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REVIEW

Dry root rot disease: Current status and future implications for chickpea production

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Abstract Chickpea is one of the most important food legumes in the world. Several abiotic and biotic factors limit chickpea yields, notably, heat, drought, and dry root rot (DRR) disease. The occurrence and severity of DRR are further magnified by abiotic stresses. This review highlights the current impact of DRR on chickpea production in India, the deepening of the economic losses caused by DRR owing to drought, and integrated management practices to curb DRR. Management strategies and research targeting this aspect are critical because the long-term consequences of this rapidly emerging disease could be severe owing to climate change.

Significance statement: Dry root rot (DRR) is an emerging disease of chickpea caused by a necrotrophic fungal pathogen. DRR is already responsible for significant yield losses in chickpea. Furthermore, drought and heat stress increase DRR severity and incidence. This implies that in the future changing climate scenario, DRR could cause even higher economic losses in chickpea. Research in this field would aid in understanding the mechanisms of the disease and possibly reduce future losses caused by the disease.

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Keywords Dry root rot · Chickpea · Drought · Heat stress · *Macrophomina phaseolina*

Introduction

Among legumes, chickpea (*Cicer arietinum* L.) production ranks fifth in the world, with a significant portion of the production contributed by India [1]. Like most legumes, chickpea is a good source of protein, minerals, and phytochemicals. The protein content of chickpea is 21.2 g/100 g of seed fresh weight, which is lower than that of some other legumes such as pea (23.4 g/100 g seed fresh weight) [2]. However, once cooked, it has a relatively higher protein digestibility score of 0.71 among legumes, implying that chickpea protein is of superior quality and is easily digestible owing to its amino acid composition [1]. It is an affordable source of protein for vegetarians and vegans and is also known as poor man's meat. There are mainly two types of chickpea, i.e. desi and kabuli. Desi chickpea is the preferred type in India, mainly due to the various forms in which it can be consumed. Desi varieties are consumed as whole or split seeds/gram, also known as *chana dal*, which can also be ground into a flour known as gram flour. The consumption of sprouted seeds is also common. In contrast, kabuli varieties are consumed as whole grain, either as a curry or in salads.

The season for cultivating chickpea varies with geography. For instance, in the USA, Turkey, and the Mediterranean region, chickpea is a spring crop, sown between February and March. However, in Southeast Asia and Australia, chickpea is a winter crop, sown between September and November [3]. These can be referred to as spring-sown and winter-sown chickpea, respectively. In India, chickpea cultivation occurs during the rabi season, spanning October to March (winter) [3]. Chickpea can be cultivated in both irrigated and rainfed conditions. It is cultivated mainly under rainfed conditions in India; only ~ 31% of chickpea cultivation area is under irrigation (Supplementary Table 1). Under rainfed conditions, chickpea encounters terminal drought, i.e. drought towards the end of the growing season, which significantly compromises crop yield. Hence, soil water content is one of the key limiting factors of chickpea production.

Over the last decade, an average of 12.84 million tonnes of chickpea was produced each year globally. India was the largest producer of chickpea, contributing to an average of 8.68 million tonnes of chickpea per annum, followed by Australia and Myanmar, with 0.75 and 0.52 million tonnes per annum, respectively (Fig. 1a) [1]. Over the past decade, Egypt was the largest importer of chickpea, followed by India. Meanwhile, Australia was the largest exporter of chickpea in the last decade [1]. India has the highest area under chickpea cultivation, at 9.05 million hectares, which explains the highest chickpea output in the world (Fig. 1b) [1]. However, India remains one of the largest importers of chickpea, demonstrating a supply–demand gap, partly attributable to the yield loss due to numerous biotic and abiotic factors and factors such as low adoption of high-yielding varieties and a large population (Fig. 1c). Chickpea yield loss caused by different biotic and abiotic factors in India is depicted in Fig. 1d (Supplementary Table 2). DRR disease is a major biotic factor that has the potential to widen the current supply–demand gap and affect the affordability of chickpea to low-income groups. This review provides information on the roles of drought, heat, dry root rot (DRR), and integrated disease management in affecting chickpea yield in India.

DRR Disease Threatens Chickpea Cultivation

DRR is an emerging and potentially destructive disease, especially in Indian chickpea farms. *Macrophomina phaseolina* (Tassi) Goid. (previously referred to as *Rhizoctonia bataticola* (Taub.) Butler), a soil-borne necrotrophic fungus, is the causal agent of DRR. The name *M. phaseolina* is currently the accepted name. Upon interaction with chickpea, *M. phaseolina* propagates via dark-coloured branched hyphae and produces black microsclerotia as resting structures [4]. It infects the roots by causing necrosis of

