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**Review Paper**

# Transforming lentil drought tolerance through physio-biochemical and molecular innovations

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## ABSTRACT

**Drought stress is a significant constraint to lentil production, particularly in arid and semi-arid regions. To develop resilient cultivars, it is essential to understand the mechanisms underlying drought tolerance. Recent advances in morpho-physio-biochemical and molecular studies have provided valuable insights into lentil drought tolerance. Key traits and responses, including deep rooting, stomatal regulation, osmotic adjustment and antioxidant enzyme activation, have been identified. Further, molecular biology advances led to availability of the lentil genome, transcriptomes and proteome resulting an identification of drought-responsive genes, transcription factors and signaling pathways. Integrating these findings into breeding programs offers a promising shift towards molecular assisted and precision breeding strategies, enhancing the development of drought-tolerant lentil cultivars.**

***Key words***: Artificial Intelligence, Ionomics, Drought tolerance, Lentil, Nanobionics and QTL.

## INTRODUCTION

Lentil (*Lens culinaris* Medik.), is a vital crop legume renowned for its exceptional nutritional value. It is cultivated globally, with key production regions including Australia, Western Asia, the Middle East, Africa, Southern Europe, Americas and the Indian subcontinent. Lentils offer numerous benefits due to a rich source of vitamins, antioxidants, dietary fiber and protein (a nutritional powerhouse) and its contribution to soil health by fixing atmospheric nitrogen (Kumar *et al*. 2016, Priya *et al*. 2021). Notably, they are an excellent plant-based source of protein, containing approximately 22.7% protein by content, including all essential amino acids (Atudorei *et al*. 2022). In addition to high protein content, lentils are rich in dietary fiber (approximately 13.8%), complex carbohydrates, bioactive compounds, such as polyphenols, antioxidants, essential micronutrients composition per 100 grams including iron (6.5-7.7 mg), zinc (3.3-5.9 mg), folate (479-555 µg), potassium (677-943 mg), magnesium (47-69 mg), etc. and extremely low fat content (< 1%). These nutrients make lentils a valuable part of a balanced diet, aiding in chronic disease prevention and supporting a healthy pregnancy (Kaale *et al*. 2022; Warne *et al*. 2019; Choukri *et al*. 2022, Liberal *et al*. 2023). Lentils are indeed a vital crop in India, and their importance extends beyond the country's borders. Globally, lentil production stands at approximately 7.068 million tons, spread across 5.676 million hectares, with an average productivity of 1245.4 kg per hectare (FAOSTAT 2023). In India, lentil cultivation spans about 1.224 million hectares, which produces around 1.75 million metric tons, i.e., a productivity of about 1023 kg per hectare (Figure 1) (AICRP. 2024).

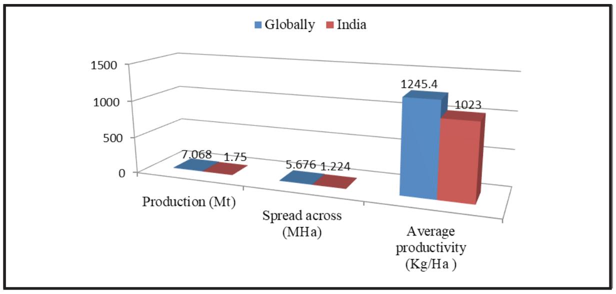

**Fig. 1.** Production, spread across and average productivity

Madhya Pradesh (8.24 lakh tones), Uttar Pradesh (5.77 lakh tones), West Bengal (1.44 lakh tones), Bihar (1.14 lakh tones) and Jharkhand (0.53 lakh tones) are top lentil producing states in India (https://upag.gov.in/). Lentil is a rainfed crop and hence its vulnerability to climatic fluctuations significantly impacts yields. Consequently, the average productivity of lentils lags behind the global average. To bridge this gap, it is essential to focus on enhancing lentil productivity through better agricultural practices and genetic improvements in lentil breeding, ultimately raising the potential yield (Murugananthi *et al*. 2024, Kesari 2024). Recent research underscores the importance of combining cutting-edge breeding techniques with sustainable agricultural practices to boost lentil production and productivity in the region (Kumar *et al*. 2023).

Environmental factors and processing methods significantly impact the nutritional composition of lentils. For example, temperature fluctuations during the pod filling period substantially influence the levels of different micronutrients including iron, zinc and phytic acid in lentil seeds. This highlights the importance of optimal environmental conditions and processing techniques to preserve the nutritional value of lentils (Thavarajah *et al*. 2010). Among abiotic stresses, drought condition is an important abiotic stress that significantly impairs lentil growth and yield. Hence it, underscores the need for comprehensive research on tolerance mechanisms in lentils especially unraveling the complex interplay between morpho-physiological, biochemical and molecular traits in conferring drought tolerance in lentil. This knowledge will facilitate in developing resilient lentil varieties, enabling farmers to overcome drought stress challenges to achieve sustainable and climate-resilient lentil production. Recent studies have emphasized the significance of understanding the mechanisms of drought tolerance in lentils to inform breeding programs aimed at developing more resilient cultivars. Several comprehensive reviews have elaborated on the different mechanisms employed by lentil plants to withstand drought stress through complex interplay of morpho-physiological, biochemical, and molecular adaptations (Noor *et al*. 2024). Drought stress has a profound impact on the morphological characteristics of lentil plants, particularly affecting rooting patterns (altered root architecture in response to water scarcity) and shoot branching patterns (modified shoot development to conserve water and nutrients). Phenotypic plasticity enables certain lentil populations to exhibit drought tolerance traits, even when grown in non-arid environments. This suggests that drought tolerance is not an exclusive characteristic of plants originating from arid regions, but rather a complex trait that can be expressed in diverse environments (Teso *et al*. 2022). Furthermore, it also impairs key physiological processes in lentils, including reduced germination rates, decreased photosynthetic activity and lower biomass production. These cumulative effects ultimately lead to lower lentil yield, emphasizing the need for drought-tolerant varieties and effective crop management strategies (Zeroual *et al*. 2022). Root growth is a crucial adaptation that enhances plants ability in extracting water from deeper soil profiles, thereby improving its drought stress tolerance. Notably, the evaluation of lentil genotypes for drought tolerance has successfully identified resilient genotypes based on their root characteristics, which are essential for withstanding drought stress. This approach holds great promise for breeding programs aimed at developing drought-tolerant lentil varieties (Priya *et al*. 2021 and Idrissi *et al*. 2016). Remarkably, drought stress has shown to decrease chlorophyll content and relative water content (RWC). These reductions compromise effective photosynthetic processes, ultimately affecting lentil growth and productivity (Singh *et al*. 2017). Maintaining the higher RWC and chlorophyll levels in drought tolerant genotypes compared to susceptible ones is crucial for sustaining photosynthetic activity during periods of water deficit leading to enhanced drought tolerance and resilience (Dash *et al*. 2020, Sehgal *et al*. 2017). To counteract the negative consequences of drought stress on lentil plants, a strategic approach involve enhancing the activity of antioxidant enzymes and water content in lentil plants (Biju *et al*. 2021). Moreover, drought stress, when combined with other abiotic stress factors such as heat, can have synergistic effects on lentil plants, further altering their physiological responses. This emphasizes the importance of adopting an integrated and holistic framework to understand plant resistance, one that considers the complex interactions between multiple stress factors and the plants response mechanisms (Sehgal *et al*. 2017).

