



# Breeding Techniques on Pulse Crops to Enhance Climate Resilience: A Review

Nuru Seid TEHULIE<sup>1,2\*</sup>, Fikru MEKONNEN<sup>1</sup>, Agegehu MEKONNEN<sup>1,4</sup>, Ahmed HASSEN<sup>1,3</sup>, Semira EBRAHIM<sup>1,3</sup>, Solomon ABEBE<sup>1,5</sup>

<sup>1</sup> Department of Plant Science, College of Agriculture, Wollo University, Dessie, Ethiopia

<sup>2</sup> Department of Plant Science, College of Agriculture, Mekdela Amba University, Gimba, Ethiopia

<sup>3</sup> Department of Biology, College of Natural and Computational Science, Woldia University, Woldia, Ethiopia

<sup>4</sup> Sirinka Agricultural Research Center (SARC), Sirinka, Ethiopia

<sup>5</sup> Department of Agriculture, Kombolcha College of Agriculture, Wollo University, Kombolcha, Ethiopia

\* Corresponding author: N.S. Tehulie email: befikrnuru@gmail.com

## REVIEW

### Abstract

The major food and economic crops known as pulse crops is produced in tropical and temperate countries. Due to their advantages, pulse crop production and consumer demand have grown significantly over the past 20 years. Low yield and variability, which are partially attributable to the effects of environmental stress, preclude future pulse crop production despite enhanced breeding efforts and the development of pulse crop production in diverse agro-climatic areas. Pulse crops physiology, morphology, and capacity for reproduction are all impacted by environmental stress, which affects yield. It is believed that the most important time for yield production is during the reproductive stage, when exposed to environmental challenges. In this review, we assess the effects of environmental stress on the growth and productivity of pulse crops during the reproductive stage, as well as the features that may confer adaptation. The present research's shortcomings, such as the small number of genotypes, shortage of field trials, and incomplete experimental data are listed. In order to speed up breeding efforts and produce more resilient pulse crop cultivars for the present and the future, the review highlight the potential to take advantage of new tools and technologies like high-throughput phenotyping platforms, gene editing, and genomic selection.

**Keywords:** Breeding; climate change; drought; environmental stress; heat; salinity.

## INTRODUCTION

Pulse crop is an important food and cash crop grown in tropical and subtropical regions (Kim et al., 2015). Pulse crop seed is a rich source of easily digestible dietary protein, minerals and vitamins that can aid in supplementing and diversifying cereal-based diets (Hou et al., 2019). Pulse crop has become an important choice for double and intercropping systems, particularly between cereals, due to its short growing season (e.g. 55–100 days depending on cultivar and season) and ability to fix atmospheric nitrogen (58–109 kg ha<sup>-1</sup>) to improve overall soil fertility (Yaquub et al., 2010). There are many different ways to consume pulse crops worldwide, and some of these methods call for particular qualities in the grain. The market for pulse crops is diversified. For instance, pulse crop sprouts are used as garnish, the dry grains are used for dash, and the bean is processed to make transparent noodles in East and Southeast Asia. On the other hand, pulse crops are usually eaten as a main ingredient in beef stew in East African countries (Nair et al., 2020). Over the past 20 years, there has been a

Received: 18 December 2023

Accepted: 04 November 2024

Published: 15 November 2024

DOI:

10.15835/buasvmcn-agr:2023.0025



© 2024 Authors. The papers published in this journal are licensed under the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License

significant growth in Pulse crop production and consumer demand due to the bean's growing agronomic, nutritional, and economic benefits on a global scale (Kim et al., 2015).

Nowadays, pulse crops are produced on more than 6 million hectares (ha) worldwide, and they are cultivated in a variety of latitudes and seasons (Chauhan and Williams, 2018). Southeast Asia is the primary producer of pulse crops, with India and Myanmar producing 1.6 million tons (Mt) and 1.597 Mt, respectively, according to Nair et al. (2020). The low average yield and poor yield stability of pulse crops are projected to impede continued expansion of the crop, even with increasing research and development activities (Tripathi et al., 2020). According to Nair et al. (2020), the average production of pulse crops varies between <math><1.0</math> and <math>1.5\text{ t ha}^{-1}</math> depending on the growing conditions. This is significantly lower than the yield observed in research plots (Chauhan et al., 2018; Rachaputi et al., 2019) and the yield predicted by crop models like the Agricultural Production Systems Simulator (APSIM) (Chauhan and Williams, 2018; Geetika et al., 2022). Significant efforts have been undertaken in the last ten years to produce superior cultivars.

Up until now, the majority of crop development efforts have concentrated on developing biotic tolerance and raising yield potential (Nair et al., 2020). Environmental stress, on the other hand, also contributes to agricultural losses globally by adversely affecting crop development and yield through physiological and biochemical alterations. By increasing climatic variability and the frequency of extreme weather events, climate change is making this problem worse (Jägermeyr et al., 2021). Therefore, it is imperative to increase pulse crop yield stability and tolerance to environmental stress. Drought and heat are examples of environmental stressors that can negatively impact pulse crop physiology, morphology, and reproductive capacity, ultimately affecting grain quality and production. Although environmental stress can affect a crop at any stage of growth, pulse crops are most susceptible during the reproductive stage (De Costa et al., 1999; Hanif and Wahid, 2018). To improve the adaptability of novel cultivars and inform management techniques, a thorough understanding of the key mechanisms of adaptation and the effects of environmental stress on growth during reproductive development is necessary (Redden, 2013). Breeding for genetic improvement provides a means of focusing on features related to environmental stress tolerance or adaptability throughout the reproductive period. We can improve breeding program selection efficacy and efficiency by learning more about the underlying adaptation mechanisms and how stress affects growth at this vital period. The main environmental stresses that affect pulse crops during the reproductive stage from a physiological standpoint are highlighted in this paper, with particular attention paid to heat, cold, drought, water logging, and salinity challenges. Furthermore, we highlight the significance of utilizing novel instruments and technologies to expedite the creation of pulse crops that will exhibit increased resilience to climate change in the future.

## **ENVIRONMENTAL STRESSES IMPACTING PULSE CROP YIELD**

Globally, salinity, water logging, extremes in temperature, and drought are the primary environmental stresses limiting pulse crop output (Chauhan and Williams, 2018). This section discusses the effects of environmental stress throughout the reproductive stage. In situations where there is a dearth of research, we highlight qualities that may be researched to enhance pulse crop adaptation by citing effective studies done in other crops.