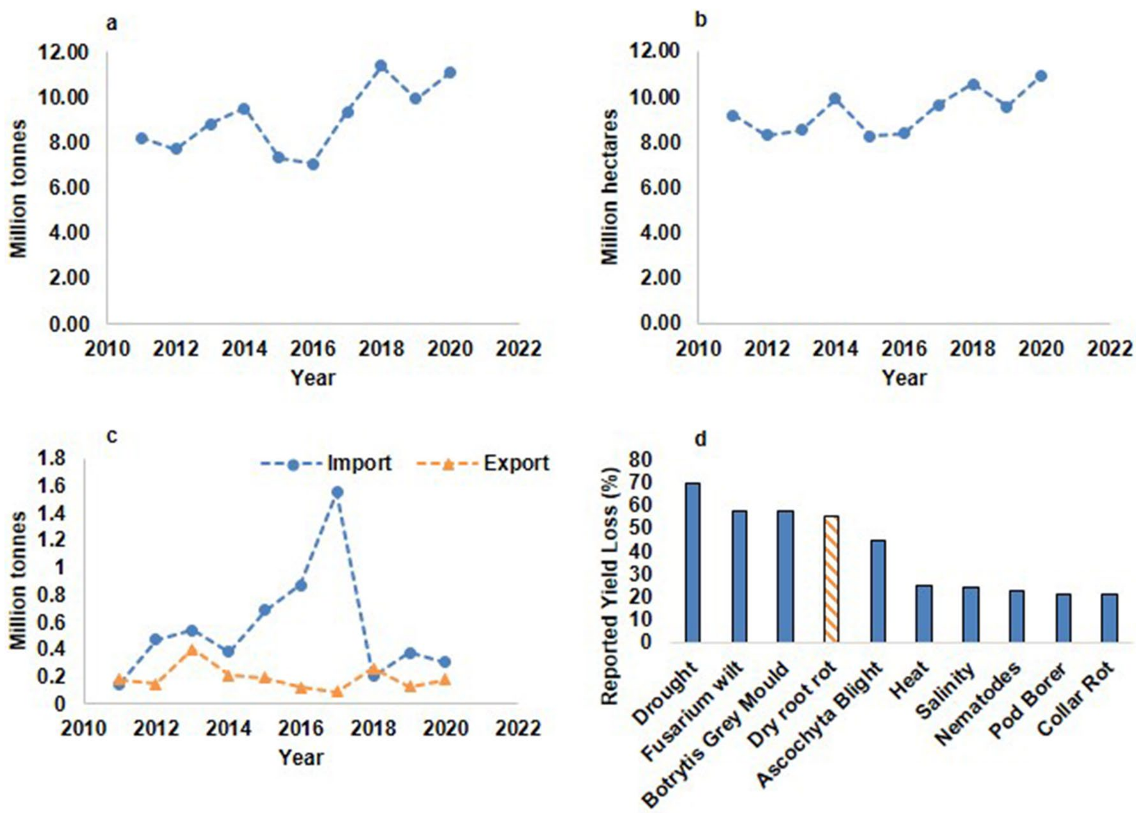


Fig. 1 Status of chickpea production and yield loss due to various factors in India. **a** Total production of chickpea in India during the last ten years. **b** Area under chickpea cultivation in India during the last ten years. **c** Import and export quantity of chickpea in India during the last ten years. **d** Average yield loss in chickpea caused by various biotic and abiotic factors reported in various studies (also refer to Supplementary Table 2)

the epidermal cells. The hyphae then grow inter- and intracellularly, causing extensive cortical necrosis before finally colonizing the vascular bundles [4]. However, aerial symptoms are not commonly observed in field conditions during the vegetative stage (Fig. 2). This poses a challenge in the early detection and prediction of the disease, as plants in the farmers' fields generally appear healthy until the flowering or podding stage. However, under extremely hot and dry conditions, even seedlings can be infected, leading to early disease [5]. Once symptoms appear, several plants in the field become entirely straw-coloured in uneven patches and die shortly after (Fig. 2a). In terms of root symptoms, the taproot becomes rotten and black, devoid of lateral roots (Fig. 2b, c). The plant can be easily uprooted without much force due to the rotten tap root. Several minute black microsclerotia can be observed in the root's central pith region when split open (Fig. 2d, e). These are the typical symptoms of DRR and can differentiate DRR from *Fusarium* wilt [4].

M. phaseolina is widely distributed across India (Fig. 3). The broad host range permits its extensive distribution in India. Further, the genetic diversity of *M. phaseolina* within India is very high [6]. The strains have a high degree of variability in their virulence and vary in sensitivity to chlorate and fungicides [6]. *M. phaseolina* survival in the soil depends on several factors such as moisture, pH, and temperature [4]. These factors influence the survivability and germination of microsclerotia, disease incidence, and disease severity. Microsclerotia survivability in the soil can be as long as 15 years [5]. The fungus can also survive on host plant debris and residues even after harvest [5]. Thus, monocultures without crop rotation can increase soil inoculum every year [4, 7]. Future research aimed at understanding the pathogen biology and host–pathogen interaction in this disease is required for employing effective management strategies.

