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# CLIMATE CHANGE AND CHICKPEA: IMPACTS OF WARMING AND INCREASED VARIABILITY ON GROWTH AND YIELD ACROSS THE INDIAN SUB-CONTINENT

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## ABSTRACT
In Indian sub-continent, chickpea (*Cicer arietinum* L.) is the most important winter (rabi) grain legume crop. It is a dietary protein source for more than one billion people, and also plays an important role in the cereal-legume farming system. The phenology and crop production is highly sensitive to the slow climatic changes, and also to the fast short-term variations induced on these changes, since the crop is cultivated almost exclusively from the residual soil moisture from a narrow period of post-monsoon. It is a review that puts together all the knowledge gained from the physiology, agronomy, genetics and models on the possible interactions of the increase in mean temperature, rainfall variability, terminal heat and drought stress, occasional chilling events and the higher concentration of $CO_2$ in the atmosphere and how all these are likely to influence the growth and productivity of the chickpea in the sub-continent. The information is based on reproductive stage physiology (pollen viability, sucrose metabolism, anther and stigma function), root-trait and drought-avoidance studies, genomics-assisted breeding, crop-simulation studies (DSSAT, InfoCrop) and climate-pest interaction studies. Major abiotic constraints identified from the review are due to delayed sowing, often coupled with abiotic stress such as terminal heat stress and drought that could cause a 20-60% loss in the yields in susceptible cultivars, and cold events during flowering period, which are locally important in the northern plains and hills. There is a localised, irregular, positive compensatory effect from increased $CO_2$ that is probably not enough at many sites to offset the warming effects. Biotic pressure from the gram pod borer (*Helicoverpa armigera*) and Ascochyta blight is also expected to get more intense due to climate variability. The review concludes with the discussion on the genetic, agronomic and policy level adaptation options, and gaps in research, including a lack of free air $CO_2$ enrichment (FACE) experiments in chickpea. The Indian sub-continent is at significant risk, based on the climate change and climate variability observed due to the observed trends and is very much sensitive to the impacts of climate change and climate variability.

## INTRODUCTION
Chickpea (*Cicer arietinum* L.) is the second most planted grain legume, and the most important rabi (post-monsoon/winter-sown) pulse crop of South Asia. The production (11.04 mt, FAOSTAT 20026) in chickpea is maximum in India accounting for 70-75% and the remaining 25-28% from Pakistan, Bangladesh, Nepal, and Myanmar, which also have significant areas of chickpeas grown (Merga & Haji, 2019; Samriti et al., 2020; USDA Foreign Agricultural Service, 2023). Due to its high nutritional and energy value, it is rich in protein, dietary fibres and complex carbohydrates along with high micronutrient content. Chickpea is a key player in the food and nutritional security of the sub-continent and is the main source of protein in the diets of people who do not have easy access to animal protein (Jukanti et al., 2012). As per agronomical point of view, chickpea is equally useful as it is a legume, owing to its capability to fix N2 from the air; enhancement in soil fertility and a natural successor of kharif (summer) crops (rice, cotton/maize).

The chickpea productivity in the sub-continent is relatively low and unstable with farm performance being significantly less than 1.2 t/ha, while potential in the experiments has been found to be higher than 2–3 t/ha (Gaur et al., 2012). Much of the yield loss is due to abiotic stresses to the crop. Growing chickpea is solely as rainfed relying on monsoon season has a narrow window of sowing, of just a few weeks in October-November. This reliance on an extremely short window of opportunity for moisture means that the crop is susceptible to the slow pace of climate change, over a decade to centuries, as well as to the shorter-term variability and fluctuations it experiences within that slow change.

Here two different though inextricably entangled climatic situations come into play. Climate change over the past 40-50 years is clearly documented with an increase in the mean climate variables like maximum and minimum temperature on the Indo-Gangetic Plains and peninsular India (Pathak et al., 2003; Kalra et al., 2008; Nageswararao et al., 2016). Climate variability, on the other hand, describes the differences in weather between seasons and years - late monsoon break, early or late pre-harvest shower, or early warm spell in February. Hence, altering or intensifing the trend in any season or year of any crop. This difference is important especially for a crop with a very short growth period like chickpea where small