### **Heat stress**

Production of pulse crops occurs in areas with comparatively warm temperatures (Chauhan et al., 2018). Despite this, heat stress which is often experienced throughout production regions caused by an extended period of extremely high temperatures (e.g., >40°C) during blooming and pod development can have a significant negative influence on growth and output (Rachaputi et al., 2019). Development of flowers and pods is directly impacted by heat stress. The impact of heat stress on yield components, including pod set plant<sup>-1</sup>, total pods plant<sup>-1</sup>, and total seeds plant<sup>-1</sup>, can vary in timing and severity, resulting in yield reductions ranging from 10% to 80% (Hanif and Wahid, 2018; Sharma et al., 2016). Pulse crop plants bloom profusely when conditions are right, but only few of them set pods. This is due to high levels of floral abscission 70%–90%. This is comparable to other subtropical legume crops including pigeon pea 70%–96% (Rahman et al., 2011) and soybean (60–92%). Grain legumes frequently undergo reproductive organ abscission in response to heat stress (Rainey and Griffiths, 2005). Flower abscission is a major factor in yield under heat stress since it is significantly increased at high temperatures (Khattak et al., 2009; Tickoo et al., 1996). High rates of pod abortion and reductions in grain fill have been recorded under heat stress in pulse crops. If heat stress occurs during pod development, it can also cause pod abortion and drastically diminish pod filling (Hanumantha Rao et al., 2016; Tzudir et al., 2014). Damage to the stigma, ovaries, or pollen viability, which results in infertility, is probably the cause of abscission. According to Patriyawaty et al. (2018), exposing pulse crops to 45°C for ten days during blooming could result in deformed and/or smaller pollen grains, which could limit pollen viability by as much as 60%. The size and length of pollen tubes, which are essential for transferring sperm cells to the female gametophyte, can also be distorted by high temperatures (Basu et al., 2019). Similar results were reported by Kaur et al. (2015), who discovered that cultivars that were subjected to heat stress had reduced pollen load and stigma responsiveness. High temperatures during the reproductive period

can also have a significant effect on canopy development. Warm temperatures during the reproductive phase may prevent vegetative development and maintenance due to the unpredictable growth habit displayed by certain genotypes. The effects of heat stress on photosynthetic machinery, such as decreased chlorophyll fluorescence 20%, decreased chlorophyll content 11–65% (Hanifand Wahid, 2018), decreased stomatal conductance (Hanifand Wahid, 2018; Patriyawaty et al., 2018) and restricted sucrose synthesis and transport (Awasthi et al., 2014) may be connected to a decrease in canopy biomass in pulse crops. According to a recent study, pulse crops grown under heat stress had 40% less RuBisCO activity. This was probably due to reduced stomatal conductance or lower rates of RuBP regeneration. Leaf burning, chlorosis, wilting, and premature leaf senescence exacerbate the effects even further (Sharma et al., 2016). Furthermore, high temperatures can hasten flowering and shorten flowering length since temperature has a major role in pulse crop phenological development (Sharma et al., 2016). In certain situations, a reduction in the time it takes for vegetation to grow, which limits the amount of assimilate available to support pod development, as well as a reduction in the total amount of time it takes for pod initiation and maturity, might result in yield penalties (Basu et al., 2019). Numerous crops face significant production risks due to heat stress, which has led to an abundance of research emphasizing desirable features to enhance adaptability. A successful tactic to help the crop avoid heat stress during the crucial reproductive phase is to manipulate or reduce phenological development, for example, by altering the sowing timing (Yadav et al., 2022). Days to flowering, maturity, and seeds per pod were shown to be the main characteristics impacting yield under heat stress during the flowering stage in a recent multi-environment study comparing different pulse crop genotypes across three agro ecological zones in Pakistan (Iqbal et al., 2021). These results imply that early maturing genotypes fared better in environments with high heat stress (Devasirvatham and Tan, 2018) observed similar results in other pulse crops, therefore it is worthwhile to investigate the best times to seed pulse crops to prevent heat stress during the critical period. Enhancing root architecture could be an additional tactic to raise heat tolerance. According to Patriyawaty et al. (2018), heat-tolerant pulse crop cultivars exhibited 120% greater root biomass than highly susceptible cultivars. This finding may have contributed to the genotypes' more favorable water usage mechanisms, which in turn boosted shoot growth. This emphasizes the opportunity to investigate the function of roots, which may enhance the crop's ability to access water in the soil profile during crucial times and minimize production losses, especially when heat stress and water stress coexist (Voss-Fels et al., 2018). One of the main environmental challenges that pulse crops experience is heat stress, especially during the reproductive development stage. The quantity of studies in this area compared to the other stresses in this study clearly shows how important heat stress is for pulse crops. Furthermore, few of these studies examined fewer than five genotypes, while the majority assessed a high number of genotypes. Researchers have been able to determine several characteristics that could be of interest to confer adaptation. The great majority of research has assessed heat stress in field settings, which introduces confounding factors because vapor pressure deficit is not controlled. To the best of our knowledge, no research has been done on the role of vapor pressure deficit in pulse crops, despite the enormous relevance of these field investigations. In addition, not much research has been done on how heat stress affects physiological characteristics (including photosynthetic capacity and stomata conductance) and morphology, which are best studied in controlled environments. Since early research has indicated a decrease in yield components as a result of high day and nighttime temperatures, more analysis of the timing of heat stress during the day and night should also be done (Williams et al., 2022).

### **Cold Stress**

Low temperatures might hinder the growth and output of pulse crops when they are grown outside of their usual growing region or sowing period. The effect of low temperatures on yield when exposed during the reproductive stage has not received much attention (Hu et al., 2022). Planting pulse crops later than necessary may expose them to frost during the reproductive period in some regions, such as Australia's northern grains region. This could result in plant death or lower grain quality or yield, especially if exposed to immature pods (Gentry, 2010). Two pulse crop cultivars were tested in a recent greenhouse study conducted in northern China by Hu et al. (2022) for both short-term and longer exposure (1–4 days) to cold (15°C) during flowering. Short- and long-term cold exposure reduced yield by lowering chlorophyll content and yield components; however, longer-term exposure had more significant effects, such as down regulating genes involved in the synthesis of lipids in the leaf cuticle and chlorophyll biosynthesis. This points to a possible mechanism that should be looked into more in order to increase pulse crop cold tolerance. However, it is crucial to remember that the study only looked at tolerance in two genotypes in a controlled setting; hence, more research utilizing genetically varied material is needed, ideally from within the wild. Frost resistance in field peas has been found to be correlated with flowering time; in this study, genes connected to delay flowering were found to be co-located with genes that were up regulated in cold temperatures (Lejeune-Hénaut et al., 2008). Comparable results have been noted for barley and wheat (Galiba et al., 2009). Early blooming genotypes have a higher chance of avoiding frost because reproductive development takes place during a period that lowers the total risk, especially since pulse crops are usually planted in the spring or summer. Further research into the impacts of cold stress on growth and productivity, as well as possible tolerance qualities, will be necessary

due to the increased interest in expanding pulse crop production outside of conventional sub-tropical producing zones and sowing seasons in Australia (Christy et al., 2022).

### **Drought Stress**

Since most crops are grown in rainfed agricultural systems, drought commonly affects the production of pulse crops (Sivaji et al., 2021). Due to the significant impact that water deficit has on yield during the flowering and pod development stages, the majority of original research studies examining environmental stress at reproductive development center on drought (Sadeghipour, 2009). Water stress in pulse crops causes a decrease in leaf water potential and can hinder photosynthesis by causing stomatal closure and chlorophyll degradation (Baroowa et al., 2016). Transpiration is limited by reduced stomatal conductance, and during flowering, pulse crops usually have a high rate of transpiration. Pulse crops have the ability to recover from a water deficit; one study found that photosynthesis and stomatal conductance resumed after a drought, despite a notable yield decline. Another significant consequence of drought stress is reduced canopy formation, which results in a significant decrease in plant height and leaf area (El-Nakhlawy et al., 2018). The key strategy for reducing cell damage under water stress and moderating water use is to reduce the area of the canopy. Additionally, it has been determined that pulse crop's ability to maintain leaf area during drought is a trait of interest. Plants have developed a variety of adaptation strategies that help them thrive in dry conditions. Effective stomatal regulation, a crucial physiological feature assessed in drought research, is one tactic plants employ to reduce water loss in response to reduced water potential. According to a field study conducted in India, the genotype Pratap, which is drought tolerant, was able to retain its higher leaf water potential during drought circumstances, resulting in a better yield (Baroowa et al., 2016). A correlation between canopy temperature and yield has been observed in numerous crops, making canopy temperature in the field another helpful measure for assessing drought adaptation (Karimizadeh and Mohammadi, 2011; Ninanya et al., 2021). A recent field study on pulse crops, however, did not find a correlation between yields and canopy temperature; instead, it identified a number of tolerant lines that were able to maintain high SPAD and chlorophyll fluorescence in spite of a relatively hot canopy, which is usually linked to decreased stomata conductance. To ascertain the trait value in a variety of situations, more investigation into the physiological features supporting crop water usage, specifically water demand during development, is necessary in pulse crops. Accessing soil moisture that has been stored is essential for adapting to drought. A physiological breeding approach to produce cultivars that are drought-tolerant is made possible by the discovery of root architecture features in crops like wheat that enhance water availability during dry spells (Ober et al., 2021).