Fig. 2 Typical dry root rot disease symptoms in chickpea. **a** Field image showing DRR-affected prematurely dried plants in a farmer's field. **b** Individual plant showing healthy foliage and roots. **c** Individual plant with dried yellow foliar symptoms. **d** Image of a split non-infected root. **e** Tap root with fungal microsclerotia in vascular and pith regions (arrows head). Chickpea fields in Anantpur, Andhra Pradesh (14.922662° N, 77.263522° E), were visited for dry root rot disease occurrence. Scale bar = 5 cm (**b** and **d**) and 1 mm (**c** and **e**)

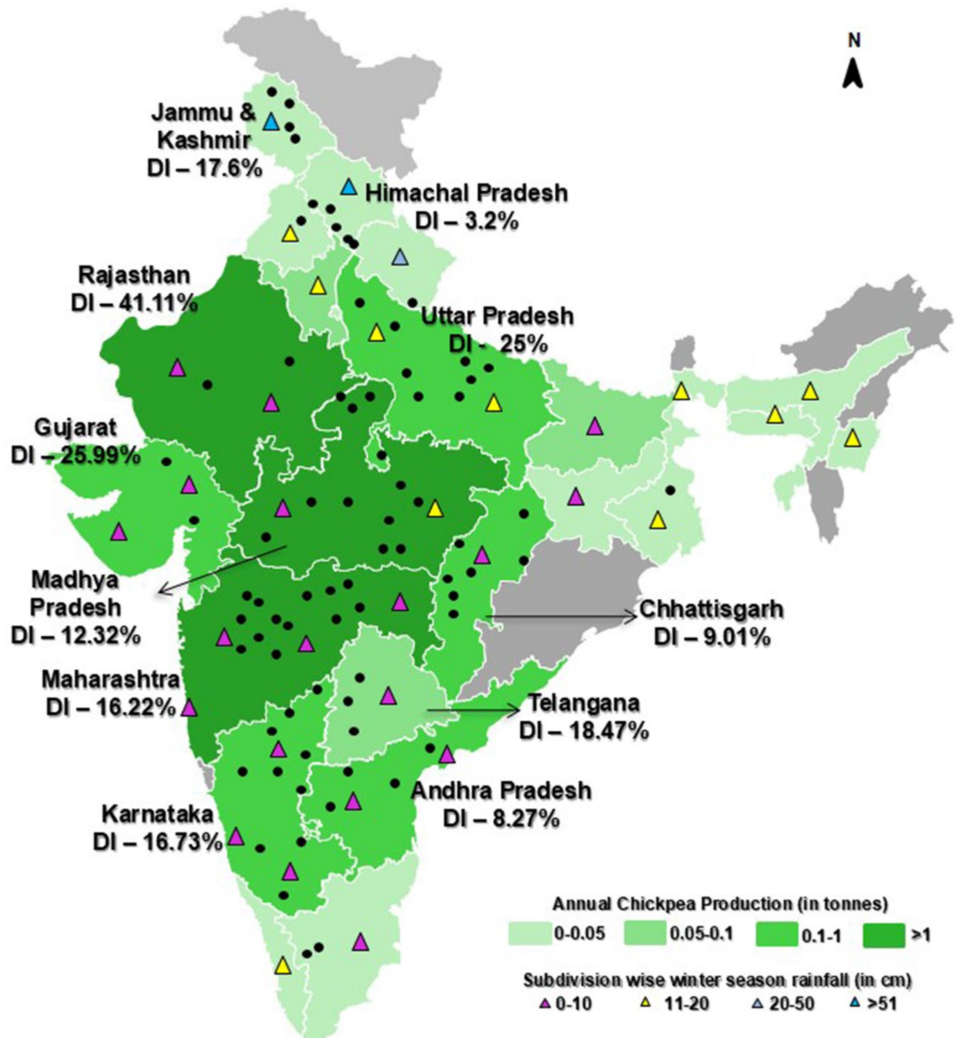


Fig. 3 Map of India depicting state-wise average annual chickpea production, dry root rot disease incidence, and meteorological subdivision-wise winter season rainfall. The colour gradient of the states is based on the average chickpea production. Major chickpea-producing states and dry root rot (DRR) disease incidence in various districts from field trials or surveys (Supplementary Table 4). Black dots represent the districts where DRR has been reported and/or studied (Supplementary Tables 4). The triangles represent the winter season (January to February) over 10 years (2008–2017) in meteorological subdivisions in India. The triangles are colour-coded according to the amount of rainfall during the winter months in millimetres (Supplementary Table 3)

Climate Change Aggravates DRR Disease Occurrence and Severity

One of the most prevalent abiotic factors limiting chickpea yield is drought [8]. Areas under drought/desertification are increasing in India. It can cause yield losses to the tune of 40–100% in susceptible genotypes and under concurrent combined stress factors such as heat [9]. About 44% of India's total area is under mild or severe drought, highlighting that a significant area of chickpea cultivation in India experiences drought (DEWS, iitgn.ac.in, 2020). Terminal drought can hamper reproductive success and thus, pod formation, thereby reducing yield [3]. Late sowing (late November to December) can further lead to an increased chance of encountering terminal drought, which is also accompanied by deficient rainfall during January and February (Supplementary Table 3). Moreover, mycelial growth, sclerotial germination, and sclerotial viability in the soil are higher at elevated temperatures and low soil moisture [10]. Consistent with this, several reports have shown that drought and high temperatures intensify DRR symptoms, root colonization and increase disease incidence [11–13]. Major chickpea-growing regions are already under drought stress and would thus be highly susceptible to DRR, potentially adding to the economic losses caused by drought alone. Further, as peak DRR symptoms appear during the reproductive and post-reproductive stage, terminal drought can worsen yield losses. Erratic rainfall can occur in the early stages of chickpea's life cycle, which drives a significantly higher number of potential DRR outbreaks even during the early stages of the plant's life cycle [3].