seasonal increases in temperature can be accommodated but a hot week in the flowering stage can lead to the loss of a major portion of the crop (Devasirvatham et al., 2012, Summerfield et al., 1984).
In the last 20 years, scientific knowledge about how chickpea responds to temperature and water stress has significantly increased, recognised and expressed by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and partner universities. The terminal drought and terminal heat are the two most important abiotic constraints on chickpea yield in South Asia (Gaur et al., 2008; Gaur et al., 2013). The advent of the draft genome sequence (Varshney et al. 2013) and large scale re-sequencing (Varshney et al. 2022) have paved the way for the development of new varieties with a climate-smart approach to the cultivation of chickpea. Meanwhile, crop-simulation modelling has started to produce location-specific yield projections for scenarios, with the platforms DSSAT-CROPGRO and InfoCrop, for the sub-continent (Kadiyala et al., 2016).
This review brings together the strewn literature in a single synthesis of this information, using a mechanistic approach. It looks at distribution and economic importance of chickpea in the Indian sub-continent; observed and projected climate change and variability for the rabi season; physiological sensitivity of the crop to heat, drought, cold stress, elevated $CO_2$; impact of climate change on yield and seed quality; yield projections using climate change models; changes in biotic stress due to climate change; adaptation strategies through genetic, agronomic and policy approaches and identifies priority gaps.

## 2. Distribution, Importance and Production Trends of Chickpea in Indian Sub-continent

Chickpea is cultivated in the trans Indo-Gangetic regions of Punjab, Haryana, Uttar Pradesh and Bihar, semi-arid areas of Rajasthan, Madhya Pradesh, Maharashtra, Karnataka and Andhra Pradesh, irrigated plains of Pakistan's Punjab and Sindh and in drier tracts of the Terai and central Bangladesh . The two main types, the smaller-sized brown coloured desi type (dominated in India and Pakistan) and the larger-sized, cream coloured kabuli type (preferred for export and speciality markets) have some differences in their agronomic requirements but the same fundamental developmental biology and climatic sensitivities (Jukanti et al., 2012).
Indeed, India is the largest producer, consumer and importer (240.97 million kg with 12.51 % import share) of chickpea in the world for decades (Samriti et al., 2020; USDA Foreign Agricultural Service, 2023). The crop is generally sown during the second half of October to first half of November, following the harvest of kharif rice, maize, cotton, sorghum or groundnut and is mostly harvested in February-March, with Madhya Pradesh, Rajasthan, Maharashtra, Uttar Pradesh and Karnataka contributing to the bulk of the national production (Parthasarathy Rao et al., 2010). The benefits of this close cropping with the preceding kharif crop are agronomic in nature – chickpea gets the soil moisture that has remained after the kharif crop, and does not have to compete with it for water for irrigation; however, it also reduces farmer's flexibility to shift the sowing date as climate variability increases.
Pakistan is the second largest producer in the sub-continent with chickpea produced mainly as rainfed crop in Barani tracts of Punjab and in Sindh, while the smaller contribution of Bangladesh, Nepal and Myanmar comes mainly from relay and utera cropping systems following rice (Parthasarathy Rao et al., 2010; USDA Foreign Agricultural Service, 2023). The sub-continent as a whole is the largest producer and consumer of chickpeas in the world while India is the largest producer and importer of chickpeas, suggesting an ongoing imbalance between supply and demand. Successive governments have attempted to resolve the imbalance by increasing area and marketing policy interventions in chickpea production and trade (Merga & Haji, 2019; Samriti et al., 2020).
In spite of its significance in vegetarian diets due to its nutritional value, the productivity of chickpea is still very low, around 1.2 t/ha, much lower than highest experimental management (2-3 t/ha) achieved in optimal experiments (Gaur et al., 2012). This yield gap is driven in large part by the persistent concern of terminal drought, terminal heat and in northern latitudes chilling injury at flowering, all of which are being modified by the ongoing effects of climate change and variability; and primarily rainfed production.

