**Legumes: Breeding Strategies and Adaptive Traits for Drought Tolerance**

**Abstract**

Legume crops such as chickpea, cowpea, common bean, lima bean, mung bean, faba bean, and lentil are vital to global agriculture due to their nutritional value, environmental benefits, and role in sustainable farming systems. Rich in protein, fiber, and micronutrients, legumes support low-input farming, particularly in arid and semi-arid regions. However, their productivity is increasingly affected by drought and other climate-related stresses. This review synthesizes current knowledge on breeding strategies and adaptive traits that enhance drought tolerance in legumes. Key traits contributing to water-use efficiency and yield stability under stress include early flowering, stay-green phenotype, deep rooting, enhanced root hydraulic conductivity, and strong antioxidant-based defense mechanisms. Physiological indicators such as canopy temperature depression, chlorophyll retention, relative water content, and membrane stability also play crucial roles in legumes for drought adaptation. The review emphasizes the importance of genotypic variability and trait heritability across legume species, which serve as resources for developing climate-resilient varieties. While conventional breeding methods such as pedigree and recurrent selection have driven past progress, modern approaches like marker-assisted selection, genomic selection, GWAS, and CRISPR-based gene editing are now accelerating genetic gain in legume crops. Despite these advancements, challenges remain, including limited multi-environment testing, underutilization of wild germplasm, inadequate phenotyping tools for complex traits and poor adoption of improved cultivars. Addressing these requires a systems-based breeding framework that combines genomics, high-throughput phenotyping, and participatory approaches. Integrating adaptive traits with innovative breeding tools will enable the development of drought-resilient, high-yielding, and nutritionally rich legume cultivars, supporting food security and sustainable agriculture in a changing climate.

**Key words:** Legume breeding, Drought tolerance, Water use efficiency, Marker assisted selection (MAS), Genomic selection (GS)

**Introduction**

 Legumes such as chickpea, lima bean, cowpea, common bean, mung bean, faba bean and lentil are crucial crops important for their high protein content and therefore nutritional value. Globally, legumes grow on approximately 96.64mha of land, with an annual production of around 94.34mt and productivity of 976.2kg/ha. In India, legumes are extensively cultivated, covering about 34.79mha with production of 25.73mt and yielding approximately 739.6kg/ha (FAOSTAT 2023). These legumes play a significant role in improving soil fertility through nitrogen fixation, enhancing dietary protein intake and providing sustainable crop options for farmers (Pierre J. F., 2024). However, legume production faces considerable challenges, particularly in drought-prone and irrigated environments. Legume production faces major constraints from biotic and abiotic stresses. Biotic stresses, including insect herbivory, viral infections and bacterial pathogens, significantly impact productivity and food security (Akram *et al*., 2021). Pests and diseases such as Helicoverpa, Ascochyta blight, and Fusarium blight cause up to 20% annual yield losses (Dhaliwal *et al*., 2020; Singh *et al*., 2022). Abiotic stresses such as drought, extreme temperatures, salinity and waterlogging lead to 51–82% global yield losses annually (Oshunsanya *et al*., 2019), with drought being the most severe, reducing photosynthesis, nutrient uptake and overall productivity. Drought stress can severely affect growth and yield, while issues such as waterlogging and salinity are common in irrigated areas. Recent studies emphasize the source necessity to develop drought-tolerant and high-yielding legume varieties to address these environmental challenges. Breeding efforts, supported by advances in genetic research, are key to overcoming these barriers. Identification of genes linked to drought tolerance and improved nitrogen fixation has been a significant development, with molecular breeding techniques offering promising solutions. These efforts are essential for ensuring food security and promoting sustainability in the face of climate change and other environmental pressures. Thus, breeding resilient legumes is vital for enhancing productivity and supporting sustainable agriculture worldwide.

**Traits Performance in Legumes under Drought Conditions**

Drought is a major abiotic stress affecting legume production worldwide, especially in rainfed and semi-arid regions. Legumes are particularly sensitive to drought during reproductive development, which significantly impacts grain yield and seed quality. Understanding trait performance under water-deficit conditions is critical for breeding drought-resilient legume cultivars. A suite of morpho-physiological and yield-related traits collectively contribute to legume adaptation under drought stress, and their expression often varies with genotype, phenology, stress intensity and timing. The Impact of drought stress in different traits are described in detail table 1.

1. **Yield Stability and Reproductive Resilience**

Yield stability under drought is a cornerstone trait for legume improvement. Drought stress predominantly reduces pod number and seed count rather than seed size, indicating that reproductive success, more than individual seed development, is the limiting factor (Kumar *et al.*, 2021). Drought-tolerant genotypes-such as early maturing chickpea lines often exhibit a drought escape mechanism by accelerating development, or a drought avoidance mechanism by conserving soil moisture during the vegetative phase to support reproductive success. Traits such as pod setting efficiency, seed filling duration, and harvest index become critical in determining final yield under moisture stress. Cowpea, for instance, demonstrates superior reproductive plasticity and yield retention under terminal drought, attributed to its stable harvest index and low water demand (Muchero *et al.*, 2008).

1. **Water Use Efficiency (WUE)**:

WUE is a central physiological trait for drought adaptation, representing the ratio of biomass or yield to water consumed. Drought-resilient legumes exhibit genotypic variation in WUE, enabling some cultivars to produce more biomass or yield per unit of water transpired. For instance, certain chickpea and common bean genotypes show enhanced WUE under deficit irrigation by optimizing stomatal regulation, reducing transpiration, and maintaining photosynthetic activity (Tavara *et al.*, 2018). Key physiological determinants of WUE include stomatal resistance, leaf area index (LAI), and transpiration efficiency. Moreover, indirect selection for WUE through traits like carbon isotope discrimination (Δ¹³C) has shown promise in legumes such as lentil and chickpea.