Heat stress is another key factor impacting chickpea production. Heat stress often occurs concurrently with drought. Such concurrent stresses can cause significantly higher losses than each of these individual stresses alone [14]. Heat stress has been known to increase the susceptibility of several plants to pathogen attack [14]. Spring-sown chickpea encounters high temperatures (> 30 °C) but rarely faces terminal drought, while winter-sown chickpea faces relatively lower temperatures [3]. Chickpea yield has been found to be associated with anthesis and pre-anthesis mean temperature and seasonal rainfall, implying that heat stress during the reproductive stage is particularly detrimental [15]. The impact of heat stress on reproductive growth causes yield losses of up to 100% [9, 16]. In India, the southern states with higher temperatures are usually associated with lower yield than those of the northern states [15] (Fig. 3 and Supplementary Table 1). Studies conducted by Berger et al. [15] showed an association of phenological differences in chickpea genotypes developed and adopted in northern and southern parts of India and yield. Low yield was associated with lower latitudes, early flowering for drought escape, higher temperatures and low biomass. Further, similar to the correlation between drought and DRR severity and incidence, heat is also directly associated with DRR in chickpea. High temperatures (> 30 °C), especially those during the reproductive stages, can increase disease incidence and DRR severity, which would further compromise chickpea yields [17]. Moreover, temperature extremes and drought frequencies and severity are predicted to increase in the current climate change scenario, making the situation worse in the coming years [3, 18–20]. It has been shown that temperature and rainfall fluctuations over long periods of time can directly impact the yield of crops. The association among chickpea yield, drought, temperature, and DRR indicates that in the coming years, DRR along with heat and drought could cause significant yield losses. As chickpea is of importance to poor and marginalized people, it is particularly concerning that this crop will become increasingly expensive or out of reach. This could also affect the marketability and increase the dependency on imports to meet the domestic demand.

Impact of DRR on Chickpea Production in India

The average annual chickpea production in the past decade for each state in India is depicted in Fig. 3. The average yield ranges from 0.6 to 1.41 kg/ha (Supplementary Table 1). The high variability in yield across Indian states could be due to variations in climatic factors and subsequent predisposition to DRR, as well as the chickpea varieties adopted and cultural practices employed. In terms of national yield, the annual average is 0.94 tonne/ha. This is significantly lower than the world average of 1.38 tonnes/hectare (Fig. 4a). One of the possible factors could be the different climatic conditions and their direct effect on DRR disease occurrence between high- and low-yielding countries. Australia and most of the chickpea-producing countries in Southeast Asia except China usually have a lower-than-average yield, while those in the Mediterranean and the Americas, where chickpea is primarily spring-sown, have a higher yield (Fig. 4a). Due to sowing time differences between these two chickpea-growing regions, spring-sown chickpea evades terminal drought and therefore the amplification of DRR stress by drought; this escape might contribute to a higher yield [3]. Furthermore, the impact of *M. phaseolina* is likely more pronounced in lower-yielding countries as it is commonly distributed in these regions since the climatic conditions are conducive for the fungus. In addition, the low adoption rate of chickpea varieties resistant to abiotic and biotic stresses in India compared to other countries such as Israel might explain the lower yields [21].

DRR disease incidence among different states of India is highly variable, ranging from 3.2 to 41.11% (Fig. 3 and Supplementary Table 4). According to several field studies and surveys, Rajasthan has the highest (41.11%) reported disease incidence in the only surveyed district, followed by Gujarat, where data are available for multiple districts. Himachal Pradesh, Andhra Pradesh, and Chhattisgarh have significantly lower disease incidence (Supplementary Table 4). Relatively higher DRR disease incidence in Rajasthan, Gujarat, and Karnataka could likely be due to low rainfall and high temperatures towards the end of the growing season in certain regions of these states, leading to severe terminal drought stress. In addition to climatic variability, differences in cultivars adopted, sowing time, and management practices also cause high variability of disease incidence among the chickpea-producing states in India.

Nonetheless, it is challenging to correlate winter season rainfall to variability in disease incidence because consistently low rainfall is observed in most parts of India during this season (Fig. 3). The chickpea cultivation area under irrigation is variable among Indian states. Madhya Pradesh has the highest per cent chickpea cultivation area under irrigation at 77.99%, while Nagaland, Assam, and Bihar have the lowest, with approximately 5% of the total chickpea cultivation area under irrigation (Fig. 3 and Supplementary Table 1). Rajasthan has a high area under irrigation (76.16%) but still has a yield lower than the Indian average. This could be ascribed to the high DRR incidence observed in the state (Fig. 3 and Supplementary Table 1). Except for Bihar, Jharkhand and Andhra Pradesh, most states with low area under irrigation (less than 20% of the total chickpea area) have yields lower than the national average of 0.94 kg/ha, consistent with the fact that drought and subsequently drought-related susceptibility to biotic factors lead to elevated yield losses (Fig. 3 and Supplementary Table 1). Many of the states in the Indo-Gangetic plains have a relatively higher yield and production (Fig. 3), while states in the extreme south have lower yields and production. This is most likely due to the adoption of early flowering and wilt-resistant varieties in the Indo-Gangetic plains to evade drought and high-temperature stress [22]. Although a link between rainfall and DRR disease incidence and subsequently chickpea yield is expected, a clear manifestation of

