for GOGAT enzymes, i.e., Fad-GOGAT and NADH-GOGAT). In terms of improving NUE, these transgenic

produced conflicting outcomes [81]. Overexpression of OsNADH-GOGAT in rice under the direction of its own promoter, on the other hand, resulted in a significant increase in spikelet weight (up to 80%) with no change in plant height or spikelet quantity [123]. Overexpression of NADH-GOGAT can be exploited as a crucial step for N utilization and grain filling in rice and other cereal crops, according to this study. As a result, secondary N assimilation genes appear to be promising options for enhancing NUE in cereals, including wheat.

Transgenic have also been created utilizing transgenes for numerous other enzymes, including (1) GDH, which is involved in  $\text{NH}_4^+$  assimilation [71] (2) AS, which is involved in amino acid remobilization and translocation [80], (3) AspAT, and (4) Aliant [24]. Arabidopsis plants overexpressing ASN1 with a constitutive promoter showed increased NUE in seedlings in terms of seed protein and tolerance to nitrogen shortage [68].

The introduction of barley Aliant complementary DNA (cDNA) driven by the tissue-specific OsAnt1 promoter resulted in genetically modified rice [99]. Increased NUE was confirmed by increased biomass and grain yield, as well as significant changes in critical metabolites and nitrate levels in these plants. However, the over-expression of AspAT utilizing either a constitutive or tissue specific promoter in Brassica napus did not display any advantage for NUE, whether under low or high N circumstances [120]. However, in field and/or laboratory studies, transgenic B. napus and rice plants with over-expression of AlaAT showed increased biomass and seed yield under low N conditions [99]. Transgenic rice over-expressing AlaAT under the direction of a tissue-specific promoter improved NUE, according to [17].

Because of the intricacies inherent with the absorption, transport, and digestion of N in plants, transgenic crop plants genetically modified for a particular pathway implicated in NUE- and related traits have had limited success. Transgene silencing also limits the transgenic' potential utility. According to recent findings, precise modification of the endogenous RNA regulatory network has the potential to boost NUE in crop plants. It is now well accepted that one or more miRNAs or their TMs can be used to control a variety of characteristics [53].

### 3.8. Breeding Importance in Different Crops Under N-Low Stress

Wheat has been found to have genetic diversity for both NUpE and NUtE: genetic variation for N-related plant metrics (grain yield, grain N percent, total N uptake, and postanthesis N uptake) was also found in 20 elite winter wheat cultivars [16]. The rate, at which nitrogen was applied, followed by growth stage, and finally genotype, was revealed to be the most important factor in plant and crop performance. Furthermore, N was remobilized from all vegetative organs in all cultivars with efficiencies ranging from 80% to 85%; in another study involving 16 different wheat cultivars, pre-anthesis N accumulation rather than

post-anthesis N remobilization influenced genetic variation in grain yield and grain N percent under high N conditions and mild N stress [42].

A recent study involving 250 elite European wheat cultivars found that genotype N level interactions, heritability for NUtE, N harvest index (NHI), and NUE were all highly heritable [55]. The amount of nitrogen in the soil is crucial in exposing the genetic expression of wheat uptake and utilization efficiency. There is a stronger expression of uptake and overall rise in NUE at low N levels [59]. While utilization efficiency, as assessed by NHI, is better expressed at high N levels in the soil, in breeding programs conducted under high N supply, unique genetic variation for better crop performance under low N conditions may be used to generate genotypes with superior crop performance even under low N supply conditions [83].

Rice is a main food crop for about half of the world's population, and rice output must expand by 70% by 2050 to meet the world's growing population's demands [45]. Rice yields could be considerably increased by using nitrogen fertilizer [5]. The creation of enhanced NUE rice varieties could be one way to reduce N fertilizer use in rice cultivation [58]. Under low N input conditions, [60] evaluated the grain yield of two N-efficient varieties and two N-inefficient varieties, reporting that a high grain yield at a low N rate was related with deeper roots, enhanced root oxidation activity, and higher grain yield, and a higher photosynthetic NUE.

According to [121], significant differences in total N uptake at the heading stage (TNHD), total N uptake during the grain filling period (TNGF), total N uptake at maturity (TNPM), NUE for grain production (NUEg), nitrogen use efficiency for grain production (NUEb), and NHI were observed among the varieties in China. NUEg was significantly and positively connected with NUEb and NHI, while negatively correlated with N concentration in the grain, leaf, and stem, according to [121] research results. The quadratic association between NUEg and N concentration in leaf and stem revealed that improvements in NUEg were reliant on lower leaf N concentrations when the NUEg was increased. The NUEg, biomass during the grain-filling period, spikelets per panicle, and daily grain yield all showed a strong and positive connection. The NUEb or NHI were affected by the majority of the growth characteristics. The genetic breeding of both TNPM and NUEg has resulted in considerable improvements.