1. **Biomass and Canopy Dynamics**

Biomass accumulation under drought is often linked with root vigor and canopy architecture. High shoot biomass under stress, while maintaining reproductive output, is a distinguishing feature of drought-tolerant lines. Canopy conductance, a measure of stomatal behavior, is lower in tolerant genotypes, reflecting improved water conservation. The ability to sustain green leaf area under drought, or the "stay-green" trait, contributes to prolonged photosynthetic activity and assimilate partitioning to reproductive organs. This trait is associated not only with improved yield under drought but also with enhanced resistance to foliar diseases (Sivasakthi *et al*., 2019).

1. **Root System Architecture and Hydraulic Conductance**

Root traits are pivotal for water acquisition under drought conditions. Traits such as root depth, density, and root hydraulic conductivity determine the capacity of legumes to access moisture from deeper soil layers. A higher root/shoot ratio is often favored under drought as it reflects investment in water acquisition over shoot growth. In particular, genotypes with water-saving strategies such as controlled transpiration at high vapor pressure deficits and increased reliance on apoplastic water transport show greater drought tolerance. Sivasakthi *et al* (2020) demonstrated that chickpea genotypes with efficient root hydraulics and root pressure generation maintained better water uptake and biomass production under progressive soil drying.

1. **Physiological and Biochemical Traits**

Drought resilience in legumes is also underpinned by a range of physiological and biochemical markers. Chlorophyll retention, as part of the stay-green phenotype, is indicative of sustained photosynthetic function under stress. Higher levels of soluble proteins and antioxidant enzymes (e.g., superoxide dismutase, catalase, and peroxidase) have been linked with better oxidative stress mitigation and membrane stability under drought conditions (Fogaca *et al.*, 2023). These biochemical traits often reflect the plant's metabolic capacity to endure prolonged water stress and contribute to maintaining cellular homeostasis.

1. **Integrative Trait Selection for Breeding**

The expression and stability of these adaptive traits vary across environments and developmental stages. Hence, a multi-trait approach integrating phenology, morphology, physiology, and root architecture is essential for breeding drought-resilient legume varieties. Modern breeding programs increasingly combine high-throughput phenotyping, genomic tools (e.g., QTL mapping, GWAS), and physiological trait selection to identify elite genotypes. Nonetheless, challenges such as limited multi-environment testing, narrow genetic base in breeding populations, and poor integration of root traits in phenotyping platforms persist.

**Table 1: Impact of drought stress in different traits**

|  |  |  |
| --- | --- | --- |
| **Trait/Process Affected** | **Impact of Drought Stress** | **References** |
| Nutrient Uptake and WUE | Reduces nutrient absorption and water use efficiency | Conesa *et al.*, 2016 |
| Cell Growth and Leaf Development | Impairs cell expansion and leaf morphology | Chowdhury *et al.*, 2016 |
| Photosynthesis | Inhibits photosynthetic efficiency, alters gas exchange, reduces carbon assimilation | Conesa *et al*., 2016 |
| Leaf Area and Turgor Pressure | Decreases leaf surface area and cellular turgor | Chowdhury *et al.*, 2016 |
| Oxidative Stress | Increases reactive oxygen species, leading to oxidative damage | Conesa *et al.*, 2016 |
| Reproductive Development | Reduces flowering, pod set, and seed development due to impaired assimilate partitioning | Sehgal *et al.*, 2019 |
| Pollen Viability | Causes pollen sterility, abortion, and abnormal morphology | Fang *et al.*, 2010 |
| Photosynthesis in Reproductive Phase | Reduces translocation and photosynthetic rate during seed development | Sehgal *et al.*, 2019 |
| Protein and Oil Content in Seeds | Lowers total protein and oil yield; in some cases, protein content increases while oil content declines | Farooq *et al.*, 2018;  |
| Yield Loss | Overall reduction in productivity due to metabolic disruptions and impaired physiological processes | He *et al.*, 2017 |

**Key Traits for Improving Productivity and Drought Tolerance in Legumes**

Drought stress is one of the most critical constraints to legume productivity worldwide, particularly in rainfed agricultural systems. To enhance drought resilience and ensure sustainable productivity, recent research has emphasized the importance of identifying and utilizing key morpho-physiological and agronomic traits with high genetic variability and heritability. These traits serve as the foundation for breeding climate-resilient legume cultivars. The role of drought tolerance in different traits are given in detail in table 2.

1. **Genetic Variability and Trait Heritability**

Several studies have demonstrated significant genetic variation in legume crops for yield-contributing and drought-responsive traits. In chickpea, high heritability coupled with substantial genetic advance was observed for traits such as plant height, number of pods per plant, 100-seed weight, and seed yield per plant, indicating their potential utility in selection for drought tolerance (Basavaraja *et al.*, 2021; Meena *et al.*, 2021). Similarly, Ketema *et al.* (2022), reported high heritability for plant height, pod length, and seed yield in common bean, suggesting these traits are strongly controlled by genetic factors and could be effectively exploited in breeding programs. In cowpea, Swathi *et al.* (2024), reported strong genetic control for pod-related traits, emphasizing their importance for improving yield under both irrigated and water-deficient conditions.

1. **Physiological Indicators of Drought Tolerance**

Drought tolerance in legumes is also associated with physiological traits that reflect the plant’s capacity to maintain functionality under stress. Canopy temperature depression (CTD) and chlorophyll content have emerged as reliable physiological indicators of drought adaptation (Karimizadeh *et al.*, 2021). Raju *et al.* (2021) highlighted the role of pod and seed numbers as critical contributors to grain yield under drought, supporting the importance of reproductive resilience. Sachdeva *et al.* (2022) reported a significant yield loss (~33.23%) in chickpea under drought stress, emphasizing the need for selecting tolerant genotypes. Traits such as relative water content (RWC), membrane stability index (MSI), and chlorophyll index were associated with superior drought performance, demonstrating their relevance in breeding programs focused on physiological resilience.

