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Climate Change and Plant Abiotic Stress Tolerance

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Clockwise beginning at the top: Chickpea plant, © Swapan, Fotolia.com; Schematic illustration of plant water stress responses, Yuriko Osakabe (for more information see Figure 4.1); *In vitro* multiplication of shoots of *A. vera*, Narpat S. Shekhawat, (for more information see Fig. 32.2); Antarctic iceberg, © Goinyk Volodymyr, Fotolia.com; Avicennia_resinifera; weather icons, © Paulista, Fotolia.com; Background: dry land, © fotola70, Fotolia.com

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Climate Change and Heat Stress Tolerance in Chickpea

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Abstract

Chickpea (*Cicer arietinum* L.) is a cool-season food legume and suffers heavy yield losses when exposed to heat stress at the reproductive (flowering and podding) stage. Heat stress is increasingly becoming a severe constraint to chickpea production due to the changing scenario of chickpea cultivation and expected overall increase in global temperatures due to climate change. A temperature of 35 °C was found to be critical in differentiating heat-tolerant and heat-sensitive genotypes in chickpea under field conditions. Large genetic variations exist in chickpea for reproductive-stage heat tolerance. Many heat-tolerant genotypes have been identified through screening of germplasm/breeding lines under heat stress conditions in the field. A heat-tolerant breeding line ICCV 92944 has been released in two countries (as Yezin 6 in Myanmar and JG 14 in India) and is performing well under late-sown conditions. Heat stress during the reproductive phase adversely affects pollen viability, fertilization, pod set, and seed development, leading to abscission of flowers and pods, and substantial losses in grain yield. Studies on physiological mechanisms and genetics of heat tolerance, and identification of molecular markers and candidate genes for heat tolerance, are in progress. The information generated from these studies will help in developing effective and efficient breeding strategies for heat tolerance. The precision and efficiency of breeding programs for improving heat tolerance can be enhanced by integrating novel approaches, such as marker-assisted selection, rapid generation turnover, and gametophytic selection. Chickpea cultivars with enhanced heat tolerance will minimize yield losses in cropping systems/growing conditions where the crop is exposed to heat stress at the reproductive stage.

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31.1 Introduction

Chickpea (*Cicer arietinum* L.) is a cool-season food legume grown in more than 50 countries across all continents. It is the second largest grown and produced pulse in the world after beans. During 2010, chickpea was grown on 12 Mha, had a production of 11 million metric tons, and an average productivity of 911 kg ha^{-1} (http://faostat3.fao.org/home/index.html). The major chickpea producing countries include India, Australia, Pakistan, Turkey, Myanmar, Ethiopia, Iran, Mexico, Canada, and the United States. India is the largest chickpea producing country with a share of 68% in the area and production of chickpea in the world. However, this production is still not sufficient to meet the domestic demand. As a result, India imports chickpea to bridge the gap between demand and production.

Chickpea is a good source of protein (20–22%), and is rich in carbohydrates (around 60%), dietary fiber, minerals, and vitamins [1–3]. There is a growing international demand for chickpea and the number of chickpea importing countries has increased from about 60 in 1989 to over 140 in 2009. This is partially due to increased awareness about the health benefits of pulses, including chickpea. Chickpea has several potential health benefits, including beneficial effects on some of the important human diseases such as cardiovascular diseases, type 2 diabetes, digestive diseases, and some forms of cancer [3].

Like other legumes, chickpea fixes atmospheric nitrogen through symbiotic nitrogen fixation and this reduces the need for chemical fertilizer, thereby lowering costs of production and associated greenhouse gas emissions. The residual nitrogen in the soil after chickpea cultivation benefits the subsequent crop. This is particularly important when the subsequent crop is a cereal. Crop diversification with legumes is highly desired in cereal-dominated cropping systems for improving and sustaining the overall productivity of the cropping system.