## 3. Observed and projected climate change and climate variability over Indian Sub-continent regions.

Long-term climate analysis of the Indo-Gangetic plains and the surrounding chickpea cultivation areas in the region consistently indicates statistically significant warming trend in both the minimum and the maximum temperatures for the last 40-45 years. The trend is more pronounced in minimum temperature as compared to the maximum temperature Pathak et al. (2003) and Nageswararao et al. (2016). The agronomic significance of chickpea reproductive development due to temperature (especially warm nights) sensitivity despite relatively low increase in maximum temperatures during the day, is agronomically relevant as it can reduce the grain filling period and enhance the carbon loss from respiration. However, rainfall trends are not as uniform across the country; some studies have found a decrease or greater inter-annual variability in the northern plains winter (rabi-season) rainfall, while others have found an increase in the frequency of unseasonal, high intensity rainfall events during the vegetative-to-reproductive transition (Pathak et al., 2003; Nageswararao et al., 2016).
Apart from this long-term trend, there is also a huge inter-annual and intra-seasonal variability in the winter precipitation and cold month onset over the Indo-Gangetic Plains (IGP). This can be attributed to the large-scale climate like El Nino-Southern Oscillation, North Atlantic Oscillation and western disturbance tracks that traverse over northern India (Nageswararao et al., 2016). This is especially true of a short duration crop such as chickpea, which is moisture dependent, and would rely on favourable temperatures during the reproductive phase of a crop growing season/damaging heat spike /unseasonal cold snap.
A special uniqueness and agronomic importance of the climate on the sub-continent is that the effective window for the cultivation of chickpeas is reduced. The planting date is also limited at both ends; planting too early will mean that the kharif (summer) season warmth will continue through the flowering and pod-filling phase of the crop, and planting too

late will mean that the crop may not mature in time to avoid February and March, increasingly warm months (Kalra et al., 2008). Increased temperatures during the reproductive phase (10–30 days after emergence of chickpeas) have consistently been shown to translate into reduced yields, through empirical studies using historical yield records combined with dynamic crop-growth models; simulations for chickpea, wheat, mustard and barley in north-western India indicated yield losses in the range of 200–500 kg/ha per degree increase in mean seasonal temperature, with losses likely to be higher in the western, hotter regions of the region than further east (Kalra et al., 2008).

It is important to recognise that climate change is not uniform across the sub-continent, and will have a positive impact in some places more than others. Chickpea is moderately warmer crop, with a moderate warming range outlined at 20-30°C during the day and 15°C at night; therefore, there is a moderate agronomic benefit that may be realized in moderately warmer parts of the chickpea range (higher elevation tracts or eastern Indo-Gangetic Plains) and a moderate yield loss potential in areas already very close to or hotter than the upper thermal window of chickpea (central and peninsular India where chickpea is already under heat stress due to its late sowing period). Such spatial variability needs assessment of climate change impact on chickpea production using simulation modelling, to emphasize the need for region-specific qualification of all climate change impacts on chickpea productivity that are generic across the sub-continent.

**4. Physiological Response of Chickpea under Climatic Stress**

It is important to appreciate the climatic requirements of chickpea development to enable understanding of its climatic sensitivity. Chickpea is considered to be a cool-season grain legume and is best suited to be grown when the day temperatures, in the range of 20-30ºC and night temperatures in the range of 15-20ºC (Croser et al., 2003; Devasirvatham et al., 2012). High temperatures at reproductive and seed filling stage (above approximately 32-35°C) cause a qualitatively similar, but mechanistically different set of reproductive failures while low temperatures during flowering (below about 15°C) cause impairment of pollen germination, pollen-tube growth and stigma receptivity giving rise to flower and pod abortion (Croser et al., 2003, Summerfield et al., 1984).

The reproductive parts of chickpea (non-vegetative parts) are the major constraint at mechanistic level during heat and cold stress. In controlled-environment studies, pollen viability, pollen production per flower, in-vitro and in-vivo pollen germination and pollen-tube growth were significantly reduced by the increase in temperature at pre- and post-anthesis, more in Heat Susceptible than in heat-tolerant (HT-) genotype (Devasirvatham et al., 2012). Carbon metabolism is affected where heat stress reduces sucrose supply to developing anthers by suppressing the leaf photosynthesis and also inhibits the activity of sucrose-synthesising and sucrose-cleaving enzymes (sucrose phosphate synthase, sucrose synthase and invertase) which leads to reduction in fertilisation process (Kaushal et al., 2013). The reproductive stage of chickpea (flowering to pod filling) is quite short (about 4 to 6 weeks) and is very sensitive to short periods of extreme heat (Summerfield et al., 1984; Sita et al., 2017).