### **Water logging**

When a plant, including its complete root system and possibly some of its other parts, is submerged in water, it causes a lack of oxygen in the soil (Ikram et al., 2022). Water logging can have a very negative effect on pulse crops, especially in Southeast Asia where there is a lot of rainfall during the reproductive stage, which lowers grain quality and yield. Pulse crops are usually produced in Australia's subtropical regions throughout the summer, when there is a greater chance of water logging due to heavy rains and flooding. Moreover, extreme weather events, such as flooding, are becoming more frequent due to the consequences of climate change (Shukla et al., 2019). To guarantee adaptation to present and future production settings, it is crucial to find genotypes that are tolerant of water logging (Islam et al., 2007). Water logging to a certain extent won't significantly affect pulse crop growth or yield (Ahmed et al., 2002). Research has demonstrated that either short-term (1 day) flooding at any stage of development or prolonged (7 days) flooding during the vegetative stage had no appreciable effect on yield (Islam et al., 2008). Yet, as observed in other grain legumes, extended wet weather and high rainfall in areas with inadequate soil drainage can drastically lower yield in pulse crops during reproductive development because of the increased risk of pod abortion, drop and shattering, as well as premature sprouting prior to harvest (Islam et al., 2008). Different levels of tolerance in the genotypes studied may be the cause of the contradictory results about which stage—flowering or pod filling—is most susceptible (Islam et al., 2008). However, there is a notable decrease in yield components such as pods plant<sup>-1</sup>, seeds pod<sup>-1</sup>, and yield when water logging occurs during reproductive development. Crop root systems are impacted by water logging, which lowers aboveground biomass. Water logging during the flowering and pod-filling periods of pulse crops has been shown to dramatically diminish root biomass and length, probably due to root mortality. As a result, water logging may result in decreased nutrient intake necessary for aboveground biomass and pod growth, decreasing pod filling and, in certain situations, increasing pod abortion (Pan et al., 2021). Multiple physiological processes have evolved in crops to enhance their ability to respond to conditions of water logging. Aerenchyma-containing adventitious roots in faba beans can increase their resistance to water logging (Solaiman et al., 2007). Given that water logging-tolerant pulse crop genotypes developed adventitious roots that were not seen in the control genotypes, similar morphological changes may be significant in pulse crops (Ahmed et al., 2002). Additional characteristics of tolerant pulse crop lines were their capacity to sustain high aboveground biomass and rapidly resume photosynthetic activity following water logging (Ahmed et al., 2002). In summary, with an expected rise in the frequency of intense rainfall events, water logging is projected to become an increasingly significant breeding target in the near future. A small amount of study on pulse crops and other closely related

species indicates that water logging has a significant effect on productivity when it happens during the reproductive stage. The few studies that assessed water logging during reproductive development were all quite meticulous in their data gathering methods, offering a precise understanding of the ways in which this stress affects the growth and output of pulse crops. This is a helpful starting point for furthering the study of water logging to investigate further genetic diversity. To support screening more diverse genotypes in both controlled and field settings, novel phenotyping techniques will be needed.

### **Salinity**

Due to the ongoing degradation of arable land, pulse crop growers in arid and semi-arid regions are becoming increasingly concerned about salinity, or the buildup of salts in soil and water (HanumanthaRao et al., 2016). It has been demonstrated that salinity stress affects plant growth in a number of ways, such as a decrease in osmotic potential that prevents water intake and salt buildup in plant tissue that raises toxicity levels (Munns and Tester, 2008). Reduced symbiotic nitrogen fixation is another effect on legumes (Hanumantha Rao et al., 2016). Since salinity can inhibit or delay germination and reduce seedling root and shoot growth, almost all studies assessing the effect of salinity stress on pulse crop development have concentrated on early development, in particular at germination and the seedling stage (Saha et al., 2010). It is crucial to assess the effects of salinity at each developmental stage because research on rice and chickpea has revealed that tolerance to salinity at the seedling and vegetative stages is not always correlated with tolerance at the reproductive stages (Vadez et al., 2007). As with cold stress, not much is known at this time about how salinity affects pulse crop during its reproductive development. According to one study (Wahid et al., 2004), salinity during reproductive development led to high levels of burning and chlorosis at leaf tips, considerably decreased plant dry matter and leaf area, and decreased leaf mineral and chlorophyll concentrations. Another study (Mekhaldi et al., 2008) used leaf assays to explore the effect of salinity on gas exchange at the leaf level; however, this method did not look at other effects such as biomass accumulation and yield. The restricted scope and small number of genotypes examined in these two studies underscore the critical need for additional study in the future, even if they offer insightful preliminary information about the effects of salinity on pulse crop reproductive development.

## **BREEDING FOR ADAPTATION TO ENVIRONMENTAL STRESS IN PULSE CROP**

There are more possibilities to analyze the physiology and genetics of features supporting adaptability as our understanding of how environmental stress affects pulse crop yield development advances. Pulse crop breeding efforts can be accelerated by new technology and techniques, improving growers' output stability.

### **Pulse crop genetic resources**

Genetic variety must be available to breeders in order for crop improvement initiatives to achieve genetic gain. Many agronomically significant features, including as seed dormancy, phenology-related variables, plant type, and 100 seed weight, have been selected since domestication in order to increase crop productivity (Isemura et al., 2012). Nonetheless, the genetic foundation of modern pulse crop cultivars is limited (Nair et al., 2020). According to a recent study, cultivars' genetic diversity after domestication dropped to 30% of that of wild accessions (Ha et al., 2021). As a result, gene banks probably contain germplasm that has characteristics not seen in elite germplasm and that can be utilized to help modern cultivars better respond to environmental stress. Approximately 43,000 pulse crop accessions are kept in various gene banks across the globe, with the largest collections kept at the World Vegetable Center (AVRDC), Taiwan, and the Indian Council of Agricultural Research (Nair et al., 2020). The International pulse crop Improvement Network's present goal is to increase yield potential and adaptability to environmental stress; biotic stress has been the main focus of research on these collections (Nair et al., 2020). There are wild relatives of the pulse crop in many collections as well, which may provide access to allelic diversity lacking in elite gene pools (Kim et al., 2015). Although many collections of germplasm have now been genotyped, the creation of phenotypic data for complex traits remains a major barrier to the use of germplasm in breeding programs.