Drought and heat are the most important constraints to chickpea production globally. It is estimated that drought and heat stresses together account for about 50% of the yield losses caused by abiotic stresses. The economic value of these losses is estimated at US$1.28 billion [4]. Chickpea is a dry and cool-season crop, largely grown rainfed on residual soil moisture after the rainy season. The progressively receding soil moisture conditions often lead to moisture stress towards the end of the crop season (terminal drought), causing heavy yield losses. Development of cultivars that can escape (early maturity) or avoid/tolerate (greater extraction of water from the soil, enhanced water use efficiency) terminal drought has been a major objective in chickpea breeding programs [5–9].

Exposure to heat stress (35 °C and above) at flowering and podding in chickpea is known to result in drastic reductions in seed yields [10–12]. In comparison to drought and other abiotic stresses, heat stress has received relatively less attention in chickpea breeding programs in the past. However, it has drawn considerable attention during recent years. It is now well recognized that heat stress at the reproductive stage is increasingly becoming a serious constraint to chickpea productivity. This is because of (i) a large shift in the chickpea area from cooler

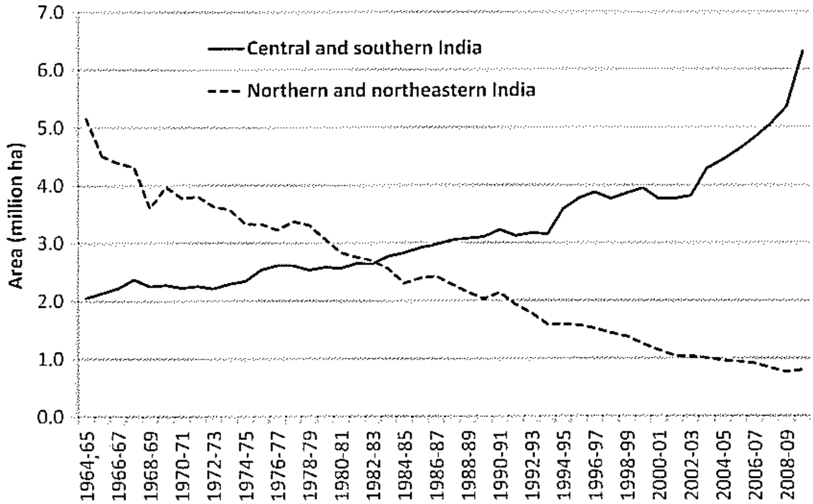

Figure 31.1 Shift in chickpea area from northern and northeastern India (cooler, long-season environments) to central and southern India (warmer, short-season environments) during 1964/65 to 2009/10.

long-season environments to warmer short-season environments, (2) increasing chickpea area under late-sown conditions due to increasing cropping intensity, and (3) expected overall increase in temperatures due to climate change [8]. In India, during 1964/65 to 2009/10, the chickpea area was reduced by 4.3 Mha (from 5.1 to 0.8 Mha) in northern and northeastern India (Punjab, Haryana, and Uttar Pradesh), which have cooler long-season environments, and increased by 4.3 Mha (from 2.0 a to 6.3 Mha) in central and southern India (Madhya Pradesh, Maharashtra, Andhra Pradesh, and Karnataka), which have relatively warmer and short-season environments (Figure 31.1). Thus, there has been a considerable increase in the chickpea area that is prone to heat stress during reproductive development.

In India, chickpea was previously sown during late September to late October in most of the areas, but now there is a wide range in sowing times extending to the end of December. This is because of increasing cropping intensity and the inclusion of chickpea in new cropping systems. Farmers are desperate to enhance their income and are making every effort to enhance cropping intensity. Some farmers with assured irrigation facilities are taking three sequential crops in a year; for example, a rainy-season crop, such as maize (July–September), followed by a short-duration vegetable crop, such as potato (October–November), which is then followed by chickpea (December–April). Irrigated chickpea in late-sown conditions suffers heavy yield losses from heat stress at the reproductive stage.

Many studies on climate change have indicated that average surface temperatures are expected to rise by 3–5 °C, posing a major threat to crop production (including legumes) and agricultural systems worldwide, especially in the semi-arid tropics [13,14]. Moreover, any increase in temperature will have more adverse effects especially on cool-season crops (e.g., chickpea) than the rainy-season crops [15].