1. **Trait Correlation and Principal Component Analysis (PCA)**

Correlation and PCA-based studies have been pivotal in identifying trait interrelationships and composite selection indices for legume improvement. Basavaraja *et al.* (2021) and Meena *et al.* (2021) in their study revealed strong positive correlations between seed yield and agronomic traits such as branches per plant, biological yield, and harvest index in chickpea. Likewise, Raju *et al.* (2021) and Ketema *et al.* (2022) confirmed the consistent association of biological yield and harvest index with seed yield in chickpea and common bean, respectively. PCA analyses conducted by Girgel (2021) and Karimizadeh *et al.* (2021) in their studies underscored the significance of seed weight, chlorophyll content, and flowering time as major components contributing to drought tolerance and overall productivity across legume species.

**Table 2: Role of drought tolerance in different traits**

|  |  |  |
| --- | --- | --- |
| **Trait/Mechanism** | **Functional Role in Drought Tolerance** | **References** |
| Soluble Proteins and Antioxidant Enzymes | Enhance cellular defense mechanisms and mitigate oxidative damage | Fogaca *et al.*, 2023 |
| Root Traits (Hydraulics, Architecture) | Improve water uptake efficiency; deeper roots and better root/shoot ratio aid drought adaptation | Sivasakthi *et al.*, 2020 |
| Stay-Green Trait | Prolongs chlorophyll retention and photosynthetic activity during terminal drought | Sivasakthi *et al.*, 2019 |
| Water Use Efficiency (WUE), Stomatal Traits | Genotypic variation in WUE, stomatal resistance, and leaf area index confers adaptability under limited water | Nemeskéri *et al.*, 2018; Tavera *et al.*, 2018 |
| Root System Plasticity | Increases root length, spread, and density under drought, especially in small-leaf legumes | Varshney *et al.*, 2018 |
| Osmotic Adjustment | Facilitates water uptake by lowering osmotic potential in roots | Vadez *et al.*, 2008 |
| Stomatal Regulation | Promotes stomatal closure to reduce transpirational water loss and maintain leaf hydration | Vadez *et al.*, 2008 |
| Turgor Pressure Maintenance | Maintains cellular hydration under drought by reducing epidermal water loss | Sinclair and Ludlow, 1986 |

**Crop Adaptive Strategies for Drought Tolerance in Legumes: Insights from Common Beans, Cowpea, Chickpea, and Lima Beans**

Drought stress remains a critical constraint to legume productivity in rainfed systems globally. However, considerable progress has been made in identifying adaptive traits and drought-tolerant genotypes across major legumes through physiological, morphological, and agronomic evaluations. This section synthesizes key findings from recent studies that explored adaptive responses and genetic variability in common bean, cowpea, chickpea, and lima bean, offering actionable insights for breeding climate-resilient legume varieties.

**Common Bean (*Phaseolus vulgaris* L.)**

Common beans demonstrate substantial diversity in response to drought, particularly in terms of water use efficiency (WUE), photosynthesis, and root traits.

* Androcioli *et al.* (2020), compared multiple genotypes under water-deficit conditions and identified BAT 477 as a promising drought-tolerant line due to superior photosynthetic efficiency, stomatal conductance, and intrinsic WUE, making it ideal for breeding programs. In contrast, IAPAR 81 exhibited poor performance under stress, highlighting genotype-dependent variability.
* Basavaraja *et al.* (2021), evaluated germplasm accessions such as EC400414 and EC540173, revealing broad genetic variability in traits like plant height, pod number, seed yield, and relative water content (RWC). This diversity underscores the potential of underutilized germplasm in enhancing drought resilience.

**Key adaptive traits:** High WUE, sustained photosynthetic rate, and stability in yield-related traits under drought.

**Cowpea (*Vigna unguiculata* L.)**

Cowpea is naturally adapted to arid environments and exhibits significant phenotypic plasticity under drought stress.

* Ayala *et al*. (2020) identified several genotypes from the Colombian-Caribbean region namely LC-021-016, LC-014-016, LC-029-016, LC-009-016, LC-002-016, LC-036-016, and LC-005-016 that exhibited high photosynthetic activity, effective canopy temperature regulation, and greater total biomass production under limited water conditions.
* Ravelombola *et al.* (2020), conducted a large-scale screening of 331 genotypes, identifying 21 highly drought-tolerant lines, including PI583550, through evaluations of chlorophyll fluorescence, leaf wilting, and yield stability.
* Ezin *et al.* (2021), demonstrated the drought adaptability of Benin, Africa local landraces like Kpodjiguegue and cultivars like KVX 61-1 and IT 06-K-242-3 which retained productivity under both vegetative and reproductive stage drought, affirming the value of indigenous germplasm.

**Key adaptive traits:** Early maturity, chlorophyll retention, canopy temperature depression (CTD), and biomass accumulation under stress.

**Chickpea (*Cicer arietinum* L.)**

Chickpea, traditionally grown in semi-arid regions, exhibits substantial intraspecific variation in drought tolerance linked to root traits, osmotic adjustment, and transpiration efficiency.

* Tiwari *et al.* (2023) in central/northern India, identified drought-resilient genotypes such as ICC4958 and JG11, characterized by deep rooting, sustained transpiration efficiency, and stable pod set under terminal drought.
* Shah *et al.* (2020) evaluated multiple breeding lines and highlighted D0091–10 as a genotype with superior drought tolerance due to its chlorophyll stability index, membrane integrity, and pod number retention.
* Some of the earlier reports such as Sivasakthi *et al.* (2019) focused on linking stay-green traits, canopy cooling, and WUE with chickpea yield stability under limited moisture.