The second main axis of sensitivity has to do with water relations. The crop is almost exclusively grown on residual soil moisture and as the crop nears flowering stage and maturity- the soil moisture is usually in a state of terminal dryness. The ability to delay the occurrence of a limiting internal water deficit is strongly linked to the genotype's root system architecture; genotypes with stronger root length density in the upper soil profile and with prolific root growth into the soil profile to access water for a longer period of the water deficit, and therefore be able to sustain seed-filling under terminal drought conditions (Kashiwagi et al., 2005; Gaur et al., 2008; Ramamoorthy et al., 2017). This drought-avoidance mechanism is one of the most well documented drought mechanisms in chickpea and also among most breeding-tractable drought mechanisms with more general principles in relation to root-length-density and water-uptake in cereals and grain legumes in general (Hamblin & Tennant, 1987), first systematically characterised with the ICRISAT mini-core germplasm collection (Kashiwagi et al., 2015; Kashiwagi et al., 2005).

Field conditions of chickpea crop do not generally suffer heat and drought stress in Indian sub-continent. The moisture loss due to delayed sowing causes the late crop to be subjected to heat stress, as it blooms during the warm season of February-March, and makes it more susceptible to the effects of high temperatures, which in turn leads to further reproductive failure. This is not a simple additive effect of heat and drought stress; the impact of dehydration on the effect of heat on sucrose transport and stomatal function also contributes to reproductive failure (Farooq et al., 2009; Farooq et al., 2017). This physiological interdependency of a narrow sowing window (with limited moisture availability) and a narrow thermal tolerance window (at the reproductive stage) is the core of the disproportionate vulnerability of Indian sub-continent to the gradual trend and short term variability of changing climate and forms the core of the following discussion of specific impacts on stress.

**5. Assessment of the Effects of Heat Stress on Growth, Phenology and Yield of Chickpea**

It has been suggested by Gaur et al. (2013) and Devasirvatham & Tan (2018) that the most important climate constraint in chickpea production in warmer regions of Indian sub-continent is the terminal heat stress (THS) i.e., high temperature during reproductive phase and pod filling stage. It occurs mainly due to the delayed sowing of kharif (summer) crop when it is sown late or due to late withdrawal of monsoon which delays the preparation of fields, thereby shifting the sowing of chickpea from the optimum time (mid-to-late October) to November/December. It is highly temperature dependent and a further delay in sowing does not necessarily result in a delay in maturity but simply a compression of the flowering and pod filling phase during the increasingly warm February and March months in which average maximum temperatures frequently rise above 32-35°C in much of central and peninsular India (Devasirvatham et al., 2012; Devasirvatham & Tan, 2018).

The large collection of chickpea germplasm has been tested at ICRISAT-Patancheru, where it is very well adapted to warm and humid conditions of the heat stress period during pod filling, and these results have shown that there is significant difference among the various germplasm in critical temperature thresholds, with the most heat-stress-tolerant germplasm setting reasonable numbers of pods at temperatures around 38°C during the heat stress period, and the most heat-stress-sensitive germplasm did not set any pods at temperatures above 35°C (Krishnamurthy et al., 2011). This difference has been consistently reported as differences in pollen viability, pollen production and pollen-tube growth, which drops off rapidly as temperatures exceed the optimum range (25–33 °C; Devasirvatham et al., 2012; Wang et al., 2006). Heat stress to yield loss can be correlated with impaired photosynthesis of leaves, sucrose metabolism, delivery of sucrose to anther pollen fertility and finally decreased number and size of pods (Kaushal et al., 2013).

The effects of this cascade on yield are significant, and these effects are well established in separate studies. Historical studies indicate that the yield reductions in north-western India are in the range of 200 kg/ha per unit increase in mean temperature of the season (Kalra et al., 2008) and delay of sowing by one month (from mid-October to mid-December) results in a significant yield loss of up to 500 kg/ha with respect to timely sowing in the region of Punjab and Haryana. Reviews of heat stress literature for chickpea and other grain legumes suggest that losses due to terminal heat stress are generally 20–40% and can be significantly more when heat stress is coupled with water stress, as observed in chickpea crops (Devasirvatham & Tan, 2018; Farooq et al., 2017; Sita et al., 2017).

Heat stress also has impacts on crop development, which occurs in addition to the impacts on the reproductive organs, and limits the time available for grain-filling and maturation. Heat-stressed chickpea would flower and physiologically mature earlier, with decreased vegetative growth phase for biomass accumulation and grain-filling period for partitioning assimilates towards the grain (Devasirvatham et al., 2012; Summerfield et al., 1984). Collectively, this leads to a smaller plant, early flowering and maturity, with fewer and less filled pods. This makes heat stress at terminal growth stage a stand-out factor, both physiologically and agronomically. Hence, forming a modelling perspective as the most important climatic driver impacting chickpea productivity in the warmer growing regions of the Indian sub-continent.