### **High-throughput phenotyping**

In breeding programs, field-based phenotyping is essential for characterizing and evaluating complex traits. In order to capture features of interest, traditional field-based phenotyping methods frequently need manual, laborious, and destructive sampling. These restrictions have made it more difficult to link genotype to phenotype, which has slowed down breeding efforts and put researchers at a standstill.

Crop improvement projects can find and develop traits more quickly with the use of high-throughput phenotyping tools (Smith et al., 2018). Due to their flexibility and inexpensive technology, unmanned aerial vehicles in particular have shown a lot of promise for large-scale field phenotyping (Das et al., 2021). High-resolution photographs of the field can be produced by attaching a variety of cameras and sensors to unmanned aerial vehicles. Vegetative and thermal indices have been successfully applied in a variety of crops, such as soybean (Roth et al., 2022) and sorghum (Gano et al., 2021). These indices can be predictive of physiological features based on the

ground. Unmanned aerial vehicles equipped with sensors can be used to measure physiological response-related proxy features and track the environmental stress response. For instance, measuring the canopy temperature during a drought can reveal the amount of water used by plants on a large scale in the field. Legume and cereal crops have also benefited from this strategy (Das et al., 2021). A variety of environmental challenges, including salt, foliar damage from temperature stress, and water logging, can be treated with similar methods. Unmanned aerial vehicle phenotyping techniques for pulse crops have not yet been reported. But a different imaging method has just been used to analyze pulse cropleaf morphological characteristics (Chiteri et al., 2023). Using image annotation software, this method involves taking pictures of the leaves and computing attributes such leaf area. Because data can be collected extensively and non-destructively throughout the reproductive window, these technologies are expected to be helpful in analyzing canopy dynamics under environmental stress. This will enable the quantification of fast changes that occur at the canopy scale.

### **Genomics-assisted breeding for environmental stress**

Breeders can combine features to produce better cultivars with the assistance of an understanding of the underlying genetics of traits linked to environmental stress adaptability. In order to track and choose the desired trait within the breeding program, phenotyping bottlenecks can be overcome by marker-assisted selection made possible by DNA markers associated with traits. In the past, plant breeding has employed markers like random amplification of polymorphic DNA (RAPD), amplified fragment length polymorphism (AFLP), restriction fragment length polymorphism (RFLP), and simple sequence repeats (SSR) for genome research. Although the use of these markers led to early advancements in the area, their low throughput and occasionally low reproducibility are drawbacks (Yang et al., 2013). Thanks to advancements in technology, genotyping is now less expensive (Hasan et al., 2021). Many crops now prefer molecular marker systems made possible by advances in sequencing technologies, such as genotyping by sequencing (GBS) and single nucleotide polymorphism (SNP) markers. The high-throughput Diversity Arrays Technology platform is a well-liked genotyping service that is frequently used in pulse crops (Kilian et al., 2012). The first draft of the whole-genome sequencing was a significant development for the pulse crop since it made it possible to investigate the genome and marker position using modern genomic research techniques (Kang et al., 2014). Researchers have discovered multiple quantitative trait loci (QTL) linked to drought adaptation in a pulse crop recombinant inbred line (RIL) population (Liu et al., 2017). Although this method is effective in mapping QTL, it is imprecise and does not allow for the exploration of a large amount of genetic variation. There are benefits to using genome-wide association studies (GWAS) to examine SNP variation in bigger and more varied populations. Researchers can now map the genetic loci linked to economically significant qualities like yield and traits supporting adaptability to biotic and environmental stress because to the widespread use of GWAS (Liu et al., 2018). Based on the statistical importance of the relationship between the SNPs and the reported phenotype, this method uses SNPs to find the variation across genomes that affect a specific trait. High resolution and objective information about the genetic architecture of the trait, such as the number of causal alleles, the distribution of their effects, and their interactions, can also be revealed by GWAS (Hansen, 2006). In order to find QTL linked to a variety of qualitative and quantitative features, including seed characteristics (i.e. seed coat color, luster and texture) (Nair et al., 2020), total leaf area (Reddy et al., 2020), phenological development flower and pod traits and behavior (Ha et al., 2021; Liu et al., 2018), leaf and canopy characteristics (Chiteri et al., 2023; Ha et al., 2021) root architecture traits (Reddy et al., 2020) and seed mineral composition (Wu et al., 2020) several pulse crop research have used GWAS. There has been less research that has shown QTL connected to characteristics related to stress adaptation in the environment. Two QTL linked to germination under salinity on chromosomes 7 and 9 were found by evaluation of a pulse crop mini-core collection. An investigation found more potential genes for salt tolerance in seedlings (Liu et al., 2017). Marker-assisted selection is a useful breeding approach for simple traits, and GWAS is useful for understanding genetics. But characteristics that give resilience to environmental stress are typically quantitative and complicated, which means that GWAS frequently reveals a large number of loci with little effect. The linked marker's potential for recombination with the original single marker GWAS techniques is another drawback. Haplotype-based GWAS methods can therefore identify a block of markers that are in linkage disequilibrium, which may be better suited for tracking and selection in breeding populations. One such method is the local genomic estimated breeding value approach (Voss-Fels et al., 2019).

### **Speed breeding**

By shortening the breeding cycle, speed breeding can hasten agricultural improvement. In order to hasten blooming and seed set and hence advance to the next generation more quickly, speed breeding entails cultivating plant populations under carefully regulated environmental parameters, such as ideal day length, light intensity, light quality, and temperature (Ghosh et al., 2018). Most pulse crop improvement efforts are found in the subtropics or the tropics, which frequently have prolonged periods of rainfall and, as a result, lower light intensity for a portion of the year. In standard glasshouse facilities, this can cause a delay in the generation time. A speed breeding facility that maintains year-round temperature and light supply control may be able to produce more plant generations annually, which would significantly speed up breeding operations. The dependability of breeding operations in the

tropics may also be increased by using specialized speed breeding facilities, since schedules are not disrupted by inclement weather like monsoons or excessive rain. In order to guarantee that field testing can be finished on time, speed breeding makes sure that new breeding lines may be developed annually at a set time. Moreover, growing high plant densities in a limited area has the benefit of increasing overall efficiency, which might hasten and expand single seeds. For instance, 100-cell trays can be used to grow wheat and barley, resulting in 900 plants per m<sup>2</sup> of plant density (Watson et al., 2018). Access to appropriate facilities with dependable power and water, staff training on protocol, and the capacity to implement significant modifications to existing breeding program designs are all necessary for speed breeding. Therefore, putting speed breeding into practice can be difficult, especially for crop development programs that have limited funding and resources (Wanga et al., 2021). Although there are currently no documented speed breeding methods for pulse crops, there are protocols available for tropical legumes like cowpea (one cycle 43–55 days) and soybean one cycle 77 days (Mobini et al., 2015), suggesting that pulse crops could be receptive to speed breeding.