**Key adaptive traits:** Deep root systems, stay-green phenotype, high transpiration efficiency, and reproductive resilience.

**Lima Bean (*Phaseolus lunatus* L.)**

Although underutilized globally, lima beans possess inherent drought adaptation mechanisms, especially among traditional landraces.

* Martínez-Nieto *et al.* (2022) evaluated both landraces and commercial varieties, revealing distinct strategies for drought avoidance and tolerance at seedling, flowering, and pod-filling stages. Landraces maintained higher relative water content, root mass ratio, and delayed senescence, contributing to improved yield under water deficit.
* These genotypes also showed variability in leaf gas exchange, osmotic adjustment, and reproductive success, supporting their use in marginal environments with erratic rainfall.

**Key adaptive traits:** Enhanced root allocation, osmotic regulation, delayed leaf senescence, and stress-resilient reproductive development.

**Breeding Strategies for Legumes: Integrating Traditional and Modern Approaches for Drought Resilience and Productivity**

Breeding strategies for legumes have evolved from conventional selection methods to encompass advanced molecular and biotechnological tools, enabling the efficient development of high-yielding, drought-tolerant, and disease-resistant varieties. Given the vulnerability of legumes to abiotic stresses such as drought, the integration of traditional and modern breeding approaches is crucial for securing legume productivity in climate-stressed environments.

**Pre-breeding:**

Pre-breeding is crucial for drought tolerance trait discovery, as it enables the exploration and utilization of genetic diversity found in wild relatives, landraces, and other unadopted germplasms that often contain stress-resilient traits (Meena *et al*., 2017). These genetic resources typically exhibit adaptive features such as enhanced root architecture, improved water-use efficiency, osmotic regulation, and stress-responsive physiological mechanisms. However, they are usually unsuitable for direct use in breeding programs due to poor agronomic performance, their beneficial traits can be transferred into intermediate lines through pre-breeding. These lines, which combine stress tolerance with desirable agronomic traits, serve as a bridge between genetic resource exploration and cultivar development. Ultimately, pre-breeding expands the genetic base of cultivated crops and facilitates the breeding of drought-resilient varieties adapted to changing climatic conditions.

**1. Conventional Breeding Approaches**

Conventional methods remain foundational in legume breeding, especially for initial trait identification and varietal improvement in resource-limited settings (Chamarthi *et al*., 2019; Jalal *et al*., 2023). Some of the grain legumes with drought resistance have been developed using conventional breeding methods, highlighting major breeding achievements and targeted traits which are presented in table 3.

* Mass Selection and Pedigree Breeding: These are widely applied to develop drought-tolerant varieties based on observable phenotypic traits such as early maturity, seed yield, canopy temperature depression, and root depth. For example, several high-yielding and drought-tolerant chickpea and cowpea varieties have been developed using pedigree selection in India and sub-Saharan Africa.
* Hybridization and Recurrent Selection: Crossbreeding of elite parents followed by recurrent selection helps accumulate desirable traits. These approaches, although time-consuming and labour-intensive, are effective in combining yield potential with stress tolerance.
* Participatory Breeding: Involving farmers in the selection process enhances the adoption of locally adapted varieties. This is particularly effective in marginal environments where genotype-by-environment interactions are significant.

However, conventional approaches are constrained by long breeding cycles, lower selection accuracy for complex traits, and environmental variability that often masks genetic potential. However, advancements such as shuttle breeding and speed breeding are helping to shorten breeding durations, while genomic selection is improving selection accuracy and accelerating genetic gains.

**2. Marker-Assisted Selection (MAS)**

MAS has significantly improved the efficiency of legume breeding by enabling indirect selection based on linked molecular markers. Properties of molecular markers enhanced the interest of application of Marker-Assisted Selection (MAS) for improving drought tolerance in cowpea and several other leguminous crops (Boukar *et al*., 2016). Quantitative trait loci (QTL) assist to locate loci for markers assisted breeding and mapped for several morpho-physiological traits under drought stress (Gupta *et al*., 2017)

* Chickpea: MAS has been employed to introgress drought tolerance QTLs such as “QTL-hotspot” from ICC4958 into elite cultivars, improving root traits and water-use efficiency (Sivasakthi *et al*., 2018)
* Cowpea: Markers linked to traits like delayed leaf senescence, pod number, and seedling vigor have enhanced selection for terminal drought tolerance (Nadeem *et al*., 2019).
* Mung bean and Lentil: MAS is used to select for disease resistance (e.g., powdery mildew in mung bean and Fusarium wilt in lentil), alongside yield stability under drought.
* Common bean: 22 QTLs have been identified for chlorophyll, leaf and stem biomass, leaf temperature, days to flowering, the number of pods per plant, number of seeds per pod, seed weight and total yield under drought (Briñez *et al*., 2017).

MAS shortens breeding cycles and enhances precision, particularly for traits with moderate to high heritability and well-characterized QTLs. Some of the QTLs have been identified across various grain legumes, each associated with distinct traits are presented in table 4.

**3. Genomic Selection (GS)**

GS leverages genome-wide markers to predict breeding values, allowing the selection of genotypes with complex quantitative traits like drought tolerance, yield stability, and multi-stress resistance. The options to increase drought tolerance in grain legumes through biotechnology led approach covers genomic selection, epigenetic variation, marker-assisted recurrent selection, transgene and genome editing (Dwivedi *et al*., 2018).