Therefore aim of this review is to enhance our knowledge for developing drought tolerance in lentil through a holistic approach integrating morphological, physiological, biochemical and molecular aspects. Thus a hybrid breeding approach, combining both traditional and modern biotechnological tools can be designed for developing climate-resilient lentil varieties under changing environmental conditions.

## MORPHOLOGICAL ADAPTATION OF LENTIL FOR DROUGHT STRESS TOLERANCE

Morphological adaptations play a crucial role in enhancing drought tolerance in lentils, enabling them to maintain productivity under water-limited conditions. One primary morphological adaptation observed in lentils under drought stress is the development of an extensive root system. Research has shown that certain lentil genotypes exhibit increased total root length and diameter, enhancing their ability to access deeper soil moisture during drought stress (Gorim and Vandenberg 2018b). The identification of quantitative trait loci (QTLs) linked to root traits has provided insights into the genetic basis of drought tolerance (Idrissi *et al*. 2016). In addition to root adaptations, the timing of flowering and maturity is another significant morphological trait contributing to tolerance to limited water conditions in lentils. Early maturity permits lentils to escape severe drought conditions before terminal drought stress occurs (EL-Haddad *et al*. 2020). Physiological responses complement these morphological adaptations. For instance, silicon application improves water relations and chlorophyll content in lentils under drought stress, enhancing photosynthetic efficiency and biomass accumulation (Biju *et al*. 2021). Osmopriming treatments increase calcium accumulation in lentils, crucial for initiating stress-related responses and improving drought tolerance (Farooq *et al*. 2019).

## PHYSIOLOGICAL AND BIOCHEMICAL ADAPTATION OF LENTIL FOR DROUGHT STRESS TOLERANCE

Lentils exhibit a range of physio-biochemical changes for tolerating to drought stress, which is a critical factor for maintaining productivity in arid and semi-arid regions. These adaptations include the regulation of osmotic potential, antioxidant enzyme activity and the synthesis of protective compounds, all of which contribute to the plant's ability to cope with water deficit conditions.

### *Osmotic adjustment and antioxidant defense*

The accumulation of osmoprotectants, such as proline is one of the primary physiological responses to drought stress in lentils. Proline works as an osmotic stabilizer, helping to maintain cell turgor and protect cellular structures during dehydration. Studies have shown that drought tolerant lentil genotypes exhibit significantly higher proline levels compared to sensitive ones, indicating a robust osmotic adjustment mechanism (Talukdar 2013, Morgil *et al*. 2017). The synthesis of proline is often linked to the activity of specific enzymes like P5CS (Δ1- pyrroline-5-carboxylate synthetase) and P5CR (Δ1-pyrroline-5-carboxylate reductase), which are up-regulated under drought stress conditions (Jiang *et al*. 2010). This biochemical pathway is crucial for enhancing drought resilience, as proline accumulation helps mitigate the damaging effects of osmotic stress on cellular functions. Antioxidant defense mechanisms also play an important role in the adaptation of physiological responses in lentils under water deficit conditions. The function of different antioxidant enzyme functions such as superoxide dismutase (SOD), catalase and peroxidase, increases in response to oxidative stress induced by drought stress (Biju *et al*. 2021). These enzymes facilitate the elimination of reactive oxygen species (ROS) that accumulate under water deficit stress, safeguarding the plant against oxidative damage. For instance, lentil genotypes that exhibit higher SOD activity have been correlated with improved drought tolerance, as they can better manage oxidative stress (Sehgal *et al*. 2017). Furthermore, the application of silicon has been shown to enhance the antioxidant capacity of lentils, leading to improved drought tolerance by modulating nitro-oxidative homeostasis (Biju *et al*. 2021, Biju *et al*. 2023). The application of silicon (Si) has been shown to improve the antioxidant capacity of lentils, leading to reduced oxidative stress and enhanced biomass under drought stress conditions (Biju *et al*. 202, Biju *et al*. 2023). The modulation of nitro-oxidative homeostasis by Si contributes to the overall stress tolerance of lentils allowing them to maintain physiological functions even in unfavorable environmental conditions (Biju *et al*. 2021, Biju *et al*. 2023).

### *Relative water content and hormonal regulation*

Drought stress typically leads to a decrease in relative water content (RWC), which is a key indicator of plant water deficit. The drought-stress-tolerant varieties of lentil maintain higher RWC under water deficit conditions, which correlates with better performance in terms of growth and yield (Idrissi *et al*. 2016). The ability to sustain RWC is often associated with efficient stomatal regulation, allowing the plant to minimize water loss while maximizing photosynthetic activity (Singh *et al*. 2017). Additionally, the accumulation of soluble sugars during drought stress serves as an osmotic agent and a carbon source, further supporting plant metabolism under unfavorable conditions (EL-Haddad *et al*. 2023a). The expression of genes involved in stress response pathways such as abscisic acid (ABA) signaling is upregulated in drought-stressed plants (Singh *et al*. 2017). ABA is a key hormone involved in stomatal closure regulation resulting in reducing transpiration and conserving water during periods of drought stress. This hormonal regulation is essential for maintaining physiological balance and optimizing resource use under stress conditions (Singh *et al*. 2017). The overproduction of reactive oxygen species (ROS) under water deficit conditions often leads to oxidative damage to cellular components. In response, lentil plants activate their antioxidant defense systems by producing enzymes such as superoxide dismutase (SOD), catalase and peroxidase (EL-Haddad *et al*. 2023b). For instance, the activities of SOD and catalase were found to be up-regulated in lentil plants subjected to drought, effectively converting harmful superoxide radicals into less harmful molecules (Biju *et al*. 2021). The physiological adaptations of lentils to drought stress encompass a multifaceted approach involving osmotic adjustment, antioxidant defense, water relations management and hormonal regulation. These mechanisms collectively enhance the plants resilience to water deficit, making lentil a valuable crop in regions prone to drought.

### *Regulation of metabolic pathways*

The regulation of metabolic pathways related to photosynthesis and respiration is crucial for drought stress adaptation. Drought stress often decreases the activity of key enzymes involved in photosynthesis, such as ribulose-1, 5-bisphosphate carboxylase/oxygenase (RuBisCO). Nevertheless, tolerant lentil genotypes have been observed to maintain higher RuBisCO activity under water deficit conditions, which is essential for sustaining photosynthetic efficiency and overall plant growth (Sehgal *et al*. 2017, Singh *et al*. 2017). This ability to regulate photosynthetic enzyme activity is vital for optimizing carbon fixation and energy production during periods of water scarcity. The biochemical adaptations of lentils to drought stress involve a multifaceted approach, encompassing enhanced antioxidant enzyme activity, accumulation of osmoprotectants and regulation of metabolic pathways. These mechanisms synergistically contribute to the plant's resilience against drought stress, underscoring the critical role of biochemical processes in lentil's overall drought stress tolerance.

## MOLECULAR INSIGHTS BEHIND ADAPTATION OF LENTIL UNDER DROUGHT STRESS

Molecular studies have identified a number of QTLs/genes for drought related traits in lentil which are presented in Table 1 and discussed below.