### **Genetic engineering**

In order to research and characterize genes, genetic modification can be utilized in conjunction with conventional breeding techniques (Massel et al., 2021). This can assist in pinpointing the precise genes in charge of desirable characteristics. These systems for genetic modification (such CRISPR/Cas and agrobacterium-mediated transformation) can also be utilized to produce new types with desired traits. In pulse crops, genetic transformation techniques have been used to find and assess genes linked to cold stress (Rout et al., 2020) and salinity adaptation (Sahoo et al., 2016). The strategy of overexpressing a gene initially discovered in *Arabidopsis* in pulse crop, as taken by Kumar et al. (2017) and Sahoo et al. (2016), emphasizes the significance of applying knowledge from model species to speed pulse crop improvement. In pulse crop, gene editing techniques are increasingly accessible and have been used for biotic stress (Talabayala et al., 2022). One benefit of genome editing is that many jurisdictions now regard plants produced using gene knockout techniques (designated as SDN1) as non-GM (Zhang et al., 2021). This strategy for adapting to environmental stress may have drawbacks, too, as knockouts might not produce the best physiological phenotype. Editing a gene's regulatory regions, which can result in a spectrum of phenotypic variation, is one way to get around this restriction (Crisp et al., 2022). All the same, genome editing technology provides an effective means of comprehending the function of genes and can be applied to assess well-characterized genes from other animals. The time it takes to provide producers with cultivars that are more adapted to environmental stress could be shortened if editing pipelines are produced utilizing superior variety.

## **CONCLUSIONS**

Environmental stresses during reproductive development have a major impact on pulse crop yields. Our thorough search of the literature turned up relatively few original research articles that address the impacts of environmental stress at the reproductive stage in pulse crops, despite the potential impact on production. This demonstrates the significant research gap that must be filled in order to pinpoint the characteristics that confer adaptability. It is imperative that future research be done in order to extend the application of current studies to more genotypes and habitats, especially by putting strong field experiments into practice. To analyze the physiological and genetic mechanisms underlying the features involved in environmental stress adaptation, in-depth experiments are also necessary. High-throughput phenotyping systems, including unmanned aerial aircraft equipped with sensors may be used to enable phenotyping at scale; nevertheless, protocols need to be verified for particular indices and connected to desirable features for every environmental stress. Genomic selection for pulse crops can be implemented to speed up genetic gain for environmental stress due to advancements in genotyping technologies and decreased costs. It is expected that gene editing platforms would help explore desirable features from model species to further our understanding of pulse crops. Research and technology advancements necessary to breed resilient pulse crop cultivars for the future will be guided by the knowledge now produced for environmental stress at the reproductive stage in Pulse Crops, as well as insights from other crops.

**Author Contributions:** N.S.T. Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Resources; Supervision; Validation; Visualization; Writing-original draft; Writing review and editing. F.M. Conceptualization; Formal analysis; Investigation; Resources; Supervision; Validation; Visualization A.M., A.H., S.E. AND S.A. Validation; Visualization; Writing review and editing.

### **Acknowledgments**

We would like to acknowledge Wollo University for providing the opportunity to do this review.

## Conflict of Interest

The authors declare no conflict of interest.

## REFERENCES

1. Ahmed S, Nawata E and Sakuratani T. Effects of waterlogging at vegetative and reproductive growth stages on photosynthesis, leaf water potential and yield in Pulse Crop. *Plant Production Science*. 2002; 5(2):117–123. <https://doi.org/10.1626/pps.5.117>
2. Awasthi R, Kaushal N, Vadez V, Turner NC, Berger J, Siddique KH and Nayyar H. Individual and combined effects of transient drought and heat stress on carbon assimilation and seed filling in chickpea. *Functional Plant Biology*. 2014; 41(11): 1148– 1167. <https://doi.org/10.1071/FP13340>
3. Baroowa B, Gogoi N and Farooq M. Changes in physiological, biochemical and antioxidant enzyme activities of green gram (*Vigna radiate* L.) genotypes under drought. *Acta Physiologiae Plantarum*. 2016; 38(9): 219. <https://doi.org/10.1007/s11738-016-2230-7>
4. Basu S, Pratap A, Gupta S, Sharma K, Tomar R and Singh P. Physiological traits for shortening crop duration and improving productivity of greengram (*Vigna radiata* L. Wilczek) under high temperature. *Frontiers in Plant Science* 2019; 10: 1508. <https://doi.org/10.3389/fpls.2019.01508>
5. Chauhan S, Williams R. Physiological and agronomic strategies to increase Pulse crop yield in climatically variable environments of northern Australia. *Agronomy*. 2018; 8(6): 83. <https://doi.org/10.3390/agronomy8060083>
6. Christy P, Delahunty J, Norton L, Wallace J, Riffkin A, Leary L and Nuttall G. New legume species as opportunistic summer crops for southern Australia–part 1: Environmental suitability. *Proceedings of the 20th agronomy Australia conference, Australia, AU. Cohen, D. (1976). The optimal timing of reproduction. The American Naturalist*. 2022; 110(975): 801–807
7. Chiteri O, Chiranjeevi S, Jubery Z, Rairdin A, Dutta S, Ganapathysubramanian B and Singh A. Dissecting the genetic architecture of leaf morphology traits in Pulse crop (*Vigna radiate* (L.) Wilczek) using genome-wide association study. *The Plant Phenome Journal*. 2023; 6(1): e20062. <https://doi.org/10.1002/ppj2.20062>
8. Crisp A, Bhatnagar-Mathur P, Hundley P, Godwin D, Waterhouse M and Hickey T. Beyond the gene: Epigenetic and cis-regulatory targets offer new breeding potential for the future. *Current Opinion in Biotechnology*. 2022; 73: 88–94. <https://doi.org/10.1016/j.copbio.2021.07.008>
9. Das S, Chapman S, Christopher J, Choudhury R, Menzies W, Apan A and Dang P. Unmanned aerial vehicle-thermal imaging: A technological breakthrough for monitoring and quantifying crop Environmental stress to help sustain productivity on sodic soils—a case review on wheat. *Remote Sensing Applications: Society and Environment*. 2021; 23: 100583. <https://doi.org/10.1016/j.rsase.2021.100583>
10. De Costa M, Shanmugathan N and Joseph M. Physiology of yield determination of Pulse crop (*Vigna radiate* (L.) Wilczek) under various irrigation regimes in the dry and intermediate zones of Sri Lanka. *Field Crops Research*. 1999; 61(1): 1–12. [https://doi.org/10.1016/S0378-4290\(98\)00141-5](https://doi.org/10.1016/S0378-4290(98)00141-5)
11. Devasirvatham V and Tan K. Impact of high temperature and drought stresses on chickpea production. *Agronomy* 2018; 8(8): 145. <https://doi.org/10.3390/agronomy8080145>
12. El-Nakhlawy S, Ismail M and Basahi M. Optimizing Pulse crop productivity and irrigation water use efficiency through the use of low water-consumption during plant growth stages. *Legume Research*. 2018; 41(1); 108–113. <https://doi.org/10.18805/lr.v40i04.9014>
13. Galiba G, Vágúfalvi A, Li C, Soltész A and Dubcovsky J. Regulatory genes involved in the determination of frost tolerance in temperate cereals. *Plant Science*. 2009;176(1): 12–19 <https://doi.org/10.1016/j.plantsci.2008.09.016>
14. Gano B, Dembele B, Ndou A, Luquet D, Beurier G, Diouf D and Audebert A. Using UNMANNED AERIAL VEHICLE borne, multi-spectral imaging for the field phenotyping of shoot biomass, leaf area index and height of west 1hermos sorghum varieties under two contrasted water conditions. *Agronomy*. 2021; 11(5): 850. <https://doi.org/10.3390/agronomy11050850>
15. Geetika G, Hammer G, Smith M, Singh V, Collins M, Mellor V, Wenham K and Rachaputi N. Quantifying physiological determinants of potential yield in Pulse crop (*Vigna radiata* (L.) Wilczek). *Field Crops Research*. 2022; 287: 108648. <https://doi.org/10.1016/j.fcr.2022.108648>
16. Ghosh S, Watson A, Gonzalez-Navarro E, Ramirez-Gonzalez H, Yanes L, Mendoza-Suárez M, Simmonds J, Wells R, Rayner T, Green P, Hafeez A, Hayta S, Melton E, Steed A, Sarkar A, Carter J, Perkins L, Lord J, Tester M and Hickey T. Speed breeding in growth chambers and glasshouses for crop breeding and model plant research. *Nature Protocols* 2018; 13(12): 2944–2963. <https://doi.org/10.1038/s41596-018-0072-z>
17. Gentry J. Mungbean management guide (2nd ed.). Department of Employment, Economic Development and Innovation. 2010; <https://era.daf.qld.gov.au/id/eprint/7070/1/mungmanual2010-LR.pdf>