## 6. Growth and Yield of Chickpea under Drought/ Water Deficit

The second important abiotic stress, limiting chickpea productivity is terminal drought. This is described as the gradual reduction of soil water from the flowering to the pod filling phase, and accounts for 40-50% of chickpea yield loss due to abiotic stress (Gaur et al., 2008; Farooq et al., 2009). Depending on the climatic variability, the total monsoon rainfall received during the kharif season, the water holding capacity of the soil and to a greater extent the irregularity of the monsoon rain during the post-sowing season, determines the severity of any particular season's terminal drought across most of the Indian sub-continent.

Under drought stress, the RWC (relative water content), SC (stomatal conductance), chlorophyll retention on whole plant decrease, and the accumulation of plant osmolyte compounds (e.g., proline) differs among cultivars and is closely related with drought resistance traits in the root system and yield protection (Ucak & Arslan, 2023; Muruiki et al., 2018). Genotypes with longer root length density and rooting depth can access soil water more easily during the dry period. Hence, experience a longer delay before the development of terminal drought-induced internal water deficit (IWD) that could lead to yield loss, as was first systematically quantified in the ICRISAT mini-core collection and later shown to confer a consistent yield advantage during terminal drought across sites and seasons (Ramamoorthy et al., 2017; Kashiwagi et al., 2005; Kashiwagi et al., 2015). Therefore, micronutrient status also has importance in the context of drought tolerance as zinc application has been observed to improve stomatal regulation and antioxidant activity resulting in reduced yield loss under drought stress as well as under combined heat + drought stress (Ullah et al., 2019).

The reproductive ability of the chickpea had been correlated to preceding kharif (summer) crop, and thus drought and heat stress are often occurring together and as a combination, and have an interactive and not cumulative physiological effect. In water deficit, stomatal conductance and leaf water potential declines, and affects plants ability to cool down the internal temperature by transpiration and under the same air temperature the plant under water deficit will be more damaged in its reproductive organs than that of well-watered plant (Farooq et al., 2009; Farooq et al., 2017). The heat-drought interaction is agronomically significant in the Indian sub-continent due to the delay in sowing during the advanced stage of soil moisture deficit, wherein both stresses were not independent of each other but co-varied during the season among the different genotypes.

Drought tolerance has been a known trait in chickpea and has been a focus of on-going efforts in breeding work. Drought avoidance under drought stress conditions with good yield potential have been introgressed into elite germplasm of India using marker assisted backcrossing in the well characterised drought stress QTL-hotspot genomic region (Gaur et al., 2008; Thudi et al., 2014). Progress towards phenotyping techniques and the introduction of genomic selection to breeding programme pipelines (Gaur et al., 2019; Roorkiwal et al., 2020), illustrate the significance of drought tolerance as a desired trait for an international and national breeding programme, where one of the major themes is a climate with irregular and/or low winter rainfall.

## 7. Cold/Chilling Stress Effects

Some areas in the Indian sub-continent continue to have a narrative of warming, but the chilling effect and occasional frost injury are still agronomically important limitations on the production of chickpea, especially in the northern plains of Punjab and Haryana, mid-hills of Himachal Pradesh and higher elevation tracts of Jammu and Kashmir and Nepal where early sowing or unseasonal cold spells can result in temperatures below 15°C at which reproductive function starts to decline (Croser et al., 2003). Low temperature during the reproductive stage can affect the receptivity of the stigma, germination of the pollen, growth of the pollen tubes and cause abortion of flower and pods, through mechanisms similar, but biochemically distinct, to the heat-stress pathway (Croser et al., 2003).

The risk of chilling is unlikely to monotonically decline with warming of the sub-continent and as the mean temperature increases, so will the variability between years which can also enhance the probability of a cold events during the critical period for the flowering of chickpeas (Nageswararao et al., 2016). Chilling and freezing tolerance testing of chickpea germplasm has also shown that there is a high level of genetic diversity with some accessions tolerating short periods of sub-zero temperatures during their seedling stage, thus creating breeding material for those northern and high altitude production tracts of the sub-continent that are experiencing a problem with terminal heat stress, but have not yet encountered a problem with chilling stress.