### *Adaptation of lentil to drought stress*

It is a complex trait controlled by many genes/QTLs. The application of genomics and transcriptomics in lentil research has led to the identification of QTLs and candidate genes associated with drought tolerance. (Tiwari *et al*. 2022) emphasized that there is a need to integrate high-throughput omics technologies to enhance genetic gains in lentil breeding, especially for traits related to abiotic stress tolerance. This approach can facilitate the development of molecular markers for MAS in breeding programs. Thus insight into the molecular mechanisms of drought tolerance is indispensable for creating lentil varieties that can thrive in environments with limited water availability.

### *Identification of QTLs*

Several QTLs have been identified that control drought tolerance in lentil. (Idrissi *et al*. 2016) reported QTL linked to root and shoot traits. These traits have been identified to be associated with the drought tolerance. They identified RWC as significant criteria for selection of drought resistance cultivars. Similarly, (Priya *et al*. 2021) described the identification of QTL for seedling survival traits under drought stress, reinforcing their role in drought adaptation. This includes the identification of QTLs in other legumes, such as chickpea, that could potentially help in lentil breeding due to advanced mapping techniques (Kushwah *et al*. 2022).

## IDENTIFICATION OF GENES FOR DROUGHT TOLERANCE THROUGH TRANSCRIPTOMIC ANALYSIS

Molecular analysis reveals that the abscisic acid (ABA) signaling pathway is pivotal in orchestrating lentil's response to drought. The up-regulation of genes involved in ABA biosynthesis, such as the 9-cis-epoxycarotenoid dioxygenase gene, has been observed in drought tolerant genotypes. This increase in ABA levels leads to the activation of stress-responsive genes and the closure of stomata, which reduces transpiration and conserves water (Singh *et al*. 2017, Morgil *et al*. 2017). Transcriptomic studies have revealed that drought stress triggers the activation of various metabolic pathways, including antioxidant defense and stress response mechanisms, emphasizing the significance of gene expression regulation in lentil's adaptation to drought (Morgil *et al*. 2019, Foti *et al*. 2021). Molecular studies have identified quantitative trait loci (QTLs) associated with drought resistance traits, such as root system architecture and shoot characteristics, which are essential for water uptake and utilization. The identification of these genetic markers facilitates the selection of superior genotypes for breeding purposes, enabling the development of cultivars that can better tolerate water deficit conditions (Idrissi *et al*. 2016, Kumar *et al*. 2021).

## CUTTING-EDGE APPROACH FOR IMPROVING DROUGHT TOLERANCE

In recent years some new approaches have been emerged for studying the drought tolerance in lentil. These have been discussed below for improving drought tolerant in lentil and presented in Fig 2.

### *Ionomics approaches in drought stress tolerance*

Ionomics, the study of the elemental composition of organisms, plays a significant role in understanding drought stress tolerance in lentil. Drought stress can lead to alterations in ion homeostasis, which is crucial for maintaining physiological functions in plants. Ionomics, which studies the elemental composition of organisms, is crucial for understanding drought stress tolerance in lentils (Fatiha *et al*. 2019, Priya *et al*. 2021). For example, calcium (Ca), which acts as a secondary messenger in various stress responses, is one of the primary ionomics elements. Studies have shown that increased calcium accumulation in lentil plants under drought conditions can enhance stress tolerance by initiating several physiological responses. (Farooq *et al*. 2019) demonstrated that increasing calcium levels through osmopriming enhances drought tolerance in lentils. This study also showed that drought tolerance in lentil can be improved by increasing calcium levels though the application of osmopriming (Farooq *et al*. 2019). In addition to calcium, other essential elements such as potassium (K) and sodium (Na) also play critical roles in drought stress responses. Potassium is known to regulate osmotic potential and maintain turgor pressure, which is essential for plant hydration during periods of water deficit. Conversely, excessive sodium can be detrimental, leading to ion toxicity and disrupting cellular functions. Research indicates that drought tolerant

**Table 1.** Genes/QTLs identified for different traits related to drought in lentil

| Trait Name | No. of QTL/gene | Name of QTL/gene | Reference |
|---|---|---|---|
| Lateral Root Number | 4 | $\text{QLRN}_{\text{III-98.64}}$ | Idrissi *et al*. (2016) |
| Specific Root Length | 3 | $\text{QSRL}_{\text{IV-61.63}}$ | |
| SPAD | 2 | $\text{QSPAD}_{\text{VIII-72.15}}$ | |
| Dry shoot weight | 2 | $\text{QDSW}_{\text{VII-22.94}}$ | |
| Root Shoot ratio | 2 | $\text{QRSratio}_{\text{IX-2.30}}$ | |
| Shoot length | 5 | QSL12IV-102.83, QSL12VI-170.87, QSL12VII-20.75, QSL22VII-21.75 | |
| Seedling survival drought tolerance | 1 | Sdt | Singh *et al*. (2016) |
| Chlorophyll | 2 | qChl01, qChl02 | Rana (2016) |
| Relative Water content | 2 | qRWC01, qRWC02 | |
| Shoot Length (Early plant vigor) | 1 | qSL01 | |
| Root Length (Early Plant vigor) | 1 | qRL01 | |
| Drought tolerance | 11435 upregulated and 6934 downregulated DEG | - | Singh *et al*. (2017) |
| Phenological traits | 8 | qDTT.6, qVEG.6-1, qVEG.6-2, qDTF.6-1, qDTF.6-2, qREP.5, qDTM.5 and qDTS.5 and FLOWERING LOCUS T (FT) genes | Haile *et al*. (2021) |
| Days to flowering | 2 | DTF6a | Rajandran *et al*. (2022) |
| Drought and Silicon supplementation | 7164 and 5576 | - | Biju *et al*. (2023) |
| Early Maturity | 3 | LcqDTF3.2 | Shivaprasad *et al*.(2024) |

lentil genotypes exhibit better K/Na ratios, which is crucial for maintaining ion balance and overall plant health under stress conditions (Priya *et al.* 2021). Moreover, the role of silicon (Si) in enhancing drought tolerance through ionomic mechanisms has gained attention. Silicon supplementation has been shown to improve the antioxidant capacity of lentil plants, thereby mitigating oxidative stress caused by drought (Biju *et al*. 2021). The presence of silicon can also enhance the uptake of other beneficial elements, contributing to improved physiological performance under drought conditions (Biju *et al.* 2021, Biju *et al.* 2023). This highlights the potential of integrating silicon into agronomic practices to improve drought resilience in lentil crops. Furthermore, the genetic diversity among lentil genotypes influences their ionomic responses to drought stress. Studies have identified significant variations in ion uptake and distribution among different cultivars, which can be linked to their respective drought tolerance levels (Roy *et al*. 2019). Understanding these genetic differences can aid in the selection and breeding of lentil varieties that are better equipped to handle drought conditions, thereby enhancing food security in regions prone to water scarcity (Roy *et al*. 2019). The ionomics provides valuable insights into the elemental dynamics of lentil plants under drought stress. By focusing on key elements such as calcium, potassium, and silicon, researchers can better understand the physiological mechanisms that confer drought tolerance. This knowledge can inform breeding strategies aimed at developing resilient lentil varieties capable of thriving in increasingly arid environments.