The study by [121] TNPM and NUEg were linked to the following plant traits: Primary plant parameters could be used to calculate TNPM: Total growth duration, plant height at heading, leaf area index at heading, crop growth rate before heading, biomass at heading, and grain filling percentage were all significantly and positively correlated with TNPM, but biomass accumulation during the grain filling period and panicle N concentration at heading were negatively correlated. Improvements in the TNPM at low N rates need genetically stimulating plant development prior to heading. The effect of nitrogen on carbohydrate partitioning, nitrate reduction efficiency, and remobilization of nitrogen

from senescent tissues and storage functions all affect N usage efficiency [41]. At low NUEg levels, variation in NUEg was caused by variations in the leaf N concentration at maturity, while additional increases in NUEg were caused by decreases in the stem N concentration. NUEg was significantly and positively linked with biomass buildup throughout the grain-filling stage, spikelets per panicle, and daily grain production in wheat, suggesting that delayed leaf senescence is a crucial characteristic for enhancing NUEg at low N supply [41]. Plant features linked to rapid crop development prior to heading could be exploited to boost TNPM, but biomass buildup and a big panicle are required for NUEg increases [121].

## 4. Summary and Conclusion

The majority of crop losses are caused by abiotic stressors, which account for more than half of all harvest losses. Salt and drought stress have a detrimental effect on plant growth, development, physiology, and production, according to several research findings. During the last century, conventional plant breeding played a significant role not only in improving crop quality and yield, but also in enhancing abiotic stress resistance, such as N-low, drought, and salinity tolerance. However, establishing abiotic stress tolerance varieties/hybrids will take longer. Crop varieties/lines/hybrids with improved resistance to low N, drought, salinity, heat, high temperature, and nutrient deficit are being developed, a key option for meeting global food demands with less water is to use both conventional and molecular breeding technologies, as well as genetic engineering. Traditional breeding knowledge combined with marker assisted selection makes it easier and more effective to induce drought tolerance in crop plants using genotypic data to improve and sustain productivity in drought-prone settings. Future plant breeders will need a mix of knowledge, abilities, and experience in plant breeding, genetics, genomics, statistics, experimental design, genetic diversity, and germplasm management to be successful.

They must be excellent communicators and able to work well in multidisciplinary teams. Understanding the genetic basis of drought and salinity tolerance in crop plants is required for a geneticist to generate improved genotypes using either traditional breeding or biotechnological methods. Breeders must constantly update their knowledge and skills to stay current due to rapid advances in crop science and genetic technologies. Despite the fact that scientists are working hard to raise the average yield of a variety of commercially significant crop plants, minimal progress has been made due to the increased severity of abiotic and biotic stressors. As a result, there is a pressing need to develop approaches to boost food output, particularly in the world's challenged regions. The current objective is to create MAS procedures that will speed up the breeding process, improve selection efficiency, and be affordable to partners in the National Agricultural Research and Extension Systems (NARES).