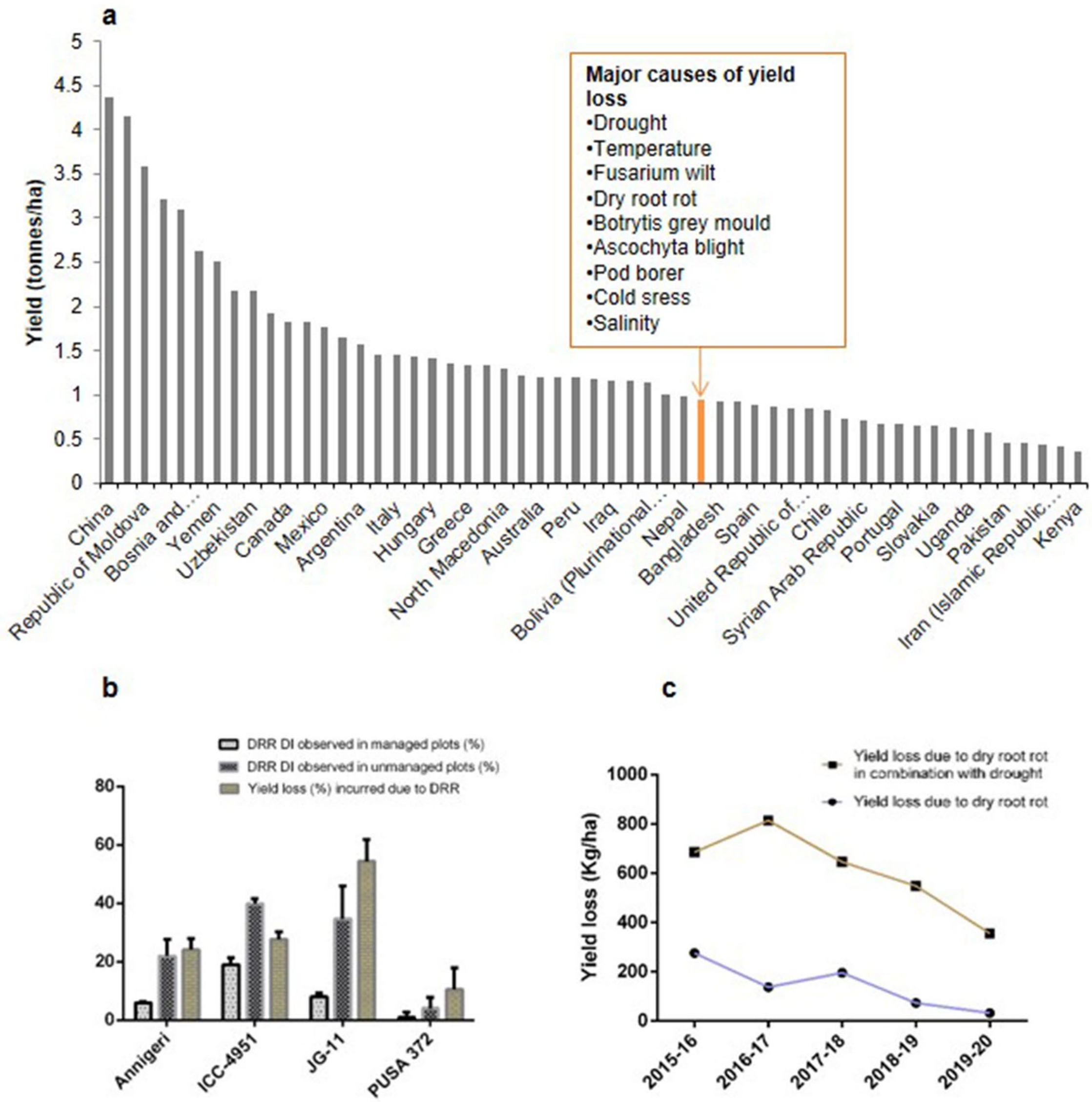


Fig. 4 The susceptibility of popular chickpea cultivars to dry root rot disease. **a** Comparison of chickpea yield in tonnes per hectare in India and other chickpea producers in the world. India is highlighted in orange. **b** DRR disease incidence and yield loss due to pathogen stress under recommended management practices and no management practices. The data were collected from the literature drawn pertaining to field experiments conducted across five locations (Dharwad, Jaipur, Bangalore, Bapatla, and New Delhi) to manage dry root disease in chickpea. **c** Yield loss (kilograms per hectare) observed under DRR disease (pathogen) and its combination with drought stress are shown. The data were taken from the yearly field trial experiments conducted at New Delhi (28.530099° N, 77.165381° E) and Bangalore (13.0876697° N, 77.5711829° E). Two varieties, PUSA-372 and JG-62, were used during the trials

this association is not observed due to unequal percentage area under irrigation for chickpea and variability in other management practices in different states (Land Use Statistics, Directorate of Economics And Statistics, Ministry Of Agriculture, Government Of India—https://aps.dac.gov.in).

