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A comprehensive review on grain legumes as climate-smart crops: Challenges and prospects

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ABSTRACT

Global food production needs to be doubled by 50% by the middle of 21st century to ensure the food and nutritional security for 9 billion people explicitly in the challenging scenarios such as land degradation, water scarcity and environmental pollution. Climate change is evident worldwide due to exponential rise in atmospheric carbon-di-oxide (eCO_2) and temperature (eT). It leads to more complexity in achieving the sustainable food security. Grain legumes are the major sources of dietary proteins with multifaceted impact on ecosystem services. Being the C_3 crops climate change (more specifically eCO_2) usually has positive impact on physiology and productivity of grain legumes as compared to C_4 cereal crops. Grain legumes can allocate the above ground photosynthates into the below ground parts like roots and nodules resulting improvement in plant biomass, rhizospheric activities and higher input (water and nutrients) use efficacy. However, the impact of eT on grain legume is not always favourable. High temperature explicitly in the reproductive phase is extremely deleterious causing flower abortion and abnormal pod filling. Besides, eT impairs the performance of grain legumes because of higher evaporative demand, poor root-microbial association and pest severity. Therefore, both agronomic and genetic interventions must be integrated to raise successful grain legumes and to achieve the targeted yield in the changing climatic conditions. The targeted breeding programmes should be selection of high yielding, biotic stress resistant and abiotic stress tolerant grain legume genotypes that are adapted to eCO_2 and eT conditions. Further, integrating the grain legumes with desirable traits to the food production system might impart resilience towards climate change. In this comprehensive review the impacts of climate change (eCO_2 and eT) on above and below ground crop growth, productivity, water use efficiency and disease-pest severity are thoroughly discussed. Further, climate smart technologies which make grain legumes as a perfect candidate crop in the future climatic condition are also highlighted.

1. Introduction

Indiscriminate use of natural resources like burning of fossil fuels, deforestation, intensive farming without crop rotation and residue inclusion, industrial waste and landfills are the factors that have led to large scale increase in the concentration of greenhouses gases (GHGs) [carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O)] (IPCC, 2014). Data from last five decades (1967–2017) depicted an average rise of CO_2 concentration (ppm yr^{-1}) by 155% with the highest concentration during 2015 (3 ppm yr^{-1}) along with spike in global temperature by 0.85°C over the last century (IPCC, 2014). Surprisingly, the world witnessed a rise in global average temperature and atmospheric CO_2 concentration by 0.2 °C and 20% over the last five years (2015–19), respectively as compared to 2011–15 (WMO, 2019). Based on the past climatic data, a jump of 0.3–0.7 °C temperature in next 15 years was predicted (IPCC, 2014). In fact, climate change is likely to exacerbate regional and global water scarcity to a great extent. It is estimated that the two third of the world population is already experiencing severe water scarcity (IPCC, 2014). Agriculture remains highly sensitive to the environmental fluctuations resulting from the global climate change (Lenka and Lal, 2012). Climate change impacts several aspects of agricultural production systems such include alteration in flowering phenology, water availability, soil fertility and erosion, increase in pathogen spread and host susceptibility (Rosenzweig and Hillel, 1995). These climate change induced vulnerabilities possess a serious threat to the global food and nutritional security. There is an urgent need to identify crops that can mitigate the threats of climate change. Grain legumes can emerge as one such suitable group of crops having prospects for future.

Grain legumes are nature's precious gift to mankind and often named 'poor man's meat' as these are rich in protein (16–50%),

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essential elements, dietary fibre (10–23%) and vitamins (Maphosa and Jideani, 2017). Apart from protein, grain legumes are store house of various nutritional components such as: carbohydrates, sugars, vitamins, more than 15 essential mineral elements and mono and poly-unsaturated fatty acids (Wang et al., 2009). These also serve as rich source of dietary fibres, folic acids, and non-nutritional bioactive components like polyphenolics, lectins, phytate and trypsin inhibitors (Burstin et al., 2011). Inclusion of pulses in daily diet prevents numerous health problems like cardiovascular diseases, type 2 diabetes and some forms of cancer. Grain legumes also help to reduce the risk of obesity (Burstin et al., 2011).