### *Nanobionics approaches for drought stress tolerance*

Nanobionics represents a cutting-edge approach in enhancing drought stress tolerance in lentil by integrating nanotechnology with biological systems. This innovative strategy leverages nanomaterials to improve plant resilience against abiotic stresses, particularly drought, by enhancing nutrient uptake, improving water retention and modulating physiological responses (Faizan *et al.* 2023). One of the primary mechanisms through which nanobionics operates is the enhancement of nutrient availability and uptake. Nanoparticles, such as silica nanoparticles, have been shown to improve the bioavailability of essential nutrients, which can be critical during drought conditions when nutrient uptake is often compromised (Biju *et al*. 2021). For instance, the application of silicon nanoparticles has been reported to improve chlorophyll content and

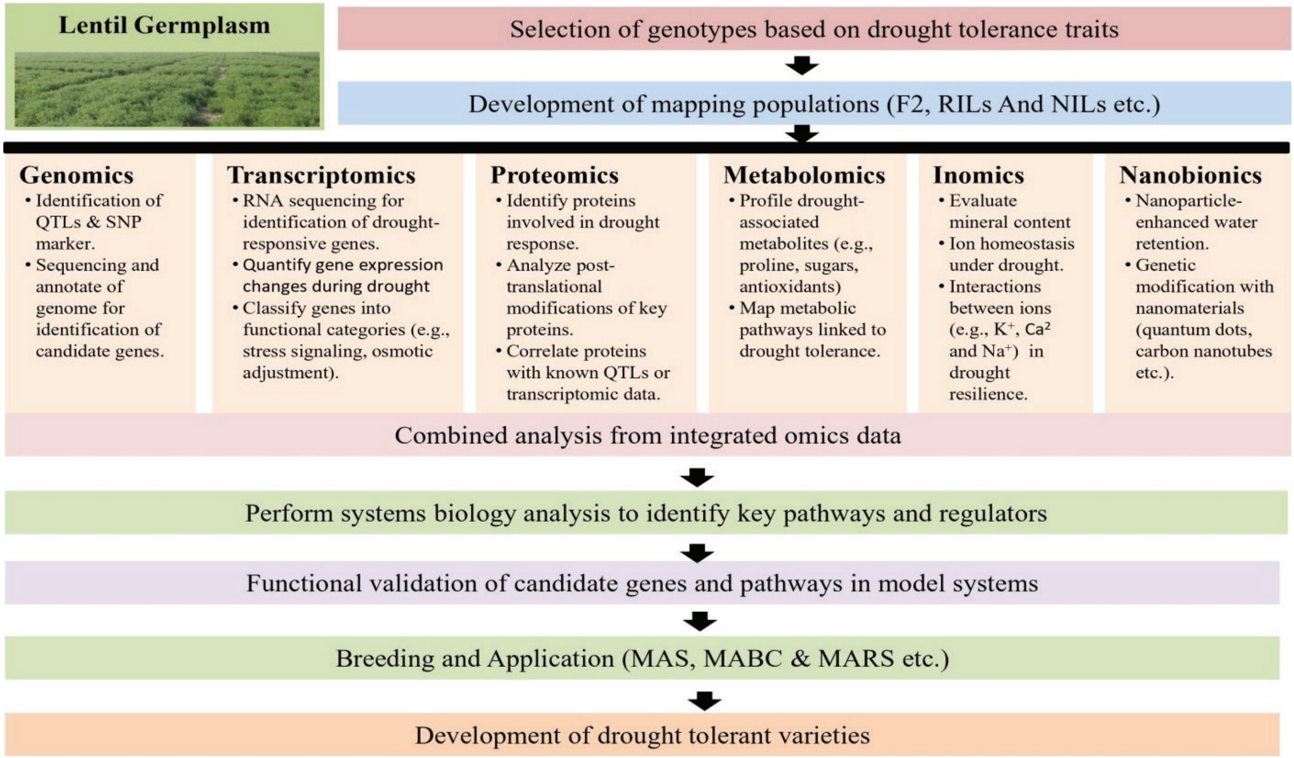

**Fig. 2.** Application of different omics approaches for developing drought tolerant cultivars in lentil

water relations in lentil plants under water deficit conditions, thereby facilitating better photosynthetic efficiency and growth (Biju *et al.* 2021, Biju *et al.* 2023). This is particularly important as chlorophyll content is directly linked to the plant's ability to perform photosynthesis effectively, which is often hindered during drought conditions (Biju *et al*. 2021). Moreover, nanobionics can modulate the physio-biochemical pathways involved in stress responses. For example, the application of nanomaterials has been associated with the upregulation of antioxidant enzymes, which make a critical contribution to mitigating the drought induced oxidative stress (EL-Haddad *et al.* 2023b). Enhanced activity of superoxide dismutase (SOD) and catalase has been observed in nanoparticles treated lentil genotypes. This indicates a strengthened defense mechanism against reactive oxygen species (ROS) generated during drought stress (EL-Haddad *et al*. 2023a). This antioxidant response is vital for maintaining cellular integrity and function, allowing plants to better withstand the adverse effects of drought. Additionally, nanobionics can influence the osmotic adjustment mechanisms in plants. The application of nanomaterials has been shown to enhance the accumulation of osmolytes such as proline, which helps in maintaining cell turgor and stabilizing proteins under drought conditions (Yasmeen *et al.* 2022). Accumulation of proline is a well-known response in drought-tolerant lentil varieties. Nanobionic interventions enhance the synthesis of proline leading to a significant improvement for drought resilience (Yasmeen *et al*. 2022). Furthermore, the use of nanobionics can also facilitate better root development, which is crucial for water and nutrient uptake during drought periods. Several studies demonstrated that use of nanoparticles promotes root growth and increases root surface area. Consequently, ability of plants is enhanced to access water and nutrients from the deeper soil profiles (Gorim, Vandenberg 2018b). This is particularly beneficial in drought prone areas where water availability is limited, as deeper and more extensive root systems can help plants tap into moisture reserves that are otherwise inaccessible.

Nanoparticles have been of particular interest in plant agriculture because they can augment different physiological and biochemical factors in plants, especially as related to nutrient transport, enzymatic processes and gene expression under stress conditions like drought. Modulation of oxidative stress and antioxidant enzyme activity is one of the main mechanisms by which nanoparticles interact with plant cells. Studies have shown that nanoparticle exposure can increase antioxidant enzyme activities, including catalase and peroxidase, in different plant species, e.g., wheat and tomatoes (Manaf *et al*. 2021, Ma *et al.* 2022). Such an increase may help the plant better tolerate oxidative stress, which in turn can increase overall growth and physiological performance under drought stress (Safiyakhanim and Ibragim, 2022). Moreover, the physical characteristics of nanoparticles, including size, charge and surface chemistry, also have a vital influence on their uptake and localization in plant cells. Studies using plant protoplasts cells lacking cell walls revealed that nanoparticles were able to cross the plasma membrane directly, gaining insights into how they interact with plant lipid bilayers (Lew *et al*. 2018). The capacity of nanoparticles to transport through cell walls makes them capable of delivering crucial nutrients or signaling compounds that can foster stress tolerance and enhance nutrient transport processes in the plant (Hu *et al*. 2020). In addition, research has indicated that nanoparticles allow ion transport in plant cells through chemical interaction with cellulose and pectins, which can potentially increase nutrient uptake under stressful conditions (Jeon *et al*. 2023). The biochemical and structural changes caused by nanoparticles also reach as far as gene expression involved in stress tolerance. For example, gold nanoparticles have been reported to alter the expression of microRNAs that control many physiological processes in plants, which results in enhanced growth and adaptation potential under stress (Siddiqi, Husen. 2016). Also, the use of nanoparticles has been reported to affect secondary metabolism by inducing a ROS burst, which can activate numerous signaling pathways that result in increased drought tolerance, as observed in a number of crop plants (Marslin *et al*. 2017). Further, the use of nanoparticles has been reported to enhance plant hormone levels, which are essential for managing responses to abiotic stress. Particularly, nanoparticles are able to stimulate the biosynthesis of phytohormones such as auxins and gibberellins, which play a crucial role in sustaining growth and developmental activities even during drought (Safiyakhanim and Ibragim 2022). The interaction between nanoparticles and plant cells is realized in a number of positive manners, especially through increased enzymatic activity essential for stress tolerance, optimized nutrient transport processes, and modulation of gene expression associated with drought resistance. Due to the intricate interactions and multi-dimensional effects of nanoparticles on plant physiology, their application in agriculture could be a promising strategy for enhancing crop productivity in adverse environmental conditions.