Reports of yield loss in chickpea caused by DRR are scarce. Studies conducted in Bihar showed a significantly higher yield loss and reduction in seed weight caused by DRR at the podding stage [23]. Using yield data from studies on management practices of DRR, yield loss percentage caused by DRR was calculated and is presented here (Fig. 4b). Over 50% yield loss was observed in certain susceptible cultivars, and as expected, disease incidence was significantly higher (~ 10 to 30%) in unmanaged chickpea plots relative to managed plots (Fig. 4b). Even in moderately resistant cultivars such as PUSA-372, a calculated yield loss of up to 10% was observed, which could be even higher under drought and temperature stress (Fig. 4b). Although PUSA-372 is tolerant to DRR, it is a late-maturing variety, which could account for some of the yield loss caused by

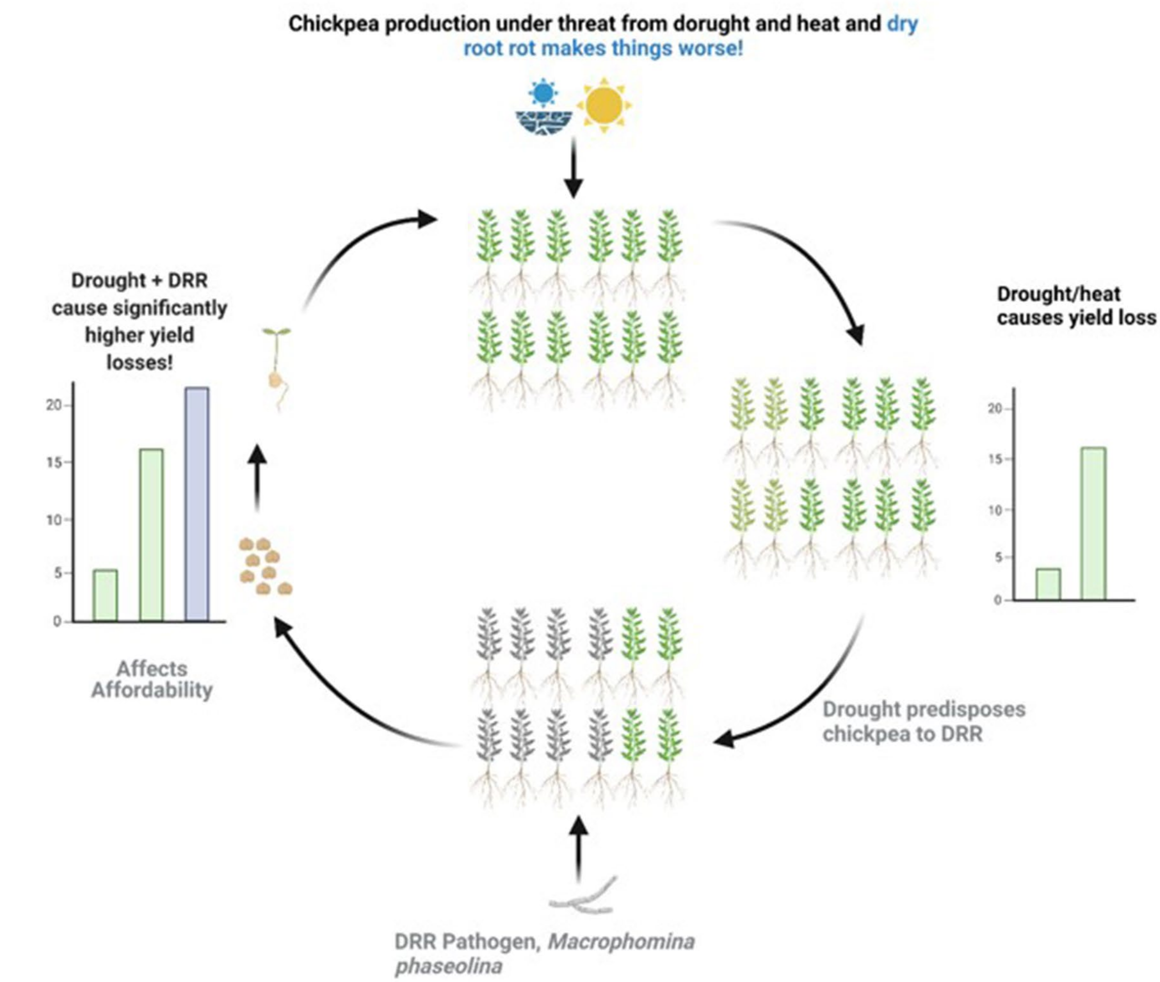
DRR (Directorate of Pulses Development, http://dpd.gov.in/, 2021). Further, field trials conducted in New Delhi and Bangalore showed that combined pathogen and drought stress deepens economic losses caused by DRR, as combined stress leads to significantly higher yield loss relative to pathogen stress alone (Fig. 4c) [11]. DRR could very likely become a major threat not only to chickpea production but also to several other hosts of the disease, such as wheat, maize and several pulse crops. Future climatic conditions conducive to the fungus are likely to have a significant impact on chickpea production.