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## References

- [1] Abay, F.; Bjorn tad, A. Specific adaptation of barley varieties in different locations in Ethiopia. *Euphytica* 2009, *167*, 181-195.
- [2] Alam, A. K. M. M., Ahmed, S., Begum, M. And Sultan, M. K. (2008). Heterosis and Combining.
- [3] Ali, A. J., Xu, J. L., Ismail, A. M., Fu, B. Y., Vijayakumar, C. H. M., Gao, Y. M., Domingo, J., Maghirang, R., Yu, S. B., Gregorio, G., Yanagihara, S., Cohen, M., Carmen, B., Mackill, D. and Li, Z. K., 2006. Hidden diversity for abiotic and biotic stress tolerances in the primary gene pool of rice revealed by a large backcross breeding program. *Field Crops Res.*, *97*: 66–76.
- [4] Andersen, J. R. and Lübberstedt, T., 2003. Functional markers in plants. *Trends in plant science*, *8* (11), pp. 554-560.
- [5] Andrews, R. W., Pollard, A. and Pearce, J. M., 2013. The effects of snowfall on solar photovoltaic performance. *Solar Energy*, *92*, pp. 84-97.
- [6] Ashraf, M. and McNeilly, T., 1988. Variability in salt tolerance of nine spring wheat cultivars. *Journal of Agronomy and Crop Science*, *160* (1), pp. 14-21.
- [7] Atkinson, J. A., L. U. Wingen, M. Griffiths, M. P. Pound, O. Gaju, M. J. Foulkes, J. Le Gouis, S. Griffiths, M. J. Bennett, J. King, and D. M. Wells, 2015: *Phenotyping pipeline reveals major seedling root growth QTL in hexaploid wheat*. *J. Exp. Bot.* *66*, 2283–2292.
- [8] Badu-Apraku, B., Fakorede, M. A. B., Oyekunle, M. And Akinwale, R. O. (2011b). Selection and exploitation of heterosis in crops. An International Symposium, Mexico. Pp 11.
- [9] Badu-Apraku, B., Oyekunle, M., Fakorede, M. A. B., Vroh, I., O Akinwale, R. and Aderounmu, M., 2013. Combining ability, heterotic patterns and genetic diversity of extra-early yellow inbreds under contrasting environments. *Euphytica*, *192* (3), pp. 413-433.
- [10] Baenziger, M. And Lafitte, H. R. (1997). Efficiency of secondary traits for improving maize for low-nitrogen target environments. *Crop Science* *37*: 1110–1117.
- [11] Baker, H. G., Opler, P. A. and Baker, I., 1978. A comparison of the amino acid complements of floral and extra floral nectars. *Botanical Gazette*, *139* (3), pp. 322-332.
- [12] Banziger, M. and Diallo, A. O., 2004. Progress in developing drought and N stress tolerant maize cultivars for eastern and southern Africa. In *Integrated approaches to higher maize productivity in the new millennium. Proceedings of the 7th eastern and southern Africa regional maize conference, CIMMYT/KARI, Nairobi, Kenya* (pp. 189-194).
- [13] Bänziger, M., Betrán, F. J. and Lafitte, H. R., 1997. Efficiency of high-nitrogen selection environments for improving maize for low-nitrogen target environments. *Crop Science*, *37* (4), pp. 1103-1109.
- [14] Edmeades, G. O., Bolaños, J., Chapman, S. C., Lafitte, H. R. and Bänziger, M., 1999. Selection improves drought tolerance in tropical maize populations: I. Gains in biomass, grain yield, and harvest index. *Crop science*, *39* (5), pp. 1306-1315.
- [15] Bänziger, M. and Long, J., 2000. The potential for increasing the iron and zinc density of maize through plant-breeding. *Food and Nutrition Bulletin*, *21* (4), pp. 397-400.
- [16] Barraclough, P. B., Lopez-Bellido, R. and Hawkesford, M. J., 2014. Genotypic variation in the uptake, partitioning and remobilization of nitrogen during grain-filling in wheat. *Field Crops Research*, *156*, pp. 242-248.
- [17] Beatty, I. D. and Gerace, W. J., 2009. Technology-enhanced formative assessment: A research-based pedagogy for teaching science with classroom response technology. *Journal of Science Education and Technology*, *18* (2), pp. 146-162.
- [18] Hemmerle, H., Burger, H. J., Below, P., Schubert, G., Rippel, R., Schindler, P. W., Paulus, E. and Herling, A. W., 1997. Chlorogenic acid and synthetic chlorogenic acid derivatives: novel inhibitors of hepatic glucose-6-phosphate translocase. *Journal of medicinal chemistry*, *40* (2), pp. 137-145.
- [19] Betrán, F. J., Ribaut, J. M., Beck, D. and De León, D. G., 2003. Genetic diversity, specific combining ability, and heterosis in tropical maize under stress and nonstress environments. *Crop Science*, *43* (3), pp. 797-806.
- [20] Beyene, Y., Katoh, S., WoldeGabriel, G., Hart, W. K., Uto, K., Sudo, M., Kondo, M., Hyodo, M., Renne, P. R., Suwa, G. and Asfaw, B., 2013. The characteristics and chronology of the earliest Acheulean at Konso, Ethiopia. *Proceedings of the National Academy of Sciences*, *110* (5), pp. 1584-1591.
- [21] Bharath, S. T., Jayaraman, S. and Nagar, V., 2013. Exit as governance: An empirical analysis. *The Journal of Finance*, *68* (6), pp. 2515-2547.
- [22] Blum, L. and Stell, G., 1979. Polydisperse systems. I. Scattering function for polydisperse fluids of hard or permeable spheres. *The Journal of Chemical Physics*, *71* (1), pp. 42-46.
- [23] Cañas, A. I. and Camarero, S., 2010. Laccases and their natural mediators: biotechnological tools for sustainable eco-friendly processes. *Biotechnology advances*, *28* (6), pp. 694-705.
- [24] Berry, P., Foulkes, J., Carvalho, P., Teakle, G., White, P., White, C. and Roques, S., 2011. Breeding oilseed rape with a low requirement for nitrogen fertiliser. *HGCA Project Report*, (479).
- [25] Chang, M. M., Leeman, S. E. and NIALL, H. D., 1971. Amino-acid sequence of substance P. *Nature New Biology*, *232* (29), pp. 86-87.
- [26] Craswell, E. T. and Godwin, D. C., 1984. The efficiency of nitrogen fertilizers applied to cereals in different climates. *Advances in plant nutrition (USA)*.
- [27] Cui, J., Chi, X. Z., Ding, H. T., Lin, L. T., Yang, Z. C. and Yan, G. Z., 2009. Transient response and stability of the AGC-PI closed-loop controlled MEMS vibratory gyroscopes. *Journal of Micromechanics and Microengineering*, *19* (12), p. 125015.
- [28] Dawson, J. C., Huggins, D. R. and Jones, S. S., 2008. Characterizing nitrogen use efficiency in natural and agricultural ecosystems to improve the performance of cereal crops in low-input and organic agricultural systems. *Field Crops Research*, *107* (2), pp. 89-101.