**8. Climate Change and Risk of Sea Level upsurge**

The positive direct physiological response of chickpea to increased $CO_2$ concentration is mainly due to the fact that being a C3 legume, it does not become $CO_2$-saturated with current atmospheric levels of $CO_2$. This benefits from $CO_2$ enrichment through an increased rate of net photosynthesis, increased water-use efficiency through partial stomatal closure, and by increased biomass and pod number (Adireddy et al., 2024). Responses of grain-legumes to elevated $CO_2$ has led to seed yield increase in chickpea as in other grain legumes such as soybean, groundnut and pigeonpea (Adireddy et al., 2024). This $CO_2$ effect, however, is by no means uniform and also does not compensate for the negative impacts of warming. There are three qualifications of importance. First, the magnitude of the $CO_2$ response will be modulated by the availability of other resources like N and water. The $CO_2$ response of a crop under terminal drought will probably be smaller than under other well-watered conditions, but subjected to experimental conditions (Adireddy et al., 2024). Second, the specific heat stress mechanisms that are known to be affected by elevated $CO_2$ (those in the reproductive phase, such as in the pollen, and in sucrose transfer to the anther) will not be alleviated by elevated $CO_2$, and will not interact with elevated $CO_2$ in a way that would substantially reduce pod-set failure for a crop experiencing both elevated $CO_2$ and terminal heat stress. Third, and following a trend seen in other C3 crops, high $CO_2$ levels also generally decrease the nitrogen and mineral levels of the harvested grain, suggesting that quantity and nutritional value of the harvested grain may be inversely related (Adireddy et al., 2024).

The overall $CO_2$ levels and warming effect also looks to be location-specific: the balance between the two effects is simulated in this section and there are supporting empirical data indicating that cooler, sub-optimal environments for chickpea growth may experience a net positive yield from moderate amounts of warming and $CO_2$ enrichment, while environments already at or near the chickpea's upper thermal optimum are likely to be dominated by the negative warming effect regardless of the $CO_2$ increase (Kalra et al., 2008).

**9. Crop Simulation Modelling and Yield Projections**

Dynamic crop-simulation models, can simulate the productivity of the crop under any combination of management and climatic scenarios. These have been increasingly used to supplement the findings of controlled-environment and field experiments that can only cover a small range of management and climatic combinations and have a limited ability to predict how productivity will change in response to future climate. The two models that have been widely used in India are the DSSAT-CROPGRO chickpea module, and the locally developed InfoCrop model, both of which relate the phenological development, canopy photosynthesis, biomass partitioning and yield formation to daily weather, soil inputs and management practices, and show a reasonable level of agreement between predicted and observed yields in multi-location field trials (Kadiyala et al., 2016).

The DSSAT sequence-analysis approach was used to simulate a fallow-chickpea sequence at four sites in Andhra Pradesh where the yield loss ranged between 4% and 19% depending on the location of the site in question relative to the site's crop thermal optimum. Importantly, the same modelling exercise indicated that the simulated yield penalty under the climate change scenario was significantly less than the yield penalty under current conditions when using simple adjustments to agronomic management-sowing one fortnight earlier to reduce exposure to the terminal heat stress, and a single supplemental irrigation (SSI) at around 60 days after sowing to reduce exposure to the terminal drought stress (Kadiyala et al., 2016).

Modelling studies of this kind also support the spatial non-uniformity referred to in Section 3- the direction of the response of yield to the model will be determined by how far a particular site is from chickpea's thermal optimum, and $CO_2$ levels will help to buffer this response in some locations but not others. These highlight the need for location-specific (rather than continental-average) modelling exercises to inform agronomic and policy decision-making and a greater uptake of modelling exercises for chickpeas, which remains largely confined to a few well-instrumented locations in India, but needs to be extended to more under-studied areas in Pakistan, Bangladesh and Nepal.