Integrated Management of DRR in Farms

As DRR is a soil-borne disease, one of the most effective ways to control the disease is by reducing the fungal inoculum, i.e. hyphae and microsclerotia, in the soil. This can be done by adopting cultural practices such as low to no-tillage, which decreases soil moisture; proper irrigation, especially during the reproductive stage; crop rotation with potential non-host crops; removal of the previous season's infected debris; and altering the sowing time, especially for early-maturing varieties to evade drought [4, 7]. Another effective technique to control soil-borne pathogens is soil solarization. This approach is effective against root rots caused by several fungal pathogens. Biosolarization, a combination of soil solarization and biofumigation, reduces the incidence of charcoal rot and could be effective against DRR as well [24]. One of the most studied and most effective ways to control the DRR of chickpea is the pre-treatment of seeds with chemical fungicides and biocontrol agents. Treatment of soil with fungicides is also a common practice that reduces fungal inoculum in the soil and likely prevents disease during the later stages of the plant's life cycle. Figure 4b depicts the difference between a managed (disease control measures and resistant varieties) plot and an unmanaged plot in terms of disease incidence from several studies. Among biocontrol agents, *Trichoderma viride* and *T. harzianum* in combination with *Pseudomonas fluorescens* showed the highest efficiency in controlling root rot of chickpea and groundnut [25]. Chemical fungicides such as carbendazim (trade names: Bavistin, Derosal), hexaconazole (Hexaconazole 5%, Contaf 5% EC), and mancozeb (Indofil M-45) restrict *M. phaseolina* growth in cultures [25]. Consistently, the treatment of chickpea seeds with such fungicides can alleviate the incidence and severity of DRR [25]. Although the efficacy of chemical fungicides has been studied and established, they come with environmental and economic costs. Thus, in most cases, especially in regions prone to drought and high temperature, an integrated management plan must be adopted to tackle DRR disease effectively. The Indian government's Directorate of Pulses Development has released a list of recommended varieties developed by several research institutions. The list includes varieties resistant or moderately resistant to DRR such as ICCV-10, JG63 and CSJ 515, which could facilitate the adoption of such varieties in Indian farms, especially in regions prone to DRR (Directorate of Pulses Development, http://dpd.gov.in/, 2021). Furthermore, recently, the Government of India along with Indian Council of Agricultural Research (ICAR) released 35 climate-resilient varieties of crops, among which, two drought-tolerant varieties IPC L4-14 and BGM 4005 were also released which can be adopted to alleviate the losses caused by the increased susceptibility to DRR due to drought.

Little is known about the molecular mechanisms of plant host resistance to DRR. However, several scientific groups have screened core germplasm collections to find resistant chickpea genotypes [26]. Screening techniques such as blotting paper, sick pot, and sick plot methods have been developed and extensively used for DRR resistance screening [27, 28]. Resistant genotypes identified by several screening techniques have rarely shown robust resistance to DRR [4]. Among the genotypes screened by several groups, lines such as GBM-2, PG06102, BG2094, ICCV-10, IC552137, GBM-6, RSG-143, RSG-896, and RSG-973, GCP-101 are resistant or moderately resistant. However, as screening is usually done under controlled laboratory or greenhouse conditions, it is difficult to evaluate the response of resistant or tolerant genotypes in varying climatic and geographic conditions [4]. Moreover, while screening in controlled conditions is efficient and easy, it should be supported by field studies wherever possible. This will provide robust results and provide better candidate cultivars for future research and cultivation. Screening with diverse *M. phaseolina* strains is essential to ensure that resistance is durable and robust. Some groups have utilized molecular mapping to identify markers in certain chickpea genotypes associated with resistance to DRR [23, 29]. Karadi et al. [23] identified a minor quantitative trait locus linked to DRR resistance on the chickpea linkage group 8 using a recombinant inbred line (RIL) population. Two markers, CCM0299 and ICCM0120b, have been shown to co-segregate with resistance to DRR. Such marker data for DRR and other stresses, and the identification of resistance sources can be effectively used to develop resilient and high-yielding varieties.

Another hurdle in the management of the disease is its efficient and timely detection. DRR is practically indistinguishable from *Fusarium* wilt and other root rot diseases [4, 30]. PCR-based molecular methods are currently extensively being used to detect root rot pathogens in plants and soil. These techniques, however, are not cost-effective and require expertise in molecular biology tools. However, a faster and easier technique based on the loop-mediated isothermal amplification assay was developed to detect *M.*