- [29] De Fraiture, C., Molden, D. and Wichelns, D., 2010. Investing in water for food, ecosystems, and livelihoods: An overview of the comprehensive assessment of water management in agriculture. *Agricultural Water Management*, 97 (4), pp. 495-501.
- [30] Derera, J., Tongoona, P., Vivek, B. S. and Laing, M. D., 2008. Gene action controlling grain yield and secondary traits in southern African maize hybrids under drought and non-drought environments. *Euphytica*, 162 (3), pp. 411-422.
- [31] Dewey, O. R., Hartley, G. S. and MacLauchlan, J. W. G., 1962. External leaf waxes and their modification by root-treatment of plants with trichloroacetate. *Proceedings of the Royal Society of London. Series B. Biological Sciences*, 155 (961), pp. 532-550.
- [32] Meena, H. P., Bainsla, N. K. and Yadav, D. K., 2016. Breeding for abiotic stress tolerance in crop plants. *Recent advances in plant stress physiology*. Daya Publishing House, New Delhi, pp. 329-378.
- [33] Raju, P. S., Clark, R. B., Ellis, J. R., Duncan, R. R. and Maranville, J. W., 1990. Benefit and cost analysis and phosphorus efficiency of VA mycorrhizal fungi colonizations with sorghum (*Sorghum bicolor*) genotypes grown at varied phosphorus levels. In *Plant Nutrition—Physiology and Applications* (pp. 165-170). Springer, Dordrecht.
- [34] Duvick, D. N., 1997. What is yield. *Developing drought and low N-tolerant maize*. CIMMYT, El Batan, Mexico, pp. 332-335.
- [35] Wheeler, D. M., Edmeades, D. C., Christie, R. A. and Gardner, R., 1992. Effect of aluminium on the growth of 34 plant species: a summary of results obtained in low ionic strength solution culture. *Plant and Soil*, 146 (1), pp. 61-66.
- [36] Fageria, N. K., Baligar, V. C. and Zobel, R. W., 2007. Yield, nutrient uptake, and soil chemical properties as influenced by liming and boron application in common bean in a no - tillage system. *Communications in soil science and plant analysis*, 38 (11-12), pp. 1637-1653.
- [37] Hill, W. G. and Mackay, T. F., 2004. DS Falconer and Introduction to quantitative genetics. *Genetics*, 167 (4), pp. 1529-1536.
- [38] Cheverud, J. M., 1984. Quantitative genetics and developmental constraints on evolution by selection. *Journal of theoretical biology*, 110 (2), pp. 155-171.
- [39] Fess, T. L., Kotcon, J. B. and Benedito, V. A., 2011. Crop breeding for low input agriculture: a sustainable response to feed a growing world population. *Sustainability*, 3 (10), pp. 1742-1772.
- [40] Fisher, S. S., McGreevy, M., Humphries, J. and Robinett, W., 1987, January. Virtual environment display system. In *Proceedings of the 1986 workshop on Interactive 3D graphics* (pp. 77-87).
- [41] Foulkes, M. J., Hawkesford, M. J., Barraclough, P. B., Holdsworth, M. J., Kerr, S., Kightley, S. and Shewry, P. R., 2009. Identifying traits to improve the nitrogen economy of wheat: Recent advances and future prospects. *Field Crops Research*, 114 (3), pp. 329-342.
- [42] Gaju, O., Allard, V., Martre, P., Le Gouis, J., Moreau, D., Bogard, M., Hubbart, S. and Foulkes, M. J., 2014. Nitrogen partitioning and remobilization in relation to leaf senescence, grain yield and grain nitrogen concentration in wheat cultivars. *Field Crops Research*, 155, pp. 213-223.
- [43] Gallais, A. and Hirel, B., 2004. An approach to the genetics of nitrogen use efficiency in maize. *Journal of experimental botany*, 55 (396), pp. 295-306.
- [44] Gethi, J. G. and Smith, M. E., 2004. Genetic responses of single crosses of maize to *Striga hermonthica* (Del.) Benth. and *Striga asiatica* (L.) Kuntze. *Crop science*, 44 (6), pp. 2068-2077.
- [45] Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Pretty, J., Robinson, S., Thomas, S. M. and Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. *science*, 327 (5967), pp. 812-818.
- [46] Pradheep, K., Gomez, S. M. and Kalamani, A., 2003. Possibilities of Broadening the Plant Wealth of Horticulture from Existing. *Asian Journal of Plant Science*, 2 (9), pp. 719-730.
- [47] Good, A. G., Shrawat, A. K. and Muench, D. G., 2004. Can less yield more? Is reducing nutrient input into the environment compatible with maintaining crop production? *Trends in plant science*, 9 (12), pp. 597-605.
- [48] Goodnight, T. M., 1997. *Perceptions and attitudes of selected swine producers and non-swine producers concerning certain social and environmental issues* (Doctoral dissertation, Oklahoma State University).
- [49] Gregorio, G. B. and Senadhira, D., 1993. Genetic analysis of salinity tolerance in rice (*Oryza sativa* L.). *Theoretical and applied Genetics*, 86 (2), pp. 333-338.
- [50] Griffing, B. R. U. C. E., 1956. Concept of general and specific combining ability in relation to diallel crossing systems. *Australian journal of biological sciences*, 9 (4), pp. 463-493.
- [51] Guei, R. G. and Wassom, C. E., 1992. Inheritance of some drought adaptive traits in maize. I: Interrelationships between yield, flowering, and ears per plant. *Maydica*, 37 (2), pp. 157-164.
- [52] Waddell, J. T., Gupta, S. C., Moncrief, J. F., Rosen, C. J. and Steele, D. D., 1999. Irrigation and nitrogen management effects on potato yield, tuber quality, and nitrogen uptake. *Agronomy Journal*, 91 (6), pp. 991-997.
- [53] Purba, J., Sharma, R. K., Jat, M. L., Thind, H. S., Gupta, R. K., Chaudhary, O. P., Chandna, P., Khurana, H. S., Kumar, A., Uppal, H. S. and Uppal, R. K., 2015. Site-specific fertilizer nitrogen management in irrigated transplanted rice (*Oryza sativa*) using an optical sensor. *Precision Agriculture*, 16 (4), pp. 455-475.
- [54] Hallauer, A. R., Russell, W. A. and Lamkey, K. R., 1988. Corn breeding. *Corn and corn improvement*, 18, pp. 463-564.
- [55] Kopke, U., Athmann, M., Han, E. and Kautz, T., 2015. Optimising cropping techniques for nutrient and environmental management in organic agriculture. *Sustainable Agriculture Research*, 4 (526-2016-37934).
- [56] Bruun, S., Luxhøi, J., Magid, J., de Neergaard, A. and Jensen, L. S., 2006. A nitrogen mineralization model based on relationships for gross mineralization and immobilization. *Soil Biology and Biochemistry*, 38 (9), pp. 2712-2721.