The optimal temperature for chickpea growth ranges between 10 and 30 °C [16]. The reproductive phase (flowering and seed development) of chickpea is particularly sensitive to heat stress. A few days of exposure to high temperatures (35 °C or above) during the reproductive phase can cause heavy yield losses through flower and pod abortion. The effect of increasing seasonal temperature on chickpea yield in northwestern parts of India was studied using crop growth simulation models [17]. The models suggested a decrease in chickpea yield in all the four states (Punjab, Rajasthan, Uttar Pradesh, and Haryana) with a rise in seasonal temperature. A maximum decrease of 301 kg ha^{-1} in grain yield was observed in Haryana, whereas a minimum decrease of 53 kg ha^{-1} was observed in Uttar Pradesh per degree rise in seasonal temperature. This indicates how heat stress is going to be a challenging issue for chickpea productivity under future climatic conditions.

This chapter provides an update on the past and current research efforts on heat tolerance in chickpea, and the future prospects for developing heat-tolerant chickpea cultivars for enhancing its resilience to impacts of climate change.

31.2
Effect of Heat Stress on Chickpea

High temperatures initially affect seed germination and crop establishment. Although genotypic variation exists in chickpea for high-temperature tolerance at seed germination, no germination was observed at above 45 °C [18]. There are diverse reports on optimum temperatures for seed germination, ranging from 10–15 °C [19] to 28–33 °C [20]. Covell *et al.* [21] showed that 80% of chickpea seed germinated between 31.8 and 33.8 °C. Crop establishment in chickpea is reduced under heat stress due to its impact on important physiological processes, such as low photosynthetic rates and high transpiration rates [18].

Heat stress affects a wide range of morphological and physiological processes, and alters the plant–water relationship, ultimately affecting crop growth and development [22]. Although reduction in the growth of legumes including chickpea has been reported [10,23–25], the biological processes that are affected by heat stress are less understood in legumes compared to cereals. Heat stress-related symptoms in legumes including chickpea are: withering and burning of leaves/stems, desiccation of plants, stunting, senescence, and abscission, shoot and root growth inhibition, flower and pod abortion, pod damage, and reduced yield [26–29]. Reduction in shoot dry mass, relative growth rate, and net assimilation have been reported in other crops under heat stress [30,31]. Root nodulation and nitrogen fixation were also affected by heat stress in chickpea [32].

Plant phenology can be modified by changing temperature and photoperiod [10,16]. A combination of different temperatures and photoperiods was imposed on chickpea plants to study their effect on phenology [33]. It was observed that the rate of progression towards flowering was a linear function of mean temperature. Further, there was no recordable interaction between temperature and photoperiod; however, the rate of progress towards flowering was increased under longer photoperiods. Chickpea flowered earlier by about 1 week under heat stress (45/25 °C) compared to optimal temperatures [34]. The occurrence of earlier phenology under high-temperature conditions can cause a reduction in number of reproductive branches and thereby reduce seed yields [35,36]. Days to flowering and maturity duration are the key phenological characters that influence crop performance, especially under heat stress conditions, therefore these parameters are important when breeding heat-tolerant chickpea cultivars.

The most sensitive organs to heat damage in chickpea are flowers [32]. Increased reproductive organ damage [22,37], reduced time interval for normal growth of reproductive organs [38,39], and accelerated growth rate [40,41] could be the major causes for yield reduction under high-heat stress conditions. Heat stress could have a negative impact on floral bud development [42] and seed composition [43]. High-temperature stress affects pollen viability and seed filling, and results in pod abortion [37,44,45]. Male sterility due to unviable pollen and anther indehiscence was observed in cowpea and bean under heat shock conditions [46,47]. Lower numbers of seeds could result due to loss of pollen or stigma viability [37,48,49] and flower abortion (as in *Brassica* sp. [38,50]) under heat stress conditions.