The grain legumes share an area of around 81 million ha with production of more than 92 million tonnes globally (FAOSTAT, 2018). India accounts for nearly 1/4th of global annual grain legumes production and the largest consumer too. China, Myanmar, Canada, Australia, Brazil, Argentina, USA and Russia are the major grain legume producing countries (FAOSTAT, 2018). Legumes are adapted to wide range of environmental conditions ranging from cool to warm season. India provides cultivating ground for various grain legumes such as, chickpea (*Cicer arietinum* L.), pigeonpea (*Cajanus cajan* L.), lentil (*Lens culinaris* L.), field pea (*Pisum sativum* L.), cowpea (*Vigna unguiculata* L.), horsegram (*Macrotyloma uniflorum* L.), greengram (*Vigna radiata* L.), blackgram (*Vigna mungo* L. Hepper), chickling pea (*Lathyrus sativus* L.) and dry bean (*Phaseolus vulgaris* L.). Globally, dry bean is the most widely cultivated grain legume with a total area of 34.5 million ha and 30.4 million tonnes productions followed by chickpea (17.8 million ha) and cowpea (dry) (12.5 million ha). In terms of productivity, field pea holds the first rank with 1718 kg ha^{-1} followed by lentil (1038 kg ha^{-1}) and chickpea (965 kg ha^{-1}) (FAOSTAT, 2018).

Grain legumes play an important role in providing the ecosystem services. Biological nitrogen fixation (BNF) capacity, deep root systems, low input requirements, propensity to survive in problem soils and withstand abiotic stresses make grain legumes as a popular choice for farming community in the intensive cereal based cropping systems (Kumar et al., 2018). Long-term cereal based cropping systems are one of the inputs intensive practices and largely responsible for GHGs emission, ground water pollution and other second generation problems (Hazra et al., 2018). The heterogeneity in the cropping system was the key to improve crop resilience to climate change and biotic or abiotic stresses (Newton et al., 2011). Grain legumes have important role in C sequestration because of their leaf fall, deep root system, symbiotic N-fixation and carbon rich root exudates (Ghosh et al., 2012). Bayer et al. (2016) reported that legumes significantly improve soil C retention in reduced tillage condition due to higher crop biomass and moderating the rate of C-mineralisation as compared to cereals. Legumes translocate a huge part of their photosynthetic C as root exudates (amino acids, phenolic acids and organic acids) and various lignin rich compounds contributing largely to the C-sequestration and reducing C foot-print (Hazra et al., 2018). Amongst the agricultural crops in China, soybean contributes around 1% of GHGs emission whereas, the contribution from cereals, vegetables, fruits and cash crops are 30%, 8%, 6% and 4% respectively (Yue et al., 2017). Alternately, legumes enrich the soil with N for the subsequent crops and curtail global CO_2 emission (>300 Tg Yr^{-1}) up to 50% that emits from N-fertiliser (urea) industries (Jensen et al., 2012). Interestingly, legume rich feeds can curtail CH_4 emission from livestock industries as it contains less fibre, faster rate of passage and contains condensed tannins and saponins which reduces cell wall digestion and modifies rumen methanogenesis (Eckerd et al., 2010). Nitrous oxide emission also found to be lower from legumes (1.02 kg N_2O–N ha^{-1} $year^{-1}$) as compared to N fertilized cereals (2.71 kg N_2O–N ha^{-1} $year^{-1}$) (Jensen et al., 2012). Positive impact of reduced GHGs emission by grain legumes has been documented by Schwenke et al. (2015). However, exceptions do exist stating more N_2O emission in legumes than cereals (Jeuffroy et al., 2013; Peyrard et al., 2016). The possible reasons behind higher N_2O emission by legumes are faster decomposition rate of N-rich residues and denitrification of symbiotically fixed N within the nodule but, more extensive multi-location research must be conducted to get concrete evidences as it is highly influenced by management practices and local climatic conditions (Bayer et al., 2016; Hauggaard-Nielsen et al., 2016). Nonetheless, role of legumes in managing GHGs and sequestering deep soil C is immense and needs thorough investigation.

In general, plants with C_3 pathways are favoured by elevated carbon-di-oxide (eCO_2) because of adaptive strategies like higher rate of photosynthesis, sharp increase in the amount of soluble sugars and starch, rise of growth promoting hormones like indole acetic acid and symbiotic nitrogen fixation (SNF) that make grain legumes superior to others (Lin et al., 2016; Palit et al., 2020). The most important mechanisms by which legume cope up with the eCO_2 is symbiotic nitrogen fixation. Legumes translocate above ground photosynthates to the nodules with symbiotic nitrogen fixation and it serves as a source of C and energy for the nitrogenase activity (Irigoyen et al., 2014). Legumes also perform well under moisture and high temperature stress conditions. One of the important mechanisms of withstanding eT and moisture stress in legumes is due to generation of anti-oxidants and trimming down peroxide production (AbdElgawad et al., 2014). Other important factors that play decisive role in adapting climate change are agronomic management practices, nutrient supplementation, water availability and frequency of occurrence of abiotic and abiotic stresses.