* Advantages: GS enables early generation selection without phenotyping, increasing the genetic gain per unit time.
* Applications in Legumes: GS has been implemented in chickpea and lentil for predicting grain yield and drought response, using genomic prediction models with high accuracy. For example, GS has outperformed MAS in scenarios where drought tolerance is controlled by many small-effect loci.

As genomic resources expand (e.g., reference genomes and SNP panels), GS is expected to become a central component of breeding pipelines for legumes.

**4. Genomics and Gene Editing Tools**

Advanced genomics and biotechnological tools are unlocking new frontiers in legume improvement. Several candidate genes associated with specific QTLs were screened and mapped in different crops for drought responsive attributes (Gudys *et al*., 2018; Jalal *et al*., 2023). Some of the Candidate genes for drought tolerance identified from a variety of grain legumes are presented in table 5.

* Transcriptomics and Genome-Wide Association Study (GWAS): These approaches identify novel drought-responsive genes and alleles across diverse germplasm collections. In chickpea, transcriptomic studies have revealed key regulators of ABA biosynthesis and root architecture under drought stress (Kasbi *et al*., 2024; Bhaskarla *et al*., 2020).
* CRISPR/Cas9: Gene editing technologies allow precise modifications in key drought-regulatory genes. Although in early stages for legumes, successful examples include editing of genes related to flowering time and stress signalling pathways (Jaganathan *et al.*, 2018).
* Speed Breeding and Doubled Haploids: These tools accelerate generation turnover and reduce breeding cycle duration, particularly when combined with genomic selection (Potts *et al*., 2023; Yel *et al*., 2023)
1. **Crop-Specific Breeding Advances**

**Chickpea (*Cicer arientinum*):**

* Drought susceptibility index, yield index, drought tolerance efficiency, superiority index are the potential traits for mass screening of chickpea for drought tolerance (Kahraman *et al*., 2016; Erdemci 2018).

**Common bean (*Phaseolus vulgaris*):**

* Deeper and vigorous roots, canopy biomass, pod partitioning index, stem biomass reduction and pod harvest index are the potential traits for mass screening of common beans for drought tolerance (Polania *et al*., 2017; Rao *et al*., 2013)

**Cowpea (*Vigna unguiculate*):**

* Terminal leaf length, stomata resistance, short duration and erect plant type are the potential traits for mass screening of cowpea for drought tolerance (Ajayi *et al*., 2018; Hall 2012)

**Mung Bean (*Vigna radiata*):**

* Focus on yield improvement, heat and drought tolerance, and resistance to powdery mildew and bacterial blight. Membrane stability index proline contents, root penetration ability and dry matter partitioning are the potential traits for mass screening of mung bean for drought tolerance (Bangar *et al.,* 2019; Prakash *et al.,* 2017; Hossain *et al.,* 2009)
* Use of MAS and tissue culture to accelerate varietal release (Nair *et al.*, 2019).

**Faba Bean (*Vicia faba*):**

* Breeding targets include resistance to Ascochyta blight, enhanced nitrogen fixation, and yield stability under diverse environments.
* Development of mapping populations and QTL identification for flowering time and disease resistance traits. Root growth is the potential trait for mass screening of faba bean for drought tolerance (Belachew *et al*., 2018; Ullah *et al.,* 2022)

**Lentil (*Lens culinaris*):**

* Emphasis on improving yield, terminal drought tolerance, and disease resistance (especially Fusarium wilt and rust). Dry root weight and root length are the potential traits for mass screening of lentil for drought tolerance (Kumar *et al*., 2012; Ullah *et al.,* 2022).
* Application of GWAS and GS for identifying drought-responsive genotypes and shortening breeding cycles.

**Table 3:** **Grain legumes with drought resistance have been developed using conventional breeding methods, highlighting major breeding achievements and targeted traits**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Legumes** | **Development Method**  | **Achievement in Breeding** | **Targeted traits** | **References** |
| Chickpea (*Cicer arietinum*) | * Line-source (ICC 4958) and ICRISAT
* Drought-susceptibility index (DSI)
 | * Drought-escaping germplasm selection
* Drought-avoidant germplasm selection
* Drought-tolerant germplasm selection
 | * Low leaf conductance
* Smaller leaf canopy
* Soil water extraction
* Early maturing
* Deeper, more extensive root system
* Increased yield during terminal drought
 | Berger, J.D. *et al.*, 2011Zaman-Allah, M *et al.*, 2011Vadez, V. *et al.*, 2012 |
| Pigeon pea (*Cajanus cajan*) | * Drought-susceptibility index (DSI)
 | * Drought-tolerant cultivated germplasm selection
 | * Polycarpic flowering habit
* Deep root
* Osmotic adjustment
* Photosynthetic maintenance
 | Odeny, D.A. 2007 |
| Faba bean (*Vicia faba*) | * Cytoplasmic genetic male sterility (CGMS)
 | * Drought-escaping and drought-tolerant germplasm selection
 | * Lower plant height
* Higher WUE
* Lower leaf temperature
* Higher water content
 | Khazaei, H. *et al.*, 2013 |
| Common bean (*Phaseolus vulgaris*) | * Recurrent selection
* Advanced backcrossing
* Double cross
* Backcrossing
 | * Drought-escaping germplasm selection
* Drought-avoidant germplasm selection
* Drought-tolerant germplasm selection
 | * High grain output
* High photosynthate remobilization
* Early maturing
* Deep roots
* Stomatal control
 | Beebe, S.E. *et al.*, 2008Blair, M.W. 2006 Devi, M.J. *et al.*, 2013 |