Further, heat stress could adversely affect meiosis in both male and female organs, style and stigmatic position, number of pollen grains retained on the stigmatic surface, and growth of endosperm and also the fertilized embryo [51]. In chickpea, development of male (pollen/anther) and female (stigma, style, and ovary) reproductive organs is most sensitive to abiotic stress [52]. High temperature has a particularly detrimental effect on two stages of pollen development: meiosis in the microspore mother cell and mature microspores [53–55]. Heat stress could also affect the development of tapetal cells, resulting in degeneration and premature development of pollen in the case of cowpea and snapbean [54,55]. Pollen germination in chickpea is optimal at 25 °C and germination is reduced under heat stress conditions, leading to reduced fertilization [56,57]. Studies indicated that heat stress in chickpea has no significant effect on the number of flowers formed, but decreased the number of days to flowering [58].

Studies have indicated that the reproductive phase of chickpea is most sensitive to heat stress [59,60]. Heat stress at the reproductive stage affects pod fill and pod set [10,35,40]. Heat stress during pod development reduces the yield to a greater extent compared to stress at early flowering. The decrease in yield under heat stress at pod development was about 59% and 53% in desi and kabuli types, respectively. Heat stress at early flowering affected pod production by 34% in desi and 22% in kabuli type chickpea [11]. Additionally, heat stress also reduces the biomass yield. Although there is considerable genetic variation for heat tolerance in chickpea, most genotypes do not set pods when the temperature exceeds 35 °C [61]. A more pronounced effect of high-temperature stress was observed on sink size than on the source in chickpea [11]. Heat stress on developing seeds inside the pod could result in reduced germination/emergence and loss of vigor [31].

31.3
Screening Techniques for Heat Tolerance

A simple and effective field screening technique for reproductive-stage heat tolerance in chickpea has been developed at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru. Long-term weather data was collected for the ICRISAT research farm to identify the sowing time that would ensure the reproductive phase of the crop coincided with high temperatures (above 35 °C). At Patancheru, chickpea is normally sown in October and harvested in January/February. The highest temperatures during the reproductive phase of the crop are generally below 30 °C (Figure 31.2). It was found that if chickpea is sown in February, the highest temperatures would be generally above 35 °C starting from the initiation of flowering to crop maturity (Figure 31.2). This will be practically a second crop at Patancheru and provide natural field screening of the crop for reproductive-stage heat tolerance. Generally, one set of test material is grown during the normal-sown condition (October) and one set during the late-sown condition (February) to compare the performance of genotypes under no heat stress and heat stress conditions.

Although the October-sown crop can be grown on residual moisture without any supplementary irrigation, the February-sown crop has to be irrigated frequently (at 10- to 15-day intervals). It was found that the number of filled pods per plant in late-sown crops can be considered as a selection criterion for reproductive-stage heat tolerance. Figure 31.3 shows the difference in pod set between a heat-sensitive line

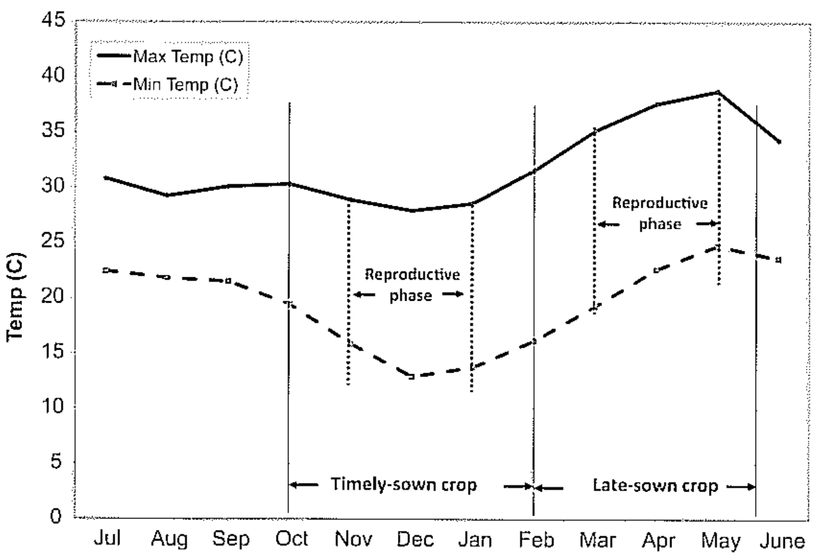

Figure 31.2 Long-term (more than 30 years) average temperatures (°C) for the ICRISAT research farm. The normal chickpea crop is sown in October and the late-sown crop for heat tolerance screening is sown in February.