- [57] Hochholdinger, F., and R. Tuberosa, 2009: Genetic and genomic dissection of maize root development and architecture. *Curr. Opin. Plant Biol.* 12, 172–177.
- [58] Cai, C., Hu, S., Guo, J., Shi, Y., Xie, G. J. and Yuan, Z., 2015. Nitrate reduction by denitrifying anaerobic methane oxidizing microorganisms can reach a practically useful rate. *Water Research*, 87, pp. 211-217.
- [59] Huggins, D. R. and Pan, W. L., 2003. Key indicators for assessing nitrogen use efficiency in cereal-based agroecosystems. *Journal of crop production*, 8 (1-2), pp. 157-185.
- [60] Ju XT, Xing GX, Chen XP, Zhang SL, Zhang LJ, Liu XJ, Cui ZL, Christie P, Zhang FS (2009) Reducing environmental risk by improving N management in intensive Chinese agricultural systems. *Proc Natl Acad Sci USA* 106: 3041–3046.
- [61] Ju, C., Buresh, R. J., Wang, Z., Zhang, H., Liu, L., Yang, J., et al. (2015). Root and shoot traits for rice varieties with higher grain yield and higher nitrogen use efficiency at lower nitrogen rates application. *Field Crops Res.* 175, 47–55. doi: 10.1016/j.fcr.2015.02.007.
- [62] Kamoshita, A., Rodriguez, R., Yamauchi, A. and Wade, L., 2004. Genotypic variation in response of rainfed lowland rice to prolonged drought and rewatering. *Plant Production Science*, 7 (4), pp. 406-420.
- [63] Kanbar, A., Toorchi, M. and Shashidhar, H., 2009. Relationship between root and yield morphological characters in rainfed low land rice (*Oryza sativa* L.). *Cereal Research Communications*, 37 (2), pp. 261-268.
- [64] Kempthorne, O., 1957. An introduction to genetic statistics.
- [65] Kochian, L. V., 2012. Rooting for more phosphorus. *Nature*, 488 (7412), pp. 466-467.
- [66] Thind, H. S., Kumar, A., Gupta, R. K., Kaul, A. and Vashistha, M., 2012. Fixed-time adjustable dose site-specific fertilizer nitrogen management in transplanted irrigated rice (*Oryza sativa* L.) in South Asia. *Field Crops Research*, 126, pp. 63-69.
- [67] Lafitte, H. R. and Edmeades, G. O., 1994. Improvement for tolerance to low soil nitrogen in tropical maize I. Selection criteria. *Field Crops Research*, 39 (1), pp. 1-14.
- [68] Lam, H. M., Wong, P., Chan, H. K., Yam, K. M., Chen, L., Chow, C. M. and Coruzzi, G. M., 2003. Overexpression of the *ASN1* gene enhances nitrogen status in seeds of *Arabidopsis*. *Plant physiology*, 132 (2), pp. 926-935.
- [69] Hardgrove, S. J. and Livesley, S. J., 2016. Applying spent coffee grounds directly to urban agriculture soils greatly reduces plant growth. *Urban forestry & urban greening*, 18, pp. 1-8.
- [70] Lian, X., Xing, Y., Yan, H., Xu, C., Li, X. and Zhang, Q., 2005. QTLs for low nitrogen tolerance at seedling stage identified using a recombinant inbred line population derived from an elite rice hybrid. *Theoretical and Applied Genetics*, 112 (1), pp. 85-96.
- [71] Gilbody, S., Lewis, S. and Lightfoot, T., 2007. Methylene tetrahydrofolate reductase (MTHFR) genetic polymorphisms and psychiatric disorders: a HuGE review. *American journal of epidemiology*, 165 (1), pp. 1-13.
- [72] Liu, M., Liu, R. and Chen, W., 2013. Graphene wrapped Cu<sub>2</sub>O nanocubes: non-enzymatic electrochemical sensors for the detection of glucose and hydrogen peroxide with enhanced stability. *Biosensors and Bioelectronics*, 45, pp. 206-212.