**Table 4: Quantitative trait loci (QTLs) have been identified across various grain legumes, each associated with distinct traits**

|  |  |  |  |
| --- | --- | --- | --- |
| **Grain Legumes** | **QTL Name** | **Characteristics** | **References** |
| Soybean (*Glycine max*) | FR\_Gm01, FR\_Gm03, FR\_Gm04, FR\_Gm08, FR\_Gm20 | Fibrous rooting/surface area  | Abdel-Haleem *et al.*, 2011 |
| SA\_Gm06, TRL\_Gm06, RDL3\_Gm07, TRL\_Gm08, qRL11  | Root length | Manavalan *et al.,* 2015.Liu *et al*., 2020 |
| qYLD3 | Yield | Lee *et al*., 2021 |
| qWDC7.1 | Morphological traits | Dhungana *et al*.,2021 |
| SWPP17, SWPP19 | Seed weight/plant | Ren *et al*., 2020 |
| Cowpea (*Vigna unguiculata*) | Mat-1, Mat-2 | Maturity | Muchero *et al.*, 2009 |
| qGY-9-1 | Grain yield | Sodo *et al*., 2025 |
| Chickpea (*Cicer arietinum*) | TR-50, SCEA19, TAA-58 | Grain weight | Hamwieh *et al.*, 2013 |
| H6C-07, H5G-01, H6C-07, H1B-04 | Grain yield |
| TA-113, TR-58, H6C-07, H1F-21 5 | Harvest index |
| qYLD1.1, qYLD5.2 and qYLD7.1 | Yield | Yadava *et al*., 2023 |
| Pigeon pea(*Cajanus cajan*) | QTL-RF-1, QTL-RF-2, QTL-RF-3, QTL-RF-4 | Fertility restoration | Saxena *et al.*, 2011 |
| Pea (*Pisum sativum*) | rl1, rl2, rl3 | Root length | Fondevilla *et al.*, 2011 |

**Table 5: Candidate genes for drought tolerance identified from a variety of grain legumes**

|  |  |  |  |
| --- | --- | --- | --- |
| **Grain Legumes** | **Identified Gene** | **Functions** | **References** |
| Chickpea (*Cicer arietinum*) | MyB, AP2/ERF, XPB1 | Transcription factors | Deokar *et al.*, 2011 |
| DREB2A | Nayak *et al.*, 2009 |
| MYB, WRKY, bZIP | Hiremath *et al.*, 2011 |
| Mung bean (*Vigna radiata*) | codA | Improve abiotic-stress tolerance | Baloda and Madanpotra., 2017 |
| VrWRKY | Enhance abiotic-stress tolerance | Srivastava *et al.*, 2018 |
| VrbZIP | Drought-responsive gene | Wang *et al.*, 2018 |
| Broad bean (*Vicia faba*) | VfPIP1 | Aquaporin/water transport | Cui *et al.*, 2008  |
| Common bean (*Phaseolus vulgaris*) | DREB2B | Non-ABA dependent responses | Cortés *et al.*, 2012 |
| Asr1, Asr2 | ABA signaling pathway |
| PvLEA3 | Protein stabilization | Barrera-Figueroa *et al.*, 2008 |
| Soybean (*Glycine max*) | GmNAC, GmDREB, GmZIP, ERF089 | Transcription factors | Manavalan *et al.*, 2009 |
| DREB1A, rd29A | Bhatnagar-Mathur *et al.*, 2009 |
| GmBIN2 | Enhance tolerance to drought | Wang *et al.*, 2018  |
| GmCaM4 | Upregulate several drought-responsive genes | Yoo *et al.*, 2005  |
| CDPK | Enhance water permeability across the membrane | Guenther *et al.*, 2003 |
| GmHK, GmCLV1A, GmCLV1B, GmRLK1, GmRLK2, GmRLK3, GmRLK4 | Osmo sensor | Yamamoto *et al.*, 2000 |
| PgTIP1 | Confers drought tolerance | An *et al.*, 2018 |
| GmDREB2 | Enhance drought tolerance | Savitri and Fauziah 2018 and 2019  |
| GmRACK1 | Improve drought tolerance during vegetative growth | Li *et al.*, 2018 |
| AtABF3 | Improve drought tolerance | Kim *et al.*, 2018 |
| GmFDL19 | Enhance drought tolerance | Li *et al.*, 2017  |
| GmSK1 | Chen *et al.*, 2018 |
| Pigeon pea (Cajanus cajan) | CcM1522–CcM1821, CcM0047–CcM2332 | Improve drought tolerance | Saxena *et al.*, 2011  |
| MyB, WRKY, NF-Y | Transcription factors | Yang *et al.*, 2006  |
| Cowpea (Vigna unguiculata) | CPRD8, CPRD12, CPRD14, CPRD22, CPRD46 phospholipase D, VuPLD1, 9-cisepoxycarotenoid dioxygenase, VuNCED1 | ABA biosynthesis | Muchero *et al.*, 2010 |

**Breeding for Early Flowering in Legumes: A Strategic Trait for Drought Escape and Yield Stability**

**1. Introduction to Early Flowering as a Drought Escape Mechanism**

Drought is one of the most significant constraints limiting legume productivity, especially in rainfed and semi-arid regions. One of the most effective strategies for coping with terminal drought stress common in these environments is drought escape through early flowering and maturity (Nadeem *et al*., 2019). Early flowering enables the crop to complete critical reproductive stages before the onset of severe water deficits, preserving grain yield and reproductive success (Liu *et al*., 2020).

In legumes, which are often cultivated under short growing seasons and erratic rainfall patterns, early flowering has emerged as a critical adaptive trait. Breeding programs have increasingly prioritized this trait to ensure crop establishment, timely flowering, and pod set before the depletion of soil moisture.