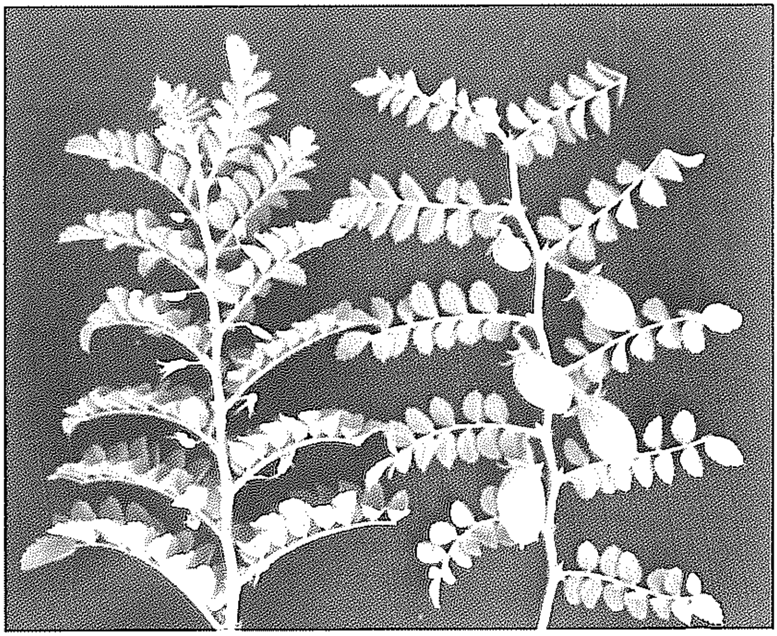

Figure 31.3 Difference in pod set between a heat-sensitive line ICC 4567 (left) and a heat-tolerant line ICC 15614 (right) grown under late-sown (heat stress) conditions at ICRISAT.

(ICC 4567) and a heat-tolerant line (ICC 15614) grown under late-sown conditions at ICRISAT.

As cellular membrane systems are sensitive to high temperatures, the measure of electrolyte leakage can give an indication of the extent of damage caused to cellular membranes by heat stress [62]. Studies conducted in sorghum (*Sorghum bicolor* (L.) Moench) suggest that the amount of electrolyte leakage from leaf segments exposed to heat shock in test tubes is an efficient means of determining the cell membrane thermostability (CMT) [63]. The method is rapid, inexpensive, and requires little space, enabling heat tolerance screening of many genotypes. Electrolyte leakage has been used effectively to measure CMT in chickpea [64] and a number of other crops, including sorghum [65], groundnut [62], soybeans [66], cowpea [27], wheat [67], and potato and tomato [68]. CMT has been correlated with whole-plant heat tolerance in some genotypes of soybean [66] and wheat [69]. However, for cowpea, electrolyte leakage of leaf disks was negatively associated with reproductive-stage heat tolerance [27]. Subsequent genetic selection experiments by Thiaw and Hall [70] confirmed that leaf electrolyte leakage under heat stress was negatively correlated with heat tolerance for the pod set in cowpea.

Pollen viability tests on plants exposed to heat stress at flowering can also be used for heat tolerance screening [71]. Flower buds are collected from plants exposed to high temperatures (35 °C or above), stained with Alexander's stain, and observed under a compound microscope. The viable pollen grains appear red, while the sterile pollen grains appear green. A temperature of 35 °C was found to be critical in differentiating the heat-sensitive line ICC 5912 and the heat-tolerant line ICCV 92944 for pollen viability.