The use of nanoparticles in agriculture has generated critical issues about their soil accumulation, toxicity to non-target species, and related regulatory issues. When it comes to cultivating crops like lentil, these aspects play a crucial role in maintaining sustainable agricultural practices. Accumulation of nanoparticles in soil can be caused by several agricultural operations, such as the use of nanoparticle-fertilizers and pesticides. Literature has indicated that the addition of nanoparticles can immensely increase metal content in soil. For example, (Peshkova *et al*. 2024) indicated that gold nanoparticles (AuNPs) can become accumulated in soil at levels ranging from 4 to 13 times the control level after being applied through a foliar approach. This deposition causes environmental concerns, especially the long-term effects on soil fertility and microbial populations. Another important aspect is the nanoparticle toxicity against non-targeted organisms. According to (Oca-Vasquez *et al.* 2020), silver nanoparticles (AgNPs) reduce soil microbial biomass without affecting general enzyme activities or microbial diversity, reflecting selective pressure on soil fauna. In addition, (Chavan and Vigneshwaran 2019) determined that long-term exposure to silver nanoparticles has been associated with changes in soil microbial communities and enzyme activities that are crucial for nutrient cycling and soil fertility. The growth inhibitory actions of silver nanoparticles on plant growth-promoting bacteria have the potential to undermine the ecosystem services of these microbes, including the fixing of nitrogen and the decomposition of organic matter (Chavan and Vigneshwaran, 2019), thus indirectly affecting lentil growth. Further-more, the physicochemical alterations nanoparticles experience when exposed to the soil environment make it challenging to determine their probable toxicity. (Galhardi *et al*. 2022) noted that since nanoparticles interact with organic matter and microbes in soil, they become able to develop biocoronas, changing their mobility, bioavailability, and toxicity. This alteration affects the capacity of scientists and policymakers to accurately anticipate the long-term environmental effects of nanoparticles. Regulatory issues related to the application of nanoparticles in agriculture are largely due to the unavailability of detailed data and regulatory guidelines to evaluate their safety. (Mahesha *et al*. 2023), (Kumari *et al*. 2023) stressed that existing regulatory mechanisms tend to be inadequate to cover the peculiar behavior and threats of nanomaterials as opposed to traditional agrochemicals.

There is a consensus evolving that intense investigation of nanoparticle toxicity, accumulation, and ecological effects must precede extensive commercialization. More importantly, the cumulative effects of nanoparticles, especially with higher rates of application in the soil, require thorough studies to define safe thresholds for use. Although nanoparticles have high potential for augmenting agricultural output, their buildup in soil, toxicity to off-target organisms, and the challenges of regulation need to be very carefully examined. Increased focus on research to provide insight into long-term effects of nanoparticles is a must for constructing effective regulatory approaches that reconcile innovation with environmental conservation.

### *Exploitation of drought tolerance related genes*

The exploitation of drought tolerance related genes in pulses is, therefore, a critical strategy because the challenges of climate change and water scarcity have become major bottlenecks in addressing crop improvement. Advances in genomics and biotechnology enabled identification and characterization of key genes associated with drought stress tolerance, making it possible to produce resilient pulse varieties. For instance, Liu (2024) points to the need to identify drought tolerant cultivars using genome wide association studies that can identify candidate genes needed to enhance crop resistance against drought stress in crops such as rice. Further, (Krannich *et al*. 2015) underscored the need to source natural genetic variation in such candidate genes to develop drought stress tolerant crops, which apparently involves the use of the Drought database in breeding programs. It also indicates a potential application in transgenic approaches that could help advance drought tolerance in different species. For instance, the over expression of the Arabidopsis vacuolar $H^+$-pyro-phosphatase gene, *AVP1,* has resulted in higher drought and salt tolerance when expressed in cotton. This then marks a potential avenue where model organisms may be used for crop improvement purposes (Pasapula *et al*. 2010). This apart, there is several transcription factors discovered in soybean that can be overexpressed in transgenic plants for drought stress tolerance and therefore, highlight the genetic engineering techniques involved in the creation of drought resistant crops (Ma *et al*. 2020). Meta-analyses of transcriptomic data have also indicated drought stress tolerance related genes that are conserved in different species and therefore provide indications about the genetics underlying drought resistance (Buti *et al*. 2019, Baldoni *et al*. 2021). This area, therefore, opens the possibility of combination of genomic data with traditional breeding methods for augmentation of drought resilience in pulses. More advanced genomics techniques like QTL mapping and marker assisted selection, once aligned with new biotechnological innovations, would become more critical in the future for the development of drought tolerant pulse varieties (Shil 2024). The exploitation of drought stress tolerance related genes through modern biotechnological approaches offers a promising possibility for improving crop resilience in pulses. By leveraging genetic insights and innovative breeding techniques, the agricultural sector can better equip itself to face the challenges of a changing climate.

### *Genome editing of drought tolerance*

Wild lentil species evolved in the environments having limited water availability. They possess adaptive traits that enable them to survive under drought conditions and hence they have been identified a genetic reservoir of valuable genes controlling drought resilience and water use efficiency (Gorim and Vandenberg 2018a, Gorim and Vandenberg 2017). For example, the galactinol synthase gene has been identified as a key regulator of drought responses in lentils. This discovery highlights the potential for genetic engineering and manipulation to enhance drought tolerance traits, offering a promising avenue for improving lentil crop resilience to water scarcity (Singh *et al*. 2017). Further many genes identified for drought tolerance in lentil can be used in gene editing for identification of desirable alleles, which are not available cultivated species. CRISPR-Cas technology helps development of elite cultivars with desirable alleles by precision gene editing as this technology successfully carried out to create mutant alleles of drought tolerance gene in other crops like rice (Santosh Kumar *et al*. 2020).