1. **Physiological and Agronomic Significance of Early Flowering**
* Drought Escape: Early flowering allows legumes to avoid the peak of water stress, particularly during the flowering and grain filling stages, which are highly sensitive to drought.
* Reproductive Assurance: By synchronizing flowering with favorable moisture conditions, early flowering genotypes improve pod formation, seed set, and harvest index under limited water availability.
* Heat Stress Avoidance: In regions where terminal drought is coupled with high temperatures, early flowering also helps the crop avoid heat-induced sterility during reproductive stages (Gaur *et al*., 2014).
* Shorter Growth Duration: Early flowering varieties are often better suited for intercropping systems, residual moisture utilization, or post-rainy season sowing.
1. **Genetic Control of Early Flowering in Legumes**

Early flowering is a quantitative trait influenced by multiple genes and affected by environmental conditions such as photoperiod and temperature. Significant progress has been made in mapping flowering-time loci in several legumes:

* **Chickpea (*Cicer arietinum*):**
	+ The Efl (early flowering) locus and QTLs such as CaLG04\_EFL have been identified (Ridge *et al*., 2017).
	+ Genotypes like ICC 4958, JG 11, and DICC 79 exhibit early flowering and are integrated into drought breeding programs (Varshney *et al*., 2013).
* **Cowpea (*Vigna unguiculata*):**
	+ Early flowering is controlled by genes interacting with photoperiod sensitivity loci.
	+ Breeding programs in West Africa and India utilize early maturing genotype like IT08K-150-12 (Aliyu *et al*., 2023).
* **Common Bean (*Phaseolus vulgaris*):**
	+ The Ppd and Fin loci are associated with photoperiod sensitivity and flowering initiation.
	+ Genotypes like BAT 477 exhibit early flowering and deeper rooting—an ideal combination for drought tolerance (Beebe *et al*., 2013).
* **Lima Bean (*Phaseolus lunatus*):**
	+ While less studied, landraces showing early flowering and determinate growth habit are prioritized in breeding for drought-prone environments (Martínez-Nieto *et al.*, 2022).
1. **Breeding Strategies Targeting Early Flowering**

Breeding for early flowering in legumes involves a multi-pronged approach combining conventional and molecular tools:

* **Phenotypic Selection:**
	+ Field screening under rainfed conditions remains the first step for identifying early-flowering, drought-escaping genotypes.
	+ Traits such as days to 50% flowering, days to maturity, and flowering-pod filling synchronization are used as selection indices.
* **Marker-Assisted Selection (MAS):**
	+ Molecular markers linked to early flowering QTLs enable early-generation selection, particularly in chickpea and cowpea.
	+ MAS has been used to introgress early flowering and root architecture QTLs into elite cultivars (e.g., introgression of QTL-hotspot in chickpea).
* **Genomic Selection (GS):**
	+ GS models incorporating flowering time, biomass accumulation, and terminal drought stress response can accelerate selection in segregating populations.
* **Speed Breeding and Controlled Environments:**
	+ Utilizing growth chambers and off-season nurseries facilitates rapid cycling and selection for early flowering genotypes.
	+ This strategy is particularly useful for integrating early flowering with other adaptive traits like deep rooting or high water-use efficiency.
* **Participatory Breeding:**
	+ Involving farmers in early selection stages helps identify early maturing varieties adapted to local rainfall patterns and cropping calendars.
1. **Challenges and Future Perspectives**

While early flowering confers advantages under drought-prone environments, trade-offs must be managed:

* Yield Potential: Extremely early genotypes may have reduced vegetative growth, leading to lower biomass and seed yield under favourable conditions.
* Photoperiod Sensitivity: Genotype x environment interaction for flowering time may limit wide adaptation.
* Integration with Other Traits: Combining early flowering with traits like deep rooting, stay-green, transpiration efficiency, and seed quality remains a key breeding goal.

**Future directions include:**

* Integrating phenomics to assess early flowering alongside whole-plant water relations.
* Exploiting wild relatives and landraces for novel alleles contributing to flowering plasticity.
* Employing CRISPR-Cas9 to modify flowering genes with high precision without linkage drag.

**2. Current Challenges and Future Prospects in Legume Breeding**

Legumes are crucial for global food security and sustainable agriculture due to their high protein content, nitrogen-fixing ability, and adaptability to marginal environments. However, the potential of legumes is often under-realized due to multiple breeding constraints, particularly under changing climate scenarios. Addressing these constraints is vital for developing climate-resilient, high-yielding, and nutritionally enriched legume varieties that can thrive under both abiotic and biotic stresses. The current challenges in legume breeding are described briefly:

1. **Limited Genetic Diversity and Germplasm Utilization**

A major bottleneck in legume breeding is the restricted use of genetically diverse and stress-adapted germplasm, especially under dual evaluation conditions (drought vs. irrigated). As Ye *et al.* (2018) noted, most breeding programs tend to evaluate genotypes under a single stress regime, which obstructs the identification of stable and broadly adapted cultivars. Furthermore, wild relatives and landraces rich sources of novel alleles for stress tolerance remain underexploited due to linkage drag and compatibility barriers.

1. **Inadequate Integration of Molecular Breeding Tools**

Despite substantial advances in genomics, the integration of marker-assisted selection (MAS), genomic selection (GS), and transcriptomics into mainstream legume breeding remains limited. This results in:

* Delayed selection cycles for complex traits like drought tolerance, root architecture, and yield stability.
* Underutilization of QTLs and genes identified for key traits in crops like chickpea, cowpea, and common bean.
* Inadequate marker-trait pipelines due to poor phenotyping and environmental characterization, limiting QTL validation and deployment.
1. **Complex Trait Architecture**

Drought tolerance, heat stress response, and nutrient-use efficiency are quantitative traits governed by multiple loci with strong genotype × environment (G×E) interactions. This complexity makes accurate selection difficult without large-scale, multi-location phenotyping, advanced statistical models, and long breeding cycles.