31.4 Physiological Mechanisms Underlying Heat Tolerance

Cellular membrane systems need to remain functional during heat stress, thus maintenance of the integrity of cellular membrane systems is an important mechanism for heat tolerance in crop plants [72]. A study conducted with different legumes showed that chickpea is more sensitive to high temperatures compared to groundnut, soybean, and pigeonpea, in terms of membrane stability and Photosystem II functions [73]. However, Malhotra and Saxena [59] reported that the critical temperature for heat tolerance in chickpea was higher than other legumes, such as lentil, pea, and faba bean. In soybean, heat stress conditions resulted in increased permeability and leakage of electrolytes, which in turn reduced photosynthetic or mitochondrial activity, and the ability of plasmalemma to retain solutes and water [74]. In chickpea, membrane integrity, chlorophyll content, photochemical efficiency, and cellular oxidizing ability were inhibited by the increase in temperature, with greater impacts on the sensitive genotypes [75]. Heat stress reduced cell respiration, relative leaf water content, and activity of enzymes, such as RuBisCO, sucrose phosphate synthase, and invertase [76]. Oxidative injury as lipid peroxidation and hydrogen peroxide content was significantly greater in sensitive genotypes [75].

Exogenous application of osmoprotectants, such as proline, was found to impart partial heat tolerance in chickpea by reducing cellular injury and protection of some vital enzymes required for carbon and oxidative metabolisms [75,76]. The role of abscisic acid (ABA) growth hormone in alleviating heat stress in chickpea was evaluated by Kumar *et al.* [64]. Results indicated that exogenous application of 2.5 μM ABA significantly mitigated the seedling growth at 40/35 and 45/40 °C, while the application of fluridone (a biosynthetic inhibitor of ABA) intensified the inhibition. Similarly, exogenous application of osmolytes (proline, glycine betaine and trehalose) also promoted growth in heat-stressed plants and their action was not significantly affected by fluridone.

Kumar *et al.* [75] found that pollen viability, pollen germination, pollen tube growth, pollen load, and stigma receptivity decreased with increases in temperatures in chickpea. The heat-tolerant genotypes (ICCV 07110 and ICCV 92944) experienced significantly less damage to pollen and stigma function than the sensitive genotypes (ICC 5912 and ICC 14183). At the metabolic level, the heat-tolerant genotypes appeared to possess a stable and more active antioxidative defense mechanism than their sensitive counterparts. Devasirvatham *et al.* [77] reported that the high temperatures reduced pod set in chickpea by reducing pollen viability and pollen production per flower. The pollen of the heat-tolerant line ICCV 92944 was viable at 35/20 °C (41% fertile) and at 40/25 °C (13% fertile), while the pollen of the heat-sensitive line ICC 5912 was completely sterile at 35/20 °C with no *in vitro* germination and no germination on the stigma. However, the stigma of ICC 5912 remained receptive at 35/20 °C and non-stressed pollen (27/16 °C) germinated on it during reciprocal crossing. These data indicate that pollen grains were more sensitive to high temperature than the stigma in chickpea.

High night temperature is reported to have a damaging effect on reproductive development, particularly pod and seed set, in other legumes, including common bean (*Phaseolus vulgaris* L. [78]), lima bean (*Phaseolus lunatus* L. [79]), and cowpea (*Vigna unguiculata* L. [80]). Mutters and Hall [81] demonstrated that there is a distinct period during the 24-h cycle when pollen development in cowpeas is sensitive to high night temperatures. The damaging effect of high night temperature on pod set was greater in long days than in short days, and red and far-red light treatments indicated that it is a phytochrome-mediated response [82]. Although it is well established that high temperatures adversely affect grain yield in chickpea; a comparison of the effects of high day temperatures and high night temperatures is yet to be made.

31.5
Genetic Variability for Heat Tolerance

Until recently there were few studies on screening of chickpea germplasm for heat tolerance. Dua *et al.* [83] screened 25 genotypes for heat tolerance and identified two genotypes (ICCV 88512 and ICCV 88513) as heat tolerant.

The recent studies on screening of chickpea genotypes for heat tolerance indicate the existence of large genotypic variation for reproductive-stage heat tolerance. Delaying the planting by 2 months compared to normal in the Mediterranean climate resulted in successful identification of heat-tolerant genotypes [84]. Several heat-tolerant genotypes were identified from screening of 377 germplasm accessions. The kabuli types were generally more drought and heat susceptible than the desi types. The desi chickpea lines ACC 316 and ACC 317 exhibited tolerance to drought and heat (above 40 °C) under field conditions. The seed size was not much affected by adverse climatic conditions and showed the highest heritability. It was suggested that days to first flowering, days to maturity, harvest index, biological yield, and pods per plant should be considered ahead of other traits while breeding for heat- and drought-tolerant genotypes.