18. Ha J, Satyawati D, Jeong H, Lee E, Cho H, Kim Y and Lee H. A near-complete genome sequence of Pulse crop (*Vigna radiata*L.) provides key insights into the modern breeding program. *The Plant Genome* 2021; 14(3): e20121. <https://doi.org/10.1002/tpg2.20121>
19. Hanif A and Wahid A. Seed yield loss in Pulse crop is associated to heat stress induced oxidative damage and loss of photosynthetic capacity in proximal trifoliolate leaf. *Pakistan Journal of Agricultural Sciences* 2018; 55(4): 777–786. <https://doi.org/10.21162/PAKJAS/18.7461>
20. Hansen F. The evolution of genetic architecture. *Annual Review of Ecology, Evolution and Systematics*, 2006; 37: 123–157. <https://doi.org/10.1146/annurev.ecolsys.37.091305.110224>
21. HanumanthaRao B, Nair M and Nayyar H. Salinity and high temperature tolerance in mungbean [*Vigna radiata* (L.) Wilczek] from a physiological perspective. *Frontiers in Plant Science* 2016; 7: 957. <https://doi.org/10.3389/fpls.2016.00957>
22. Hasan N, Choudhary S, Naaz N, Sharma N and Laskar A. Recent advancements in molecular marker-assisted selection and applications in plant breeding programmes. *Journal of Genetic Engineering and Biotechnology* 2021; 19(1): 1–26. <https://doi.org/10.1186/s43141-021-00231-1>
23. Hou D, Yousaf L, Xue Y, Hu J, Wu J, Hu X, Feng N and Shen Q. Pulse crop (*Vigna radiata*L.): Bioactive polyphenols, polysaccharides, peptides, and health benefits. *Nutrients*, 2019; 11(6): 1238. <https://doi.org/10.3390/nu11061238>
24. Hu H, Feng N, Shen X, Zhao L and Zheng D. Transcriptomic analysis of *Vigna radiata* in response to chilling stress and uniconazole application. *BMC Genomics*. 2022; 23(1): 205. <https://doi.org/10.1186/s12864-022-08443-6>
25. Ikram S, Bhattarai S and Walsh B. Characterisation of selected Pulse crop genotypes for tolerance to waterlogging stress at pod filling stage. *Agronomy*; 2022; 12(7): 1663. <https://doi.org/10.3390/agronomy12071663>
26. Iqbal J, Shabbir G, Shah N, Fayyaz-ul H and Qayyum A. Deciphering of genotype×environment interaction to identify stable heat-tolerant Pulse crop genotypes by GGE biplot analysis. *Journal of Soil Science and Plant Nutrition* 2021; 21(3): 2551–2561. <https://doi.org/10.1007/s42729-021-00546-5>
27. Isemura T, Kaga A, Tabata S, Somta P, Srinives P, Shimizu T, Jo U, Vaughan A and Tomooka N. Construction of a genetic linkage map and genetic analysis of domestication related traits in mungbean (*Vigna radiata*). *PLoS One* 2012; 7(8): e41304. <https://doi.org/10.1371/journal.pone.0041304>
28. Islam R, Hamid A, Karim A, Haque M, Khaliq A and Ahmed U. Gas exchanges and yield responses of Pulse crop (*Vignaradiata*L. Wilczek) genotypes differing in flooding tolerance. *Acta Physiologiae Plantarum*, 2008; 30(5): 697– 707. <https://doi.org/10.1007/s11738-008-0168-0>
29. Islam R, Hamid A, Khaliq A, Ahmed U, Haque M and Karim A. Genetic variability in flooding tolerance of pulse crop (*Vigna radiata*L. Wilczek) genotypes. *Euphytica* 2007; 156: 247–255. <https://doi.org/10.1007/s10681-007-9372-z>
30. Jägermeyr J, Müller C, Ruane C, Elliott J, Balkovic J, Castillo O, Faye B, Foster I, Folberth C, Franke A, Fuchs K, Guarin R, Heinke J, Hoogenboom G, Lizumi T, Jain K, Kelly D, Khabarov N, Lange S and Rosenzweig C. Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. *Nature Food* 2021; 2(11): 873–885. <https://doi.org/10.1038/s43016-021-00400-y>
31. Kang J, Kim K, Lestari P, Kim H, Ha, Hwang J, Lee T, Lee J, Shim S, Yoon Y, Jang E, Han S, Taeprayoon P, Yoon N, Somta P, Tanya P, Kim K and Lee S. Genome sequence of Pulse crop and insights into evolution within *Vigna* species. *Nature Communications*. 2014; 5(1): 5443. [https://doi.org/10.1038/ncomm\\_s6443](https://doi.org/10.1038/ncomm_s6443)
32. Karimizadeh, R and Mohammadi M. Association of canopy temperature depression with yield of durum wheat genotypes under supplementary irrigated and rainfed conditions. *Australian Journal of Crop Science*. 2011; 5(2): 138–146.
33. Kaur R, Bains S, Bindumadhava H and Nayyar H. Responses of Pulse crop (*Vigna radiata*L.) genotypes to heat stress: Effects on reproductive biology, leaf function and yield traits. *Scientia Horticulturae*. 2015; 197: 527–541. <https://doi.org/10.1016/j.scienta.2015.10.015>
34. Khattak G, Saeed I and Muhammad T. Flowers' shedding under high temperature in Pulse crop (*Vignaradiata*(L.) Wilczek). *Pakistan Journal of Botany*. 2009; 41(1): 35–39.
35. Kilian A, Wenzl P, Huttner E, Carling J, Xia L, Blois H, Caig V, Heller-Uszynska K, Jaccoud D, Hopper C, Malgorzata A and Uszynski G. Diversity arrays technology: A generic genome profiling technology on open platforms. *Data Production and Analysis in Population Genomics: Methods and Protocols*. 2012; 888: 67–89. [https://doi.org/10.1007/978-1-61779-870-2\\_5](https://doi.org/10.1007/978-1-61779-870-2_5)
36. Kim K, Nair M, Lee J and Lee H. Genomic resources in Pulse crop for future breeding programs. *Frontiers in Plant Science*. 2015; 6: 626. <https://doi.org/10.3389/fpls.2015.00626>
37. Kumar S, Kalita A, Srivastava R and Sahoo L. Co-expression of *Arabidopsis* NHX1 and bar improves the tolerance to salinity, oxidative stress, and herbicide in transgenic Pulse Crop. *Frontiers in Plant Science*. 2017; 8: 1896. <https://doi.org/10.3389/fpls.2017.01896>