1. **Infrastructural and Capacity Gaps**

Breeding programs in many developing countries lack:

* High-throughput phenotyping (HTP) platforms for rapid trait assessment under stress conditions.
* Bioinformatics and data management capabilities to handle genomic datasets.
* Skilled personnel trained in modern breeding, genomics, and data integration approaches.
1. **Weak Seed Systems and Policy Support**

Even when improved cultivars are developed, poor seed dissemination, lack of farmer awareness, and weak policy frameworks restrict adoption and scaling of improved legume varieties.

**3. Future Prospects and Strategic Directions**

To overcome these challenges, legume breeding must adopt an integrated, multi-disciplinary approach that leverages both conventional and modern tools for climate-smart variety development.

1. **Harnessing Genomic Technologies**

Advanced genomics, transcriptomics, and genome-wide association studies (GWAS) can identify novel genes and markers for key traits such as:

* Drought and heat stress tolerance
* Pest and disease resistance
* Nutrient-use efficiency
* Tools such as next-generation sequencing (NGS), exome capture, SNP arrays, and CRISPR-Cas9 gene editing offer unprecedented precision and speed in trait discovery and deployment (Tyagi *et al.*, 2024).
1. **Enhancing Phenotyping Precision**

Adopting high-throughput phenotyping (HTP) tools (e.g., Leasy Scan, UAVs, thermal and spectral imaging) is essential to capture dynamic plant responses under drought, heat, and combined stresses. These tools support the:

* Identification of component traits like transpiration efficiency, canopy temperature, stomatal regulation, and root traits.
* Trait-based breeding, allowing for effective marker-trait associations.
1. **Accelerating Breeding Cycles**

Combining speed breeding, doubled haploids, and rapid generation advance (RGA) techniques can shorten the time required for varietal development and release, particularly when integrated with genomic prediction models.

1. **Climate-Resilient Ideotype Design**

Breeding programs should focus on designing climate-resilient ideotypes by:

* Selecting genotypes with early flowering, deep rooting, stay-green traits, and recovery capacity after drought.
* Targeting specific adaptation for marginal environments using environmental characterization and target population of environments (TPEs) framework.
1. **Strengthening Pre-Breeding and Germplasm Enhancement**

Pre-breeding must focus on introgression of stress-resilience alleles from wild species and landraces into elite backgrounds. Novel gene pools and core collections must be developed and evaluated across diverse agro-ecological zones.

1. **Policy and Institutional Strengthening**

Robust legume improvement requires:

* Investment in breeding infrastructure, HTP, and data science.
* Cross-institutional partnerships (e.g., CGIAR, national programs, universities).
* Supportive seed systems, farmer engagement, and market linkages to ensure the adoption of improved varieties.

**Conclusion**

Legume crops are foundational to global food security, sustainable agriculture, and soil health, particularly in regions prone to erratic rainfall and marginal growing conditions. However, their production is severely constrained by drought and other environmental stresses, which reduce yield, impair reproductive development, and threaten their ecological benefits. Addressing these challenges through strategic breeding is essential to ensure resilient and productive legume-based agri-production systems.

This review highlights the multidimensional progress made in identifying adaptive traits, breeding strategies, and genetic resources for drought tolerance in legumes such as chickpea, cowpea, common bean, lima bean, faba bean, mung bean, and lentil. Adaptive traits including early flowering, deep rooting, high water-use efficiency (WUE), stay-green characteristics, and reproductive resilience have been consistently linked to drought tolerance and yield stability. Significant genetic variability for these traits exists across diverse germplasm, offering substantial potential for crop improvement.

Conventional breeding methods, such as mass and pedigree selection, continue to play a vital role in cultivar development, especially in resource-constrained environments. However, these approaches face limitations in speed and precision. The integration of modern genomics-assisted techniques including marker-assisted selection (MAS), genomic selection (GS), genome-wide association studies (GWAS), and CRISPR-Cas9 gene editing has accelerated the identification and deployment of key drought-responsive genes and QTLs across legumes. Coupling these tools with high-throughput phenotyping platforms and environmental characterization enhances the efficiency of trait-based selection, especially for complex traits influenced by genotype × environment interactions.

Despite notable advancements, several critical challenges continue, including the limited utilization of wild and landrace germplasm, underrepresentation of dual-stress studies (irrigated vs. drought), poor integration of physiological traits in breeding programs, and infrastructural deficits in phenotyping and data science capacity. Furthermore, the adoption and scalability of improved cultivars are hindered by weak seed systems, fragmented policy support, and limited farmer engagement.

To overcome these barriers and ensure future-ready legume varieties, a multipronged strategy such as following is needed:

* **Expand and diversify the germplasm base** by tapping into underutilized and wild genetic resources.
* **Strengthen trait dissection and ideotype development** focusing on climate resilience, nutritional quality, and agronomic suitability.
* **Integrate genomics and phenomics** for precision breeding, supported by robust bioinformatics pipelines.
* **Accelerate breeding cycles** through speed breeding, participatory approaches, and multi-environment testing.
* **Reinforce institutional and policy frameworks** to enable effective dissemination, adoption, and impact of improved legume technologies.

In an era of climate uncertainty and increasing global food demand, developing legume cultivars with stable performance under variable moisture regimes is both a scientific and socio-economic imperative. A future-oriented breeding paradigm- anchored in interdisciplinary collaboration, cutting-edge science, and farmer-centric innovation-will be key to unlocking the full potential of legumes as climate-smart crops that nourish both people and the planet.

**Disclaimer (Artificial intelligence)**

1. Author(s) hereby declares that NO generative AI technologies such as Large Language Models (ChatGPT, manuscript).

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