- [73] Maiti, R. K., Amaya, L. E. D., Cardona, S. I., Dimas, A. M. O., de la rosaibarra, M. And Castillo, H. D., 1996. Genotypic variability in maize cultivars (*Zea mays* L.) For resistance to drought and salinity at the seedling stage. *Journal of Plant Physiology*, 148: 741-744.
- [74] Maiti, R. K., dela Rosa-Ibarra, M. And Sandoval, N. D., 1994. Genotypic variability in glossy sorghum lines for resistance to drought, salinity and temperature stress at the seedling stage. *Journal of Plant Physiology*, 143: 211-244.
- [75] Makumbi, D., Betrán, J. F., Bänziger, M. and Ribaut, J. M., 2011. Combining ability, heterosis and genetic diversity in tropical maize (*Zea mays* L.) under stress and non-stress conditions. *Euphytica*, 180 (2), pp. 143-162.
- [76] Mallik, S., 1995. Rice germplasm evaluation and improvement for stagnant flooding. KT, editor. Rainfed lowland rice: agricultural research for high-risk environments, Manila (Philippines): International Rice Research Institute. p 97-109.
- [77] Mallik, S., Mandal, B. K., Sen, S. N. and Sarkarung, S., 2002. Shuttle Breeding: an effective tool for rice varietal improvement in rainfed lowland ecosystem in eastern India. *Curr. Sci.*, 83 (9): 1097-1102.
- [78] Manavalan, L. K., T. Musket, and H. T. Nguyen, 2011: Natural genetic variation for root traits among diversity lines of maize (*Zea mays* L.). *Maydica* 56, 1-10.
- [79] Manske, G. G. B., I. J. Ortoz-Monasterio, and P. L. G. Vlek. 2001. Techniques for measuring genetic diversity in roots. p. 208–218. In: M. P. Reynolds, J. I. Ortiz-Monasterio, and A. MacNab (eds), Application of physiology in wheat breeding. CIMMYT, Mexico, DF.
- [80] Masclaux-Daubresse, C., Reisdorf-Cren, M., Pageau, K., Lelandais, M., Grandjean, O., Kronenberger, J., Valadier, M. H., Feraud, M., Joulet, T. and Suzuki, A., 2006. Glutamine synthetase-glutamate synthase pathway and glutamate dehydrogenase play distinct roles in the sink-source nitrogen cycle in tobacco. *Plant physiology*, 140 (2), pp. 444-456.
- [81] Masclaux-Daubresse, C., Daniel-Vedele, F., Dechorgnat, J., Chardon, F., Gaufichon, L. and Suzuki, A., 2010. Nitrogen uptake, assimilation and remobilization in plants: challenges for sustainable and productive agriculture. *Annals of botany*, 105 (7), pp. 1141-1157.
- [82] Meseka, S. K., Menkir, A. And Ibrahim, A. E. S. (2006). Genetic analysis of performance of Nitrogen use in maize. Pp. 316-319.
- [83] Muellner, A. E., Mascher, F., Schneider, D., Ittu, G., Toncea, I., Rolland, B. and Löschenberger, F., 2014. Refining breeding methods for organic and low-input agriculture: analysis of an international winter wheat ring test. *Euphytica*, 199 (1), pp. 81-95.
- [84] Murphy, K., Lammer, D., Lyon, S., Carter, B. and Jones, S. S., 2005. Breeding for organic and low-input farming systems: An evolutionary-participatory breeding method for inbred cereal grains. *Renewable Agriculture and Food Systems*, 20 (1), pp. 48-55.
- [85] Murphy, K. M., Campbell, K. G., Lyon, S. R. and Jones, S. S., 2007. Evidence of varietal adaptation to organic farming systems. *Field Crops Research*, 102 (3), pp. 172-177.