**10. Biotic Stress Related to Climate Change**

The impact of climate change and variability on production of chickpeas is not only direct via the physiological pathways mentioned above, but also indirect via changes in the pressure from insect pests and pathogens. Chickpea is infested by a large number of insect pests; however, the gram pod borer (Helicoverpa armigera) is the most devastating insect pest of the crop in the Indian sub-continent and has a strong temperature dependency in its life cycle (Bapatla et al., 2021). Future temperature projections under various emission scenarios in agro-climatic zones of India and modelling of the pest's growing degree days (GDD) requirements indicate that the number of generations that the pest can complete in a single crop growing season may increase; with a higher emission scenario indicating the highest increase in voltinism in warmer agro-climatic zones (Bapatla et al., 2022). This is an important extra abiotic stress contributing to increased frequency of pod-borers from future generations that will result in more larval feeding and potential yield loss, and will also allow the pest to gain the ability to develop resistance to the control measures that are applied.

Climatic changes also reveal an interrelated, but mechanistically different sensitivity, in relation to diseases caused by fungi. If coupled with susceptible cultivars and dense crop canopies, epidemics can spread rapidly and cause significant yield losses with the cool moist weather in the vegetative-to-reproductive transition period in the northern plains and cooler and wetter chickpea growing areas of the hills can promote epidemics by the fungus Ascochyta rabiei. The net effect of this is that in many regions of the sub-continent, climate change is likely to superimpose, in addition to increasing abiotic stress, a similar suite of abiotic stress-induced biotic (pest, disease) stresses to the crop, and in several reported cases, biotic stress is likely to increase alongside abiotic stress (Khosla et al., 2026; Bindra et al., 2023).

**11. The Effect on Quality and Nutritional Value of Seeds**

Heat stress during the seed filling stage also has measurable effects on the nutritional composition of grain directly relevant to regional food and nutrition security in addition to its effects on seed production. There is a significant decrease in seed starch, storage protein, fat and mineral (calcium, phosphorus, iron) content in heat-sensitive genotypes compared to heat-tolerant genotypes under the heat-stressed conditions specifically during the seed-filling stage(Devi et al., 2023). In this case, disruption of sucrose production,carbon and energy transport from source to sink in the leaf disrupts the coordinated deposition of starch and storage proteins and minerals that rely on an adequate supply of carbon and energy (Devi et al., 2023; Kaushal et al., 2013).

This quality criterion is seldom sufficiently taken into account in the breeding for yield stability as genotypes that are mainly selected for yield stability under a heat stress may not guarantee the same retention of grain quality. Agronomic practices will be beneficial in partially mitigating impacts, including ensuring adequate zinc nutrition, which when combined with drought and heat stress, results in increased membrane stability and antioxidant capacity, and decreased negative impacts on yield and seed quality traits (Ullah et al., 2019). In regions where variability in total yield of the chickpea is relatively low, an increase in $CO_2$ and an increase in the frequency of terminal heat stress events would likely result in quality deterioration of chickpea grain. This would in turn affect the masses with highest reliance on the crop as their primary source of protein and micronutrients.

**12. Adaptation Strategies**

**12.1 Genetic improvement**

The most widely used adaptation pathway is the identification, characterisation and use of germplasm that is better adapted to heat and drought stress. Germplasm collections, including the ICRISAT mini-core and reference collections, have been screened on a large scale for genotypic variation in various critical temperature thresholds for pod set and root-related drought avoidance traits. This will enable breeders to have access to well characterized donor material (Upadhyaya et al., 2011; Krishnamurthy et al., 2011; Kashiwagi et al., 2005). Marker-assisted backcrossing has been previously used to introgress the drought-tolerant associated QTL-hotspot region into elite high yielding Indian cultivars yielding higher number of seeds under terminal drought without affecting other agronomic properties of the frequent parent (Gaur et al., 2008; Thudi et al., 2014). A large panel of resequenced landraces, reference genome sequence and an extensive panel of normalized seeds have accelerated the discovery of candidate regions in the genome that could be used to develop markers and/or genome-wide selection (GWSS) (Danakumara et al., 2024; Roorkiwal et al., 2020; Varshney et al., 2013; Varshney et al., 2022). In addition, chickpea's wild relatives also have a significant amount of genetic diversity, much greater than found in the cultivated gene pool, due to a strong domestication bottleneck, and thus constitute another largely untapped heat-, cold- and drought-tolerance gene pool for pre-breeding programmes (von Wettberg et al., 2018; Gaur et al., 2019).