38. Lejeune-Hénaut I, Hanocq E, Béthencourt L, Fontaine V, Delbreil B, Morin J, Petit A, Devaux R, Boilleau M, Stempniak J, Thomas M, Lainé L, Foucher F, Baranger A, Burstin J and Rameau C, Giauffret C. The flowering locus *Hrcolocalizes* with a major QTL affecting winter frost tolerance in *Pisum sativum* L. *Theoretical and Applied Genetics*. 2008; 116(8): 1105–1116. <https://doi.org/10.1007/s00122-008-0739-x>
39. Liu C, Wu J, Wang L, Fan B, Cao Z, Su Q, Zhang Z, Wang Y, Tian J and Wang S. Quantitative trait locus mapping under irrigated and drought treatments based on a novel genetic linkage map in Pulse crop (*Vigna radiata* L.). *Theoretical and Applied Genetics*. 2017; 130(11): 2375–2393. <https://doi.org/10.1007/s00122-017-2965-6>
40. Liu R, Gong J, Xiao X, Zhang Z, Li J, Liu A, Lu Q, Shang H, Shi Y, Ge Q, Iqbal S, Deng X, Li S, Pan J, Duan L, Zhang Q, Jiang X, Zou Xi, Hafeez A and Yuan Y. GWAS analysis and QTL identification of fiber quality traits and yield components in upland cotton using enriched high density SNP markers. *Frontiers in Plant Science*. 2018; 9: 1067. <https://doi.org/10.3389/fpls.2018.01067>
41. Massel K, Lam Y, Wong S, Hickey T, Borrell K and Godwin D. The latest edit on climate change. *Theoretical and Applied Genetics*. 2021; 134(6): 1691–1709. <https://doi.org/10.1007/s00122-020-03764-0>
42. Mekhaldi A, Benkhalifa M and Belkhdja M. The effect of salinity on gas exchange on different developmental stages of Pulse crop (*Vigna radiata* L. Wilczek). *International Journal of Botany*. 2008; 4(3): 4450–4454. <https://doi.org/10.3923/ijb.2008.269.275>
43. Mobini H, Lulsdorf M and Warkentin D, Vandenberg A. Plant growth regulators improve in vitro flowering and rapid generation advancement in lentil and faba bean. *In Vitro Cellular and Developmental Biology – Plant*. 2015; 51(1): 71–79. <https://doi.org/10.1007/s11627-014-9647-8>
44. Munns R and Tester M. Mechanisms of salinity tolerance. *Annual Review of Plant Biology*. 2008; 59(1): 651–681. <https://doi.org/10.1146/annurev.arplant.59.032607.092911>
45. Nair M, Schafleitner R and Lee H. The Pulse crop genome. Springer 2020 <https://doi.org/10.1007/978-3-030-20008-4>
46. Ninanya J, Ramírez A, Rinza T, Silva-Díaz C, Cervantes M, García J and Quiroz R. Canopy Temperature as a Key Physiological Trait to Improve Yield Prediction under Water Restrictions in Potato. *Agronomy*. 2021; 11(7): 1436. <https://doi.org/10.3390/agronomy11071436>
47. Ober S, Alahmad S, Cockram J, Forestan C, Hickey L, T, Kant J, Maccaferri M, Marr E, Milner M, Pinto F, Rambla, E, Reynolds M, Salvi S, Sciara G, Snowdon J, Thomelin P, Tuberosa R, Uauy C, Voss-Fels P and Watt M. Wheat root systems as a breeding target for climate resilience. *Theoretical and Applied Genetics*. 2021; 134(6): 1645–1662. <https://doi.org/10.1007/s00122-021-03819-w>
48. Pan J, Sharif R, Xu X and Chen X. Mechanisms of waterlogging tolerance in plants: Research progress and prospects. *Frontiers in Plant Science*. 2021; 11: 627331. <https://doi.org/10.3389/fpls.2020.627331>
49. Patriyawaty R, Rachaputi N and George D. Physiological mechanisms underpinning tolerance to high temperature stress during reproductive phase in Pulse crop (*Vigna radiata* (L.) Wilczek). *Environmental and Experimental Botany* 2018; 150: 188–197. <https://doi.org/10.1016/j.envexpbot.2018.03.022>
50. Rachaputi N, Sands D, McKenzie K, Agius P, Lehane J and Seyoum S. Eco-physiological drivers influencing Pulse crop [*Vigna radiata* (L.) Wilczek] productivity in subtropical Australia. *Field Crops Research*. 2019; 238: 74–81. <https://doi.org/10.1016/j.fcr.2019.04.023>
51. Rahman H, Islam A and Begum S. Comparative analysis of pod yield between wild and cultivated pigeon pea (*Cajanus cajan*) genotypes based on floral abscission. *Journal of Experimental Biosciences*. 2011; 2(1): 27–32.
52. Rainey M and Griffiths D. Inheritance of heat tolerance during reproductive development in snap bean (*Phaseolus vulgaris* L.). *Journal of the American Society for Horticultural Science*. 2005; 130(5): 700–706. <https://doi.org/10.21273/JASHS.130.5.700>
53. Redden R. New approaches for crop genetic adaptation to the Environmental stresses predicted with climate change. *Agronomy* 2013; 3(2): 419–432. <https://doi.org/10.3390/agronomy3020419>
54. Reddy P, Das S, Dikshit K, Mishra P, Aski M, Meena K, Singh A, Pandey R, Singh P, Tripathi K, Gore G, Bhagat K, Kumar S, Nair R, Sharma R. Genome-wide association analysis for phosphorus use efficiency traits in Pulse crop (*Vigna radiata* L. Wilczek) using genotyping by sequencing approach. *Frontiers in Plant Science* 2020; 11: 1546. <https://doi.org/10.3389/fpls.2020.537766>
55. Roth L, Barendregt C, Béatrix A, Hund A and Walte A. High-throughput field phenotyping of soybean: Spotting an ideotype. *Remote Sensing of Environment*. 2022; 269: 112797. <https://doi.org/10.1016/j.rse.2021.112797>
56. Rout R, Bansal A, Swain D, Jadhao R, Shelke G and Panda K. Over expression of ICE1 gene in Pulse crop (*Vigna radiata* L.) for cold tolerance. *Plant Cell, Tissue and Organ Culture (PCTOC)*. 2020; 143(3): 593–608. <https://doi.org/10.1007/s11240-020-01944-w>