## ARTIFICIAL INTELLIGENCE (AI) IN ENHANCING DROUGHT STRESS TOLERANCE

Artificial Intelligence (AI) has emerging area for improving drought tolerance in lentil as it significantly enhances drought stress tolerance in pulses by enabling precision agriculture through data-driven insights. AI applications, such as machine learning algorithms, facilitate the identification of drought resistant traits in pulse crops, allowing for targeted breeding and genetic modifications (Victoire 2023, Na and Na 2024). By analyzing vast datasets, AI can predict crop responses to varying water availability, optimizing irrigation practices and resource allocation (Witte *et al*. 2023, Ennouri *et al*. 2021). Furthermore, AI technologies which include remote sensing and smart sensors monitor the level of moisture in soil and plant health in real time. This helps farmers with actionable insights to mitigate drought impacts (Elbaşi *et al*. 2023, Soussi *et al*. 2024). This integration of AI not only improves crop resilience but also contributes to sustainable agricultural practices. In a broader context, the role of AI in agriculture encompasses various applications aimed at improving efficiency and sustainability. These include automated pest detection, yield prediction, and resource management, which collectively enhance agricultural productivity (Das *et al*. 2024, Sahoo and Sharma 2023, Oliveira and Silva 2023). AI systems analyze environmental data, enabling farmers to make informed decisions that reduce waste and increase crop yields (Nitin and Gupta 2023, Qazi *et al*. 2022). The transformative potential of AI in agriculture is evident as it addresses challenges posed by climate change and food security, ultimately fostering a more resilient agricultural sector (Patil 2023, Subeesh and Mehta 2021).

## CONCLUSION AND FUTURE PROSPECTS

The lentil genome offers a rich area of research, which could possibly provide nutritional quality and resilience in lentil crops. Such inclusive nutrition profiles from lentils combined with ongoing genetic studies should place them atop solving the daunting challenges that face food security in today's world. Decoding the morpho-physio-biochemical and molecular mechanisms of drought tolerance in lentils has unraveled crucial insights into complex interactions involving plant structure and function with genetic influences. Implications of drought stress would always carry great uncertainty attached to explaining it since; after all, lentil is one of the most critical crops among legume crops exposed to such constraints in water-scarce regions. Indeed, integration among morphological, physiological, biochemical and molecular studies has identified key traits such as architectural root length, stomatal conductance, osmotic adjustment and antioxidant enzyme activity in drought tolerance. In addition, molecular biology, especially identification of drought-responsive genes together with their regulatory networks, has opened up avenues for developing drought-tolerant varieties of lentil. This work exemplifies a paradigm shift in the approach to building drought tolerance in lentil, using the results of more focused, trait-based, and molecular-assisted breeding approaches, replacing the traditional conventional breeding approaches. The future of drought tolerance research in lentils is still integrated with some of the most advanced technologies in genomic selection, CRISPR/Cas9 gene editing, transcriptomics, etc. Such tools will be employed for the precise manipulation of the genes controlling drought tolerance and accelerate the process of the generation of drought-tolerant cultivars. In addition, research on plant-microbe interaction, particularly related to the role of rhizosphere-associated microorganisms in enhancing the chances of drought tolerance, is a major approach to improving the productivity of lentils in water-scarce regions. The massive scale of water shortages due to climate change renders it essential to progress gradually in crop development that is resource conserving and efficient. This makes it a landmark moment for geneticists, plant physiologists, breeders and farmers to pool their efforts so that the production of lentil will not experience a downturn as environmental challenges continue to increase.

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## REFERENCES

AICRP. 2024. Project Coordinator's Report 2023-24. All India Coordinated Research Project on Rabi Pulses, ICAR-IIPR, Kanpur, India. Pp. 22-23.

Atudorei D, Mironeasa S and Codina G. 2022. Effects of germinated lentil flour on dough rheological behavior and bread quality. Foods **11**(19): 2982.

Baldoni E, Frugis G, Martinelli F, Benny J, Paffetti D and Buti M. 2021. A comparative transcriptomic meta-analysis revealed conserved key genes and regulatory networks involved in drought tolerance in cereal crops. International Journal of Molecular Sciences **22**(23): 13062.

Biju S, Fuentes S and Gupta D. 2021. Silicon modulates nitro-oxidative homeostasis along with the antioxidant metabolism to promote drought stress tolerance in lentil plants. Physiologia Plantarum **172**(2): 1382-1398.

Biju S, Fuentes S and Gupta D. 2023. Novel insights into the mechanism (s) of silicon-induced drought stress tolerance in lentil plants revealed by RNA sequencing analysis. BMC Plant Biology **23**(1): 498.

Buti M, Baldoni E, Formentin E, Milc J, Frugis G, Schiavo F and Francia E. 2019. A meta-analysis of comparative transcriptomic data reveals a set of key genes involved in the tolerance to abiotic stresses in rice. International Journal of Molecular Sciences **20**(22): 5662.

Chavan S and Vigneshwaran N. 2019. Effects of nanoparticles on plant growth-promoting bacteria in indian agricultural soil. Agronomy **9**(3): 140.

Choukri H, Haddad N, Aloui K, Hejjaoui K, El-Baouchi A, Smouni A, Thavarajah D, Maalouf F and Kumar S. 2022. Effect of high temperature stress during the reproductive stage on grain yield and nutritional quality of lentil (*Lens culinaris* medikus). Frontiers in Nutrition **9**: 857469.

Das S, Kaur M, Chhabra V, Nandi T, Mishra P and Ghosh S. 2024. A Systematic Review of Artificial Intelligence: A Future Guide to Sustainable Agriculture. International Journal of Environment and Climate Change **14**(4): 562-573.

Dash AP, De DK, Nath R, Sarkar A, Mohanty S and Bhattacharyya PK. 2020. Effects of drought stress on relative water, chlorophyll and proline content in tolerant and susceptible genotypes of lentil (*Lens culinaris* Medik.). 192-198.

Elbasi E, Mostafa N, Alarnaout Z, Zreikat AI, Cina E, Varghese G and Zaki C. 2023. Artificial Intelligence Technology in the Agricultural Sector: A Systematic. a systematic literature review. Ieee Access **11**: 171-202.

El-Haddad N, En-Nahli Y, Choukri H, Aloui K, Mentag R, El-Baouchi A, Hejjaoui K and Kumar S. 2023a. Metabolic Mechanisms Underlying Heat and Drought Tolerance in Lentil Accessions: Implications for Stress Tolerance Breeding. Plants **12**(23): 3962.

El-Haddad N, En-Nahli Y, Choukri H, Aloui K, Mentag R, El-Baouchi A, Kamal H and Kumar S. 2023b. Enzymatic and biochemical responses to high temperatures and drought stress during the reproductive stage in lentil (*Lens Culinaris* Medik.). Research Square; 2023. DOI: 10.21203/rs.3.rs-2388925/v1.

El-Haddad N, Rajendran K, Smouni A, Es-Safi NE, Benbrahim N, Mentag R, Nayyar H, Maalouf F and Kumar S. 2020. Screening the FIGS set of lentil (*Lens culinaris* Medikus) germplasm for tolerance to terminal heat and combined drought-heat stress. Agronomy **10**(7): 1036.

Ennouri K, Smaoui S, Gharbi Y, Cheffi M, Braiek O, Ennouri M and Triki M. 2021. Usage of artificial intelligence and remote sensing as efficient devices to increase agricultural system yields. Journal of Food Quality **2021**: 6242228.

Faizan M, Karabulut F, Alam P, Yusuf M, Tonny S, Adil M, Sehar S, Ahmed M and Hayat S. 2023. Nanobionics: a sustainable agricultural approach towards understanding plant response to heavy metals, drought, and salt stress. Nanomaterials **13**(6): 974.