**12.2 Agronomic management.**

Outside the scope of genetic improvements, a variety of agronomic practices have been demonstrated experimentally and using crop-simulation models to alleviate the yield penalty caused by terminal heat and drought. A later sowing date within the agronomically suitable date range decreases the chance of flowering coinciding with the peak pre-monsoon temperatures and simulation studies have shown significant reductions in yield loss due to a single well-timed supplemental irrigation around the early pod-filling stage while considering climate change (Kadiyala et al., 2016). Balanced nutrition and (when needed) zinc supplementation helps to increase stress tolerance. The crop-simulation models such as DSSAT or InfoCrop have been advocated as decision support tools to guide farmers and extension services on optimal sowing dates, and on irrigation-scheduling management, in relation to specific locations and seasons (Kadiyala et al., 2016; Ullah et al., 2019 and Hajishabani et al., 2025).

**12.3 Policy and systems level considerations**

Climate adaptation value of chickpea is not limited to the farm gate as the crop is also also imported in India. Each of Indian sub-continent countries India, Pakistan, Bangladesh and Nepal depend on the crop for nutrition and for rural livelihoods (Merga & Haji, 2019; USDA Foreign Agricultural Service, 2023). A long-term investment in the public sector is needed to ensure the smallholder farmer for an easy access to the cultivars developed through the genomics-assisted breeding pipelines outlined above that are appropriate to climate change. To make sure that the current role of chickpea in the regional food and nutrition security can still be fulfilled in the future context of changing climate, complementary investments in weather-based crop advisories, weather-indexed crop insurance, and trade policies that mitigate the year-to-year production variability inherent in the historical record will be required (Samriti et al., 2020).

**13. Future Directions and Gaps**

Several areas of present gaps are in evidence that should be particularly noted. Free-air $CO_2$ enrichment (FACE) trials, which involve exposing crops to increased $CO_2$ levels in open field settings while keeping natural growing conditions intact, are scarce for chickpeas and projected effects on yield due to $CO_2$ -levels are based mainly on chamber-based experiments and from evidence provided for grain legumes as a whole. There is scope to increase confidence in future yield projections through dedicated chickpea FACE trials under representative Indian sub-continent growing conditions. Second, the majority of the experimental and modelling studies reviewed here focus on Indian locations, and limited published and peer-reviewed evidence exist on climate impacts, physiological responses and adaptation options for chickpea in other countries (Pakistan, Bangladesh, Nepal and Myanmar) with significant dependence on the crop, thereby highlighting the need to expand the geographic scope of the chickpea physiology and modelling studies. Third, the combined and interactive effects of heat and drought stress are relatively poorly studied in field conditions (not in laboratory conditions) across several seasons and locations and the prediction or apportionment of yield losses due to combined heat and drought stress is less exact. Fourth, the nutritional-quality aspect of climate impact (nutrient content of seeds can be decreased under heat stress and/or $CO_2$ elevation without a change in yields) is less well quantified at the population and food-security scale and is also a research priority that needs to be incorporated into research on the climate impacts on agriculture and dietary outcomes. Finally, continued development of integration of genomics-assisted breeding with agronomic and simulation-modelling based research in a genotype-by-environment-by-management context will provide the most promising pathway from the large body of knowledge we have regarding our plants' physiology and genetics for the deployment of climate-resilient cultivars and agronomic management practices at scale across the sub-continent.

## 14. CONCLUSION

The chickpea is not only one of the most significant crops in terms of agriculture, economy and nutrition in the Indian sub-continent but it is also sensitive to the changes and variability in climate, makeing it current subject of scientific research. The crop is very sensitive to the gradual warming trend across the sub-continent but also to the seasonality of the rainfall and temperatures on top of the warming trend. This sensitivity is manifested in reduced growth, yield and seed quality. The major constraints that prevail in majority of the chickpea growing regions of the sub-continent are the terminal heat stress and/or terminal drought, commonly encountered due to late planting of cereals dominated rotations; and chilling injury in some areas. The potential physiological gain from higher atmospheric $CO_2$ is not likely to offset the losses associated with warming at most sites, with further warming induced stress from significant pests and diseases expected, and climate variability will add more stress. Despite this, a substantial body of physiology and breeding research, genetics, genomics and modelling research are now informing specific adaptation pathways for chickpea, including the development of heat and drought tolerant germplasm, the development of breeding strategies based on root traits, genomics-assisted breeding, delayed planting dates, targeted irrigation, micronutrient management, and climate change decision support modelling. These present a realistic prospect of maintaining and enhancing chickpea productivity as climate change speeds up, provided research, breeding, and extension investment continues at the pace of climatic change.

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