- [86] Obara, M., W. Tamura, T. Ebitani, M. Yano, T. Sato and T. Yamaya. 2010. Fine mapping of qrl6. 1, a major QTL for root length of rice seedlings grown under a wide range of  $\text{NH}_4^+$  concentrations in hydroponic conditions. *Theor. Appl. Genet.*, 21: 535-547.
- [87] Obara, M., T. Takeda, T. Hayakawa and T. Yamaya. 2011. Mapping quantitative trait loci controlling root length in rice seedlings grown with low or sufficient supply using backcross recombinant lines derived from a cross between *Oryza sativa* L. And *Oryza glaberrima* Steud. *Soil Sci. And Plant Nutr.*, 57: 80-92.
- [88] Ogawa, S., M. O. Valencia, M. Ishitani and M. G. Selvaraj. 2014. Root system architecture variation in response to different  $\text{NH}_4^+$  concentrations and its association with nitrogen deficient tolerance traits in rice. *Acta Phys. Plantarum.*, 36: 2361-2372.
- [89] Paez-Garcia, A., Motes, C. M., Scheible, W. R., Chen, R., Blancaflor, E. B. and Monteros, M. J., 2015. Root traits and phenotyping strategies for plant improvement. *Plants*, 4 (2), pp. 334-355.
- [90] Paroda, R. S. and Arora, R. K., 1986. and their Conservation: Indian Perspective. *Conservation for Productive Agriculture: Commemorative Volume Released on the Eightieth Birthday of Dr. B.P. Pal*, p. 73.
- [91] Quarrie, s. a., 1996. New molecular tools to improve the efficiency of breeding for increased drought resistance. *Plant growth regulators*, 20: 167-178.
- [92] Ramage, R. T., 1980. Genetic methods to breed salt tolerance in plants. In *Genetic engineering of osmoregulation* (pp. 311-318). Springer, Boston, MA.
- [93] Raun, W. R. and Johnson, G. V., 1999. Improving nitrogen use efficiency for cereal production. *Agronomy journal*, 91 (3), pp. 357-363.
- [94] Rebouillat, P., Vidal, R., Cravedi, J. P., Taupier-Letage, B., Debrauwer, L., Gamet-Payraastre, L., Touvier, M., Hercberg, S., Lairon, D., Baudry, J. and Kesse-Guyot, E., 2021. Estimated dietary pesticide exposure from plant-based foods using NMF-derived profiles in a large sample of French adults. *European Journal of Nutrition*, 60 (3), pp. 1475-1488.
- [95] Rengel, Z. And P. Marschner. 2005. Nutrient availability and management in the rhizosphere: exploiting genotypic differences. *New Phytol.*, 168: 305-312.
- [96] Saito, R., Cranmer, B. K., Tessari, J. D., Larsson, L., Mehaffy, J. M., Keefe, T. J. and Reynolds, S. J., 2009. Recombinant factor C (rFC) assay and gas chromatography/mass spectrometry (GC/MS) analysis of endotoxin variability in four agricultural dusts. *Annals of occupational hygiene*, 53 (7), pp. 713-722.
- [97] Scharf, P. C., Schmidt, J. P., Kitchen, N. R., Sudduth, K. A., Hong, S. Y., Lory, J. A. and Davis, J. G., 2002. Remote sensing for nitrogen management. *Journal of soil and water conservation*, 57 (6), pp. 518-524.
- [98] Nobuhiro, T., Shimizu, A., Kabeya, N., Tsuboyama, Y., Kubota, T., Abe, T., Araki, M., Tamai, K., Chann, S. and Keth, N., 2007. Year-round observation of evapotranspiration in an evergreen broadleaf forest in Cambodia. In *Forest environments in the Mekong river basin* (pp. 75-86). Springer, Tokyo.
- [99] Shrawat, A. K., R. T. Carroll, M. DePauw, G. Taylor, and A. G. Good. 2008. Genetic engineering of improved nitrogen use efficiency in rice by the tissue specific expression of alanine amino transferase. *Plant Biotechnol. J.* 6: 722-732.
- [100] Shull, G. H. "Beginning of the heterosis concept in heterosis. Iowa State." (1952): 419-428.
- [101] Singh, K. K., Talat, M. and Hasan, S. H., 2006. Removal of lead from aqueous solutions by agricultural waste maize bran. *Bioresource Technology*, 97 (16), pp. 2124-2130.
- [102] Singh, RK., Gregrio, G. B. and Ismail, A. M., 2008. Breeding rice varieties with tolerance to salt stress. *J. Indian Soc. Coastal Agric. Res.*, 26 (1): 16-21.
- [103] Singh, B. D. (2003). *Plant Breeding, Principles and Methods*. Kalyani Publishers. New Delhi.
- [104] Smith, S. And I. D. Smet. 2012. Root system architecture: insights from Arabidopsis and cereal crops. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.*, 367 (1595): 1441-1452.
- [105] Machikowa, T., Saetang, C. and Funpeng, K., 2011. General and specific combining ability for quantitative characters in sunflower. *Journal of Agricultural Science*, 3 (1), p. 91.
- [106] Sthapit, B., Rana, R., Eyzaguirre, P. and Jarvis, D., 2008. The value of plant genetic diversity to resource-poor farmers in Nepal and Vietnam. *International journal of agricultural sustainability*, 6 (2), pp. 148-166.
- [107] Song, Y., Sun, H., Li, M. and Zhang, Q., 2015. Technology application of smart spray in agriculture: A review. *Intelligent Automation & Soft Computing*, 21 (3), pp. 319-333.
- [108] Tamlarasi, P. M., Arumugachamy, S., Anantha, M. S. and Utharasu, S., 2010. Identification of nitrogen (N) stress tolerant maize (*Zea mays* L.) inbred lines for low nitrogen input condition. *Indian Journal of Agricultural Research*, 44 (11), pp. 53-57.
- [109] Dublin, D. R. and Tanaka, N., 2014. Indigenous agricultural development for sustainability and "Satoyama". *Geography, Environment, Sustainability*, 7 (2), pp. 86-95.
- [110] Tilman DG, Cassman KG, Matson PA, Naylor R, Polasky S (2002) Agricultural sustainability and intensive production practices. *Nature* 418: 671-677.
- [111] Tokatlidis IS, Koutroubas SD (2004) A review of maize hybrids' dependence on high plant populations and its implications for crop yield stability. *Field Crops Res* 88: 103-114.
- [112] Trachsel, S., S. Kaeppler, K. Brown, and J. Lynch, 2011: Shovelomics: high throughput phenotyping of maize (*Zea mays* L.) root architecture in the field. *Plant Soil* 341, 75-87.
- [113] Tsai, W. T., Chang, C. Y. and Lee, S. L., 1998. A low cost adsorbent from agricultural waste corn cob by zinc chloride activation. *Bioresource Technology*, 64 (3), pp. 211-217.
- [114] Collins, N. C., Tardieu, F. and Tuberosa, R., 2008. Quantitative trait loci and crop performance under abiotic stress: where do we stand? *Plant physiology*, 147 (2), pp. 469-486.
- [115] Tuberosa, R., 2012. Phenotyping for drought tolerance of crops in the genomics era. *Frontiers in physiology*, 3, p. 347.
- [116] Wang, Q., Wang, Y., Wang, Q. and Liu, J., 2014. Impacts of 9 years of a new conservational agricultural management on soil organic carbon fractions. *Soil and Tillage Research*, 143, pp. 1-6.