FAOSTAT. 2023. Statistics data. Food and Agriculture Organization of the United Nations, Rome. http://www.fao.org/faostat/

Farooq M, Romdhane L, Sulti M, Rehman A, Al-Busaidi W and Lee D. 2019. Morphological, physiological and biochemical aspects of osmopriming-induced drought tolerance in lentil. Journal of Agronomy and Crop Science **206**(2): 176-186.

Fatiha T, Abdelkrim H, Kouadria M and Waffa R. 2019. Study of morpho-physiological and biochemical behavior of cultivated legume (*Lens culinaris* medik ssp *culinaris*) in dry area of algeria. Ukrainian Journal of Ecology **9**(4): 535-541.

Foti C, Kalampokis I and Pavli O. 2021. Metabolic responses of two contrasting lentil genotypes to peg-induced drought stress. Agronomy **11**(6): 1190.

Galhardi J, Oliveira J, Ghoshal S and Fraceto L. 2022. Soil enzyme responses to polymeric nanopesticides: an ecological risk analysis approach to promote sustainable agriculture. ACS Agricultural Science & Technology **2**(3): 443-452.

Gorim L and Vandenberg A. 2017. Evaluation of wild lentil species as genetic resources to improve drought tolerance in cultivated lentil. Frontiers in Plant Science **8**: 1129.

Gorim L and Vandenberg A. 2018a. Can wild lentil genotypes help improve water use and transpiration efficiency in cultivated lentil?. Plant Genetic Resources **16**(5): 459-468.

Gorim L and Vandenberg A. 2018b. Variation in total root length and root diameter of wild and cultivated lentil grown under drought and re-watered conditions. Plant Genetic Resources **17**(1): 45-53.

Haile TA, Stonehouse R, Weller JL and Bett KE. 2021. Genetic basis for lentil adaptation to summer cropping in northern temperate environments. The Plant Genome **14**(3): e20144.

Hu P, An J, Faulkner M, Wu H, Li Z, Tian X and Giraldo J. 2020. Nanoparticle charge and size control foliar delivery efficiency to plant cells and organelles. ACS Nano **14**(7): 7970-7986.

Idrissi O, Udupa SM, De Keyser E, McGee RJ, Coyne CJ, Saha GC and De Riek J. 2016. Identification of quantitative trait loci controlling root and shoot traits associated with drought tolerance in a lentil (*Lens culinaris* Medik.) recombinant inbred line population. Frontiers in Plant Science **7**: 1174.

Jeon S, Hu P, Kim K, Anastasia C, Kim H, Castillo C and Giraldo J. 2023. Electrostatics control nanoparticle interactions with model and native cell walls of plants and algae. Environmental Science and Technology **57**(48): 19663-19677.

Jiang Y, Watkins E, Liu S, Yu X and Luo N. 2010. Antioxidative responses and candidate gene expression in prairie junegrass under drought stress. Journal of the American Society for Horticultural Science **135**(4): 303-309.

Kaale L, Siddiq M and Hooper S. 2022. Lentil (*Lens culinaris* medik) as nutrient-rich and versatile food legume: a review. Legume Science **5**(2): e169.

Kesari R. 2024. Advancements in lentil genomics for enhanced crop breeding: a review. Journal of Experimental Agriculture International **46**(9): 1043-1060.

Krannich C, Maletzki L, Kurowsky C and Horn R. 2015. Network candidate genes in breeding for drought tolerant crops. International Journal of Molecular Sciences **16**(7): 16378-16400.

Kumar J, Gupta DS, Baum M, Varshney R and Kumar S. 2021. Genomics-assisted lentil breeding: current status and future strategies. Legume Science **3**(3): e71.

Kumar J, Gupta DS, Kumar S, Gupta S and Singh NP. 2016. Current knowledge on genetic biofortification in lentil. Journal of Agricultural and Food Chemistry **64**(33): 6383-6396.

Kumar N, Hashim M, Nath CP, Hazra KK and Singh AK. 2023. Pulses in conservation agriculture: An approach for sustainable crop production and soil health. Journal of Food Legumes **36**(1): 1-9.

Kumari R, Suman K, Karmakar S, Mishra V, Lakra S, Saurav G and Mahto B. 2023. Regulation and safety measures for nanotechnology-based agri-products. Frontiers in Genome Editing **5**: 1200987.

Kushwah A, Bhatia D, Barmukh R, Singh I, Singh G, Bindra S and Singh S. 2022. Genetic mapping of qtls for drought tolerance in chickpea (*Cicer arietinum* L.). Frontiers in Genetics **13**: 953898.

Lew T, Wong M, Kwak S, Sinclair R, Koman V and Strano M. 2018. Rational design principles for the transport and subcellular distribution of nanomaterials into plant protoplasts. Small **14**(44): 802086.

Liberal A, Almeida D, Fernandes A, Pereira C, Ferreira I, Quintana A and Barros L. 2023. Nutritional, chemical, and antioxidant screening of selected varieties of lentils (*Lens culinaris* spp.) from organic and conventional agriculture. Journal of the Science of Food and Agriculture **104**(1): 104-115.

Liu T. 2024. The identification of drought tolerance candidate genes in oryza sativa l. ssp. japonica seedlings through genome-wide association study and linkage mapping. Agriculture **14**(4): 603.

Ma J, Alshaya H, Okla M, Alwasel Y, Chen F, Adrees M and Shahid M. 2022. Application of cerium dioxide nanoparticles and chromium-resistant bacteria reduced chromium toxicity in sunflower plants.

Frontiers in Plant Science **13**: 876119.

Ma X, Yu T, Li X, Cao X, Ma J, Chen J and Xu Z. 2020. Overexpression of gmnfya5 confers drought tolerance to transgenic arabidopsis and soybean plants. BMC Plant Biology **20**(1): 1-18.

Mahesha K, Singh N, Amarshettiwar S, Singh G, Gulaiya S, Das H and Kumar J. 2023. Entering a new agricultural era through the impact of nano-fertilizers on crop development: a review. International Journal of Plant & Soil Science **35**(20): 94-102.

Manaf A, Wang X, Tariq F, Jhanzab H, Bibi Y, Sher A and Qayyum A. 2021. Antioxidant enzyme activities correlated with growth parameters of wheat sprayed with silver and gold nanoparticle suspensions. Agronomy **11**(8): 1494.

Marslin G, Sheeba C and Franklin G. 2017. Nanoparticles alter secondary metabolism in plants via ros burst. Frontiers in Plant Science **8**: 832

Morgil H, Gerçek Y, Caliskan M and Oz G. 2017. Investigation of the mechanism of physiological tolerance in lentil (*Lens culinaris* medik.) cultivars under drought stress conditions. European Journal of Biology **76**(1): 31-35.

Morgil H, Tardu M, Cevahir G and Kavaklı I. 2019. Comparative rna-seq analysis of the drought-sensitive lentil (*Lens culinaris*) root and leaf under short- and long-term water deficits. Functional & Integrative Genomics **19**(5): 715-727.

Murugananthi D, Shivakumar KM, Palanichamy NV, Prabha SA, Somasundaram E, Rohini A and Kavitha PG 2024. Demand and supply projections for pulses in India. Legume Research **47**(8): 1335-1341.

Na MH and Na IS. 2024. AI-powered predictive modelling of legume crop yields in a changing climate. Legume Research **47**(8): 1390-1395.