Canci and Toker [85] evaluated 68 accessions of eight annual wild *Cicer* species (*C. bijugum*, *C. chorassanicum*, *C. cuneatum*, *C. echinospermum*, *C. judaicum*, *C. pinnatifidum*, *C. reticulatum*, and *C. yamashitae*) for heat (up to 41.8 °C) and drought tolerance, and identified large genetic variability for these traits. Based on heat and drought tolerance scores, four accessions of *C. reticulatum* (AWC 605, AWC 616, AWC 620, and AWC 625) and one accession of *C. pinnatifidum* (AWC 500) were identified as promising.

A screening of 180 genotypes at Patancheru (southern India) during 2007/08 and 115 genotypes at Patancheru and Kanpur (northern India) during 2008/09 revealed large genotypic variation for heat tolerance in chickpea [86]. The genotypes that showed high heat tolerance and gave higher yields than the best-known heat-tolerant line ICCV 92944 over 2 years at Patancheru included ICCV 07104, ICCV 07105, ICCV 07110, and ICCV 07115. The genotypes that showed high levels of heat tolerance both at Kanpur and Patancheru included ICCV 07104, ICCV 07105, and IPC 2006-99.

The reference set of chickpea showed large genotypic variability for heat tolerance [87]. The reference set consists of 300 genotypes, and represents genetic variability present in the chickpea germplasm available at ICRISAT and the International Center for Agricultural Research in the Dry Areas [88]. The reference set ($n = 280$), excluding 20 genotypes (accessions of wild species and very late genotypes), was evaluated under heat stress conditions at Patancheru and Kanpur. A heat tolerance index (HTI) was calculated using a multiple regression approach where grain yield under heat stress is considered as a function of yield potential and time to 50% flowering. There were large and significant variations for HTI, phenology, yield, and yield components at both locations. Based on the HTI, 18 accessions (ICC 456, ICC 637, ICC 1205, ICC 3362, ICC 3761, ICC 4495, ICC 4958, ICC 4991, ICC 6279, ICC 6874, ICC 7441, ICC 8950, ICC 11944, ICC 12155, ICC 14402, ICC 14778, ICC 14815, and ICC 15618) were identified as stable tolerant. Some of these genotypes (e.g., ICC 4958 and ICC 14778) were earlier identified as drought tolerant [89], thus these are good sources for both drought and heat tolerance. Several genotypes were heat sensitive at both the locations, and the most sensitive genotypes included ICC 4567, ICC 10685, ICC 10755, and ICC 16374.

Upadhyaya *et al.* [90] screened 35 early maturing chickpea germplasm accessions for heat tolerance. Heat stress affected traits such as flowering duration, days to maturity, pod number, seed weight, and grain yield. For every degree rise in temperature beyond the optimum, a 10–15% yield loss among genotypes was recorded. They identified ICC 14346 to be highly tolerant to heat stress along with nine other tolerant entries (ICC 5597, ICC 5829, ICC 6121, ICC 7410, ICC 11916, ICC 13124, ICC 14284, ICC 14368, and ICC 14653).

Devasirvatham *et al.* [91] screened 167 chickpea genotypes for heat tolerance over 2 years at ICRISAT. The genotype ICCV 98902 had a critical temperature of 38 °C or above during the pod-filling period and produced the highest grain yield under heat stress. In another study, it was found that the heat-tolerant genotypes ICC 1205 and ICC 15614 had greater pod-setting ability compared to the heat-sensitive genotypes ICC 4567 and ICC 10685 when exposed to heat stress at the reproductive stage under both field and controlled environmental conditions (V. Devasirvatham, unpublished results).