Chickpea production under threat from dorught and heat and dry root rot makes things worse!
Drought + DRR cause significantly higher yield losses!
Drought/heat causes yield loss
Affects Affordability
Drought predisposes chickpea to DRR
DRR Pathogen, *Macrophomina phaseolina*
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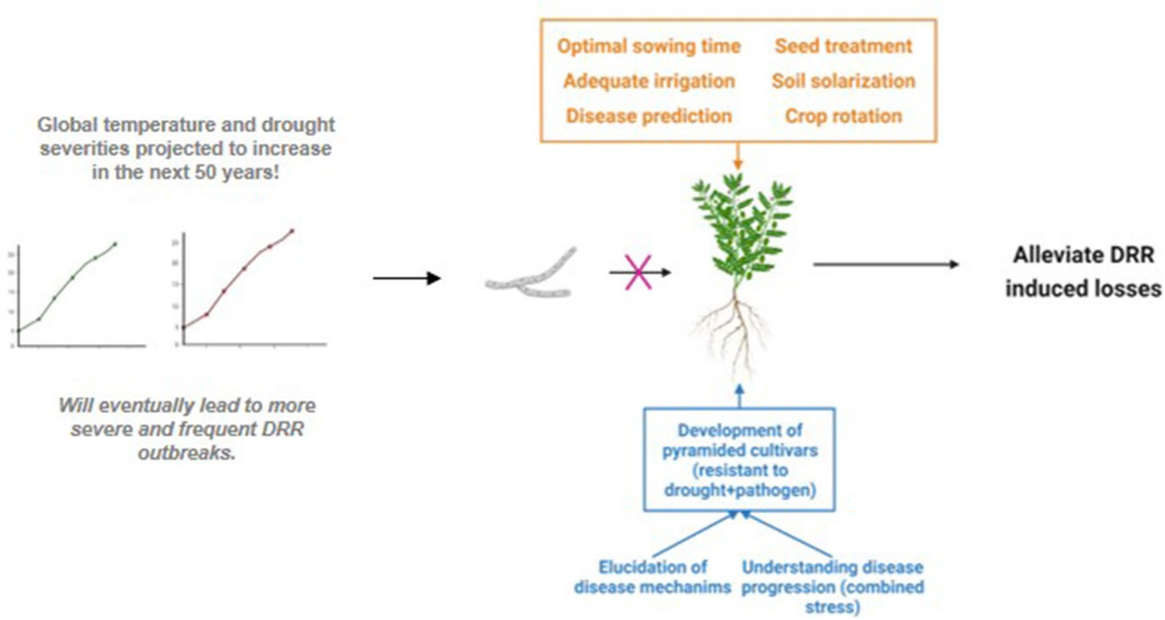
Optimal sowing time
Seed treatment
Adequate irrigation
Soil solarization
Disease prediction
Crop rotation
Global temperature and drought severities projected to increase in the next 50 years!
Will eventually lead to more severe and frequent DRR outbreaks.
Alleviate DRR induced losses
Development of pyramided cultivars (resistant to drought+pathogen)
Elucidation of disease mechanims
Understanding disease progression (combined stress)

◂**Fig. 5** Infographics depicting the current and future threat of DRR to chickpea production and affordability. Drought and heat are major yield-limiting factors of chickpea. These stresses subsequently predispose chickpea to DRR disease caused by the pathogenic fungus *M. phaseolina*. These stresses occurring together lead to severe losses in chickpea farms. It also widens the supply–demand gap, which could potentially affect the affordability of chickpea. Climate change projections indicate that global temperatures and drought frequencies and severity are on the rise. Coupled with DRR, this could put chickpea production in India under significantly higher pressure in the future. However, efficient agronomic practices can reduce the impact of DRR in chickpea farms. Targeted research on the mechanisms of the disease will aid in developing pyramided varieties resistant to DRR, as well as heat and drought, which will support such cultural practices. Infographics was created using biorender.com. *Graphs used in the infographic are for representative purposes only and are based on trends and data observed in literature and in public databases*

phaseolina [30]. Further research in this area could lead to developments allowing easier detection even by a layperson. This will aid efficient and timely management of DRR in chickpea farms and will also benefit deeper research on this disease.

Conclusion and Future Perspectives

Abiotic factors such as heat and drought increase the susceptibility of chickpea to DRR, further worsening yield losses. Although several DRR tolerant genotypes have been recommended, resistance is often not durable, and generally, such genotypes are not tested in diverse climatic conditions. Wilt-resistant varieties have a high adoption rate in the semi-arid tropics, but several of these varieties show moderate to little tolerance to DRR. Although some chickpea varieties moderately resistant or resistant to DRR, such as ICCC-37, JG63 and RSG 974 have been released for cultivation, poor adoption of DRR-resistant varieties remains a concern. This points to a lack of awareness among farmers. Generating awareness through agricultural extension systems at State Agricultural Universities and Krishi Vigyan Kendras will increase the acceptance and cultivation of varieties resistant to DRR and combined stress.

In addition, there is a need to deploy pyramided varieties with robust and durable tolerance/resistance to multiple biotic and abiotic stresses or a combination thereof to reduce losses caused by drought and alleviate drought-induced susceptibility to DRR. Elucidation of molecular mechanisms of resistance to DRR and drought-related susceptibility will be fundamental in developing such varieties. This should be bolstered by adopting new and improving existing management techniques to offset the losses caused by DRR. Further, climate change will usher in temperature extremes and more frequent and severe drought in the future. Disease incidence, pathogen distribution, and yield loss are all likely to increase. These factors will dictate the availability and affordability of chickpea in the market for a common person (Fig. 5). Collective efforts are required to utilize available knowledge and literature (Supplementary Table 5) and further understand the mechanisms of the disease, predict its occurrence, and tackle it to improve food security.

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Author contributions MS-K conceptualized and outlined the review. RM wrote the initial draft. MS-K and RM revised and edited the manuscript. VI and ARC contributed to Fig. 2 and Fig. 4, respectively, and to the supplementary Table 5.

Declarations

Conflict of Interest The authors declare that they have no conflict of interest.

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