Nitin and Gupta SB. 2023. Artificial intelligence in smart agriculture: applications and challenges. Current Applied Science and Technology e0254427.

Noor MMA, Tahjib-Ul-Arif M, Alim SA, Islam MM, Hasan MT, Babar M A and Mostofa MG. 2024. Lentil adaptation to drought stress: response, tolerance, and breeding approaches. Frontiers in Plant Science **15**: 1403922.

Oca-Vasquez G, Solano-Campos F, Vega-Baudrit J, López-Mondéjar R, Odriozola I, Vera A and Bastida F. 2020. Environmentally relevant concentrations of silver nanoparticles diminish soil microbial biomass but do not alter enzyme activities or microbial diversity. Journal of Hazardous Materials 391: 122224.

Oliveira R and Silva R. 2023. Artificial intelligence in agriculture: benefits, challenges, and trends. Applied Sciences **13**(13): 7405.

Pasapula V, Shen G, Kuppu S, Paez-Valencia J, Mendoza M, Hou P and Payton P. 2010. Expression of an arabidopsis vacuolar h$^+$-pyrophosphatase gene (avp1) in cotton improves drought- and salt tolerance and increases fibre yield in the field conditions. Plant Biotechnology Journal **9**(1): 88-99.

Patil A. 2023. Use of artificial intelligence to hasten progress in plant genetics. Intelligence (AI) **1**: 3.

Peshkova A, Zinicovscaia I, Cepoi L, Rudi L, Chiriac T, Yushin N and Corcimaru S. 2024. Effects of gold nanoparticles on mentha spicata l., soil microbiota, and human health risks: impact of exposure routes. Nanomaterials **14**(11): 955.

Priya S, Bansal R, Kumar G, Dikshit H, Kumari J, Pandey R and Kumar A. 2021. Root trait variation in lentil (*Lens culinaris* medikus) germplasm under drought stress. Plants **10**(11): 2410.

Qazi S, Khawaja B and Farooq Q. 2022. Iot-equipped and ai-enabled next generation smart agriculture: a critical review, current challenges and future trends. Ieee Access **10**: 21219-21235.

Rajandran V, Ortega R, Vander Schoor JK, Butler JB, Freeman JS, Hecht V F and Weller JL. 2022. Genetic analysis of early phenology in lentil identifies distinct loci controlling component traits. Journal of Experimental Botany **73**(12): 3963-3977.

Rana M. 2016. Molecular mapping of quantitative trait loci for drought tolerance and yield traits in lentil. Doctoral Dissertation, CSKHPKV, Palampur, India. http://krishikosh.egranth.ac.in/handle/1/5810039712

Roy S, Roy D, Noor M, Ghosh S, Ahmed F and Sushmoy D. 2019. Binamasur-10, the first drought tolerant lentil variety registered in bangladesh. Research in Agriculture Livestock and Fisheries **6**(2): 253-262.

Safiyakhanim B and Ibragim A. 2022. Effect of nanoparticles on physiological and biochemical parameters of corn plants cultivated in the field conditions. Acta Botanica Caucasica. **1**:2.

Sahoo P and Sharma D. 2023. Economic impact of artificial intelligence in the field of agriculture. International Journal of Horticulture and Food Science **5**(1): 29-34.

Santosh Kumar VV, Verma RK, Yadav SK, Yadav P, Watts A, Rao MV and Chinnusamy V. 2020. CRISPR-Cas9 mediated genome editing of drought and salt tolerance (OsDST) gene in indica mega rice cultivar MTU1010. Physiology and Molecular Biology of Plants **26**: 1099-1110.

Sehgal A, Sita K, Kumar J, Kumar S, Singh S, Siddique K and Nayyar H. 2017. Effects of drought, heat and their interaction on the growth, yield and photosynthetic function of lentil (*Lens culinaris* medikus) genotypes varying in heat and drought sensitivity. Frontiers in Plant Science **8**: 1776.

Shil S. 2024. Developing drought tolerance in field crops towards current century: an integrated bio-molecular approach. International Journal of Bio-Resource and Stress Management **15**(Mar, 3): 01-10.

Shivaprasad KM, Dikshit HK, Mishra GP, Sinha SK, Aski

M, Kohli M and Varshney RK. 2024. Delineation of loci governing an extra-earliness trait in lentil (*Lens culinaris* Medik.) using the QTL-Seq approach. Plant Biotechnology Journal **22**(10): 2932-2949.

Siddiqi K and Husen A. 2016. Engineered gold nanoparticles and plant adaptation potential. Nanoscale Research Letters **11**(1): 1-10.

Singh D, Singh CK, Taunk J, Tomar RSS, Chaturvedi AK, Gaikwad K and Pal M. 2017. Transcriptome analysis of lentil (*Lens culinaris* Medikus) in response to seedling drought stress. BMC genomics **18**(1): 1-20.

Singh D, Singh CK, Tomar RSS, Taunk J, Singh R, Maurya S and Dubey SK. 2016. Molecular assortment of Lens species with different adaptations to drought conditions using SSR markers. PLoS One **11**(1): e0147213.

Soussi A, Zero E, Sacile R, Trinchero D and Fossa M. 2024. Smart Sensors and Smart Data for Precision Agriculture: A Review. Sensors **24**(8): 2647.

Subeesh A and Mehta C. 2021. Automation and digitization of agriculture using artificial intelligence and internet of things. Artificial Intelligence in Agriculture **5**: 278-291.

Talukdar D. 2013. Comparative morpho-physiological and biochemical responses of lentil and Grass pea genotypes under water stress. Journal of Natural Science Biology and Medicine **4**(2): 396.

Teso M, Lara-Romero C, Rubiales D, Parra-Quijano M and Iriondo J. 2022. Searching for abiotic tolerant and biotic stress resistant wild lentils for introgression breeding through predictive characterization. Frontiers in Plant Science **13**: 817849.

Thavarajah D, Thavarajah P, See C and Vandenberg A. 2010. Phytic acid and Fe and Zn concentration in lentil (lens culinaris l.) seeds is influenced by temperature during seed filling period. Food Chemistry **122**(1): 254-259.

Tiwari M, Singh B, Min D and Jagadish S. 2022. Omics path to increasing productivity in less-studied crops under changing climate-lentil a case study. Frontiers in Plant Science **13**: 813985.

Unified portal for Agricultural Statistics (UPAg). 2024. https://upag.gov.in/

Victoire D. 2023. Leveraging artificial intelligence for enhancing agricultural productivity and sustainability. Quing International Journal of Innovative Research in Science and Engineering **2**(2): 141-156.

Warne T, Ahmed S, Shanks C and Miller P. 2019. Sustainability dimensions of a north american lentil system in a changing world. Frontiers in Sustainable Food Systems **3**: 88.

Witte J, Gao K and Zoll A. 2023. Artificial intelligence: The future of sustainable agriculture? a research agenda.

Yasmeen S, Wahab A, Saleem M, Ali B, Qureshi K and Jaremko M. 2022. Melatonin as a foliar application and adaptation in lentil (*Lens culinaris* medik.) crops under drought stress. Sustainability **14**(24): 16345.

Zeroual A, Baidani A and Idrissi O. 2022. Drought stress in lentil (*Lens culinaris*, medik) and approaches for its management. Horticulturae **9**(1): 1.