- [117] Wasson, A.; Richards, R.; Chatrath, R.; Misra, S.; Prasad, S. S.; Rebetzke, G.; Kirkegaard, J.; Christopher, J.; Watt, M. Traits and selection strategies to improve root systems and water uptake in water-limited wheat crops. *J. Exp. Bot.* 2012, 63, 3485–3498.
- [118] Wasson, A. P., G. J. Rebetzke, J. A. Kirkegaard, J. Christopher, R. A. Richards, and M. Watt, 2014: Soil coring at multiple field environments can directly quantify variation in deep root traits to select wheat genotypes for breeding. *J. Exp. Bot.* 65, 6231–6249.
- [119] Watt, M.; Schneebeli, K.; Dong, P.; Wilson, I. W. The shoot and root growth of Brachypodium and its potential as a model for wheat and other cereal crops. *Funct. Plant Biol.* 2009, 36, 960–969.
- [120] Wolansky, M. A. 2005. Genetic manipulation of aspartate amino transferase levels in *Brassica napus*: Effects on nitrogen use efficiency. M. Sc. Thesis, University of Alberta.
- [121] Wu, H., Zhang, Y., Yuan, Z. and Gao, L., 2016. A review of phosphorus management through the food system: identifying the roadmap to ecological agriculture. *Journal of cleaner production*, 114, pp. 45-54.
- [122] Xu, Y., R. Wang, Y. Tong, H. Zhao, Q. Xie, D. Liu, A. Zhang, B. Li, H. Xu, and D. An. 2014. Mapping QTLs for yield and nitrogen-related traits in wheat: Influence of nitrogen and phosphorus fertilization on QTL expression. *Theor. Appl. Genet.* 127: 59–72.
- [123] Yamaya T. M. Obara, H. Nakajima, S. Sasaki, T. Hayakawa, and T. Sato. 2002. Genetic manipulation and quantitative-trait loci mapping for nitrogen recycling in rice. *J. Expt. Bot.* 53: 917–25.
- [124] Yapi, A. M.; Kergna, A. O.; Debrah, S. K.; Sidibe, A.; Sanogo, O. *Analysis of the Economic Impact of Sorghum and Millet Research in Mali*; International Crops Research Institute for the Semi-Arid Tropics: Andhra Pradesh, India, 2000.
- [125] Srivastava, R. B., Paroda, R. S., Sharma, S. C. and Yunus, M. D., 1989. Genetic variability and advance under four selection procedures in wheat pedigree breeding programme. *Theoretical and applied genetics*, 77 (4), pp. 516-520.
- [126] Zhan, A.; Lynch, J. P. Reduced frequency of lateral root branching improves N capture from Low-N soils in maize. *J. Exp. Bot.* 2015, doi: 10.1093/jxb/erv007.
- [127] Ju, X. T., Xing, G. X., Chen, X. P., Zhang, S. L., Zhang, L. J., Liu, X. J., Cui, Z. L., Yin, B., Christie, P., Zhu, Z. L. and Zhang, F. S., 2009. Reducing environmental risk by improving N management in intensive Chinese agricultural systems. *Proceedings of the National Academy of Sciences*, 106 (9), pp. 3041-3046.
- [128] Zhao, Y., Y. He, J. Sun, J. Zhang and Y. Zhan. 2018. Effects of nitrogen deficiency on physiology and growth of *Fraxinus mandshurica*. *Pak. J. Bot.*, 50 (1): 179-187.
- [129] Restuccia, D., Yang, D. T. and Zhu, X., 2008. Agriculture and aggregate productivity: A quantitative cross-country analysis. *Journal of monetary economics*, 55 (2), pp. 234-250.
- [130] DoVale, J. C. and Fritsche-Neto, R., 2015. Root phenomics. In *Phenomics* (pp. 49-66). Springer, Cham.
- [131] Cartea, M. E., Francisco, M., Lema, M., Soengas, P. and Velasco, P., 2010. Resistance of cabbage (*Brassica oleracea capitata* group) crops to *Mamestra brassicae*. *Journal of economic entomology*, 103 (5), pp. 1866-1874.