31.6 Breeding Strategies for Heat Tolerance

Breeding efforts exclusively dedicated to developing heat-tolerant chickpea cultivars have been limited. However, several breeding lines (e.g., ICCV 07104, ICCV 07105,

ICCV 07108, ICCV 07109, ICCV 07110, ICCV 07115, ICCV 07117, ICCV 07118, and ICCV 98902) and cultivars (JG 14, JG 16, JG 130, JAKI 9218, JGK 2, KAK 2, ICCC 37, NBEG 3, Vishal, and Vaibhav) developed from the breeding material selected at ICRISAT were found to have good levels of tolerance to heat stress at the reproductive stage. These were basically selected for drought tolerance, but as drought and heat stresses often occur together at Patancheru, these may have also been selected for heat tolerance. Patancheru is indeed an ideal location for screening chickpea for heat tolerance because of its climatic conditions. It is located at latitude 17° 36′ 10″ N and longitude 78° 20′ 39″ E, and has a warm and short growing season (90–100 days) for chickpea.

The effective, efficient, and simple field screening technique for heat tolerance developed at ICRISAT and several sources of heat tolerance identified from chickpea germplasm/breeding lines have opened new opportunities for chickpea breeding for heat tolerance. ICRISAT in partnership with the Indian National Agricultural Research Systems has initiated concerted efforts to develop heat-tolerant chickpea cultivars adapted to different agroecologies.

The breeding method being used involves crossing of selected popular cultivars with heat-tolerant sources. Rapid generation turnover, as suggested by Gaur *et al.* [92], is often used to advance the generations and accelerate the breeding process. F4 or F5 populations are grown under late-sown conditions for selecting heat-tolerant plants based on the number of filled pods per plant. Single-plant progenies are developed from the selected heat-tolerant plants with the desired seed quality (seed size, color, and shape). The progenies are further screened for heat tolerance and also evaluated separately for resistance to key diseases, like *Fusarium* wilt and dry root rot. The top progenies are evaluated in replicated yield trials at the research station and then short-listed progenies are further evaluated in multilocation yield trials.

Marker-assisted selection for heat tolerance can further accelerate the breeding process and facilitate combining different desired traits (e.g., resistance to diseases, seed quality, etc.). Excellent progress has been made in the development of genomic resources for chickpea during the past decade. The availability of a large number of molecular markers, dense genetic maps, and markers associated with some desired traits have made it possible to integrate genomics technologies into chickpea breeding programs [93]. Recombinant inbred lines are being developed from crosses between highly tolerant and highly sensitive lines for heat tolerance. These will be used to identify molecular markers linked to heat tolerance genes. Efforts will also be made to identify candidate genes for heat tolerance.

There is also a possibility of developing a pollen selection method for heat tolerance, similar to that developed for cold tolerance. Clarke and Siddique [94], at the Centre for Legumes in Mediterranean Agriculture in Australia, developed a pollen screening method for cold tolerance in chickpea based on *in vitro* germination of pollen pre-exposed to chilling temperature and used it for transferring cold tolerance from ICCV 88516 (CTS 60543) to the popular variety Amethyst. Pollen grains of ICCV 88516 were exposed to chilling temperature for 3 days before using them for pollination on Amethyst. Similarly, pollen from the resultant F1s were subjected to cold tolerance screening before their use in backcrossing to Amethyst. The pollen-selected progenies were as good as the cold-tolerant parent in pod setting, and led to the development and release of chilling-tolerant cultivars Sonali and Rupali [95]. A pollen selection method for heat tolerance has been developed in cotton [96] and can be developed for chickpea. Pollen selection through heat treatment will further improve the efficiency of chickpea breeding for heat tolerance.

A heat-tolerant chickpea breeding line ICCV 92944 developed at ICRISAT has been released for cultivation in Myanmar (as Yezin 6) and India (as JG 14). Owing to its heat tolerance, it was specifically released for late-sown conditions in India. JG 14 has emerged as a promising variety for late-sown conditions in India, particularly in rice-fallows where sowing is delayed due to late harvest of rice.

It is anticipated that several new heat-tolerant cultivars of chickpea will be released in the coming years and provide greater choices to the farmers. The heat-tolerant cultivars will further improve adaptation of chickpea to climate change and help in expanding chickpea cultivation to areas/growing conditions prone to heat stress.

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