57. Sadeghipour O. The influence of water stress on biomass and harvest index in three Pulse crop (*Vigna radiata* (L.) R. Wilczek) cultivars. *Asian Journal of Plant Sciences*. 2009; 8(3): 245. <https://doi.org/10.3923/ajps.2009.245.249>
58. Saha P, Chatterjee P and Biswas K. NaCl pretreatment alleviates salt stress by enhancement of antioxidant defense system and osmolyte accumulation in Pulse crop (*Vigna radiata* L. Wilczek). *Indian Journal of Experimental Biology*. 2010; 48(6): 593–600.
59. Sahoo P, Kumar S, Mishra S, Kobayashi Y, Panda K and Sahoo L. Enhanced salinity tolerance in transgenic Pulse crop overexpressing *Arabidopsis* antiporter (NHX1) gene. *Molecular Breeding*. 2016; 36(10): 144. <https://doi.org/10.1007/s11032-016-0564-x>
60. Sharma L, Priya M, Bindumadhava H, Nair R and Nayyar H. Influence of high temperature stress on growth, phenology and yield performance of Pulse crop [*Vigna radiata*(L.) Wilczek] under managed growth conditions. *Scientia Horticulturae*. 2016; 213: 379–394. <https://doi.org/10.1016/j.scien ta.2016.10.033>
61. Shukla R, Skea J, Buendia, E, Masson-Delmotte V, Pörtner H, Roberts C, Zhai P, Slade R, Connors S, Van Diemen R, Ferrat M, Haughey E, Luz S, Neogi S, Pathak M, Petzold J, Pereira P, Vyas P and Huntley W. Climate Change and Land. In An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems *IPCC* 2019 <https://doi.org/10.25561/76618>
62. Sivaji M, Pandiyan M, Thilagavathi T, Yuvaraj M, Suganyadevi M and Sasmitha R. Production strategies of Pulse crop under drought stress: Physicochemical modifications, plant responses and management approaches. In M. L. Bech (Ed.), *Vigna radiata: Production, cultivation and uses* (pp. 126–166) 2021 Nova Science Publishers.
63. Smith R, Rao M and Merchant A. Source-sink relationships in crop plants and their influence on yield development and nutritional quality. *Frontiers in Plant Science*. 2018; 9: 1889. <https://doi.org/10.3389/fpls.2018.01889>
64. Solaiman Z, Colmer D, Loss P, Thomson D and Siddique M. Growth responses of cool-season grain legumes to transient waterlogging. *Australian Journal of Agricultural Research* 2007; 58(5): 406–412. <https://doi.org/10.1071/AR06330>
65. Talakayala A, Mekala K, Malireddy K, Ankanagari S and Garlandinne M. Manipulating resistance to Pulse crop yellow mosaic virus in greengram (*Vigna radiata* L): Through CRISPR/Cas9 mediated editing of the viral genome. *Frontiers in Sustainable Food Systems*. 2022; 6: 911574. <https://doi.org/10.3389/fsufs.2022.911574>
66. Tickoo J, Mahto G and Manji C. Plant type in Pulse crop (*Vigna radiata* L. Wilczek). In A. N. Asthana and D. H. Kim (Eds.), *Recent advances in Pulse crop research* (pp. 197–213). Indian Society of Pulses Research and Development. Togun, A. O., and Tayo, T. O. (1990). Flowering and pod and seed development in pigeon pea (*Cajanus cajan*). *The Journal of Agricultural Science*. 1996; 115(3): 327–335. <https://doi.org/10.1017/S0021859600075742>
67. Tripathi K, Meena K, Panwar S, Lal H, Rana C and Singh K. Understanding genetic variability in the Pulse crop (*Vigna radiata* L.) genepool. *Annals of Applied Biology*. 2020; 177(3); 346–357. <https://doi.org/10.1111/aab.12624>
68. Tzudir L, Bera P and Chakraborty H. Impact of temperature on the reproductive development in Pulse crop (*Vigna radiata* L.) varieties under different dates of sowing. *International Journal of Bio-Resource and Stress Management* 2014; 5(2): 194. <https://doi.org/10.5958/0976-4038.2014.00555.7>
69. Vadez V, Krishnamurthy L, Serraj R, Gaur M, Upadhyaya D, Hoisington A, Varshney K, Turner C and Siddique M. Large variation in salinity tolerance in chickpea is explained by differences in sensitivity at the reproductive stage. *Field Crops Research*. 2007; 104(1): 123–129. <https://doi.org/10.1016/j.fcr.2007.05.014>
70. Vargas Y, Mayor-Duran M, Buendia F, Ruiz-Guzman and Raatz B. Physiological and genetic characterization of heat stress effects in a common bean RIL population. *PLoS One*. 2021; 16(4): e0249859. <https://doi.org/10.1371/journal.pone.0249859>
71. Voss-Fels P, Snowdon J and Hickey T. Designer roots for future crops. *Trends in Plant Science*. 2018; 23(11): 957–960. <https://doi.org/10.1016/j.tplants.2018.08.004>
72. Voss-Fels P, Stahl A, Wittkop B, Lichthardt C, Nagler S, Rose T, Chen T, Zetzsche H, Seddig S, Baig M, Ballvora A, Frisch M, Ross E, Hayes J, Hayden J, Ordon F, Leon J, Kage H, Wolfgang W and Snowdon J. Breeding improves wheat productivity under contrasting agrochemical input levels. *Nature Plants*. 2019; 5(7): 706–714. <https://doi.org/10.1038/s41477-019-0445-5>
73. Wahid A, Hameed M and Rasul E. Salt-induced injury symptoms, changes in nutrient and pigment composition, and yield characteristics of Pulse Crop. *International Journal of Agriculture and Biology* 2004; 6(6): 1143–1152.

74. Wanga A, Shimelis H, Mashilo J and Laing D. Opportunities and challenges of speed breeding: A review. *Plant Breeding* 2021; 140(2): 185–194. <https://doi.org/10.1111/pbr.12909>
75. Watson A, Ghosh S, Williams, J, Cuddy S, Simmonds J, Rey M, Hatta M, Hinchliffe A, Steed A, Reynolds D, Adamski M, Breakspear A, Korolev A, Rayner T, Dixon E, Riaz A, Martin W, Ryan M, Edwards D and Hickey T. Speed breeding is a powerful tool to accelerate crop research and breeding. *Nature Plants*. 2018; 4(1): 23–29. <https://doi.org/10.1038/s41477-017-0083-8>
76. Williams A, Wenham K, Smith M, Rachaputi N and Collins M. Pulse crop responses to elevated day-and night-time temperatures [paper presentation]. Proceedings of the 20th agronomy Australia conference. 2022.
77. Wu X, Islam F, Limpot N, Mackasmiel L, Mierzwa J, Cortés J and Blair W. Genome-wide SNP identification and association mapping for seed mineral concentration in Pulse crop (*Vigna radiata* L.). *Frontiers in Genetics*. 2020; 11:656. <https://doi.org/10.3389/fgene.2020.00656>
78. Yadav R, Choudhary M, Singh J, Lal K, Jha K, Udawat P, Gupta K, Rajput D, Garge K, Maheshwari C, Hasan M, Gupta S, Jatwa K, Kumar R, Yadav K and Prasad V. Impacts, tolerance, adaptation, and mitigation of heat stress on wheat under changing climates. *International Journal of Molecular Sciences*. 2022; 23(5): 2838. <https://doi.org/10.3390/ijms23052838>
79. Yang W, Kang X, Yang Q, Lin Y and Fang M. Review on the development of genotyping methods for assessing farm animal diversity. *Journal of Animal Science and Biotechnology*. 2013; 4(1): 1–6. <https://doi.org/10.1186/2049-1891-4-2>
80. Yaqub M, Mahmood T, Akhtar M, Iqbal M and Ali S. Induction of Pulse crop [*Vigna radiata* (L.) Wilczek] as a grain legume in the annual rice-wheat double cropping system. *Pakistan Journal of Botany*. 2010; 42(5): 3125–3135. <https://doi.org/10.1016/j.fcr.2009.03.013>
81. Zhang Y, Restall J, Crisp P, Godwin I and Liu G. Current status and prospects of plant genome editing in Australia. *In Vitro Cellular and Developmental Biology-Plant*. 2021; 57(4): 574–583. <https://doi.org/10.1007/s11627-021-10188-y>