Globally, open top chambers (OTC) and free air CO_2 enrichment (FACE) studies on deciphering the impact of eCO_2 on shoot biomass, plant height and productivity on legumes are reported by various workers (Bindumadhava et al., 2018; Jin et al., 2012; Srinivasarao et al., 2016). De Graaffet al. (2006) interpreted using meta-analysis that eCO_2 have negligible impact on legumes under poor management conditions and nutrient deficient soils but, the situation get reversed after satisfying the necessary requirements. However, the insubstantial impact of eCO_2 on photosynthesis is known as photosynthetic acclimation or photosynthetic down regulation (Aranjuelo et al., 2014; Rogers et al., 2009). Moreover, the positive sides of eCO_2 on various legumes dilated with nutrient supplementation especially nitrogen (N) and phosphorus (P) (Palit et al., 2020; Saha et al., 2016). Inability of legumes to perform under poor N supply was due to reduced content of chlorophyll and other photosynthetic pigments, negative N-balance and development of biotic stresses (Sharma et al., 2016). The cynical impact of climate change can be seen in nutritional composition of grain legumes. Myers et al. (2014) showed the striking difference of climate change on diminution of protein and micro-nutrient content in grain legumes (C_3 crops) as compared to cereals (C_4 crops).

Climate change (eCO_2) has binary impact on water use efficiency (WUE) depending upon soil moisture content. In moderate drought condition eCO_2 increase crop WUE by lowering the transpiration rate and increasing the leaf area. Reports also suggested that legumes productivity would drastically reduce under arid and semi-arid ecologies where water availability is a great concern (Jagadish et al., 2016; Palit et al., 2020). Moisture stress in combination with eT and eCO_2 have a catastrophic impact on legume growth and productivity. Changing climate has modified the geographical distribution of pests and consequently their outbreak. Besides, secondary pest infestation increased exponentially resulting in loss of valuable produce (Sharma et al., 2016). Therefore, climate change has multi-faceted impact on legume growth and physiology. In the upcoming section, the impact and adaptation strategies of legumes as affected by climate change drivers are comprehended.

Legumes can adapt either positively or negatively under climate change depending upon internal physiological adjustment and crop husbandry practices. Indeterminate nature of legumes makes the task more daunting for climate scientists to ascertain the adaptation strategies or phenological triggers that empower legumes under changing climate. These heterogeneous and complex aspects needs to be addressed by experts considering single or sometimes multiple stressors like eCO_2, temperature or biotic or abiotic hassles through agronomical, physiological and microbiological studies. Therefore, comprehending the growth

response and adaptation of various grain legumes to climate change is important and requires multi-disciplinary interventions to meet global food and nutritional security. The objective of this paper is to undertake exhaustive review on multi-disciplinary challenges associated with global climate change and to find out the prospects of grain legumes to consider as climate smart crop.

2. Above ground response

2.1. Impact on shoot biomass

The prospects of future use of grain legumes as climate smart crop might sound exciting, but the adverse effect of climate change on the performance of legumes raises questions and invites challenges to deal with. Climatic anomalies and rise of GHGs and temperature makes the task of achieving targeted yield and ensuring nutritional security more challenging and complex. Studies showed that the rising levels of temperature and CO_2 concentration exert direct and indirect impacts on physiology and bio-chemical characteristics of grain legumes. Extensive work has been done to understand out-turns of climate change on legume growth. The basic anatomical difference of C_3 crops is to sequester atmospheric C which keeps legumes many steps ahead of C_4 in terms of adaptability; however, the extent of exposure is one of the key factors always to be considered (Palit et al., 2020). Growth response of a C_3 plant differs from that of C_4 because of differential CO_2 saturation point (50–150 mg L^{-1} CO_2 in C_3 and 1–10 mg L^{-1} CO_2 in C_4 respectively), which in turn facilitates C_3 to acquire higher photosynthetic response and maintain the positive growth rate (Jin et al., 2012; Lee, 2011). Multifaceted studies clearly highlighted significant positive response of eCO_2 in different grain legumes. Srinivasarao et al. (2016) from an OTC study reported the increase in shoot and overall biomass of blackgram and pigeonpea by 35.4%, 27.3% and 33.3%, 26.8% from ambient (350 ppm CO_2) to elevated condition (550 ppm CO_2), respectively. C_4 crops like pearl millet, sorghum failed to perform better under elevated CO_2 condition (Srinivasarao et al., 2016). Higher substrate (CO_2) availability in legumes escalated the rate of photosynthesis via carboxylase activity and simultaneously curtailed reduced photorespiration (Srinivasarao et al., 2016). Similar positive response of eCO_2 on growth and yield attributes are seen in other grain legumes too such as chickpea (Jin et al., 2013), pigeonpea (Saha et al., 2011), lentil (Nasser et al., 2008), fieldpea (Lam et al., 2012) and greengram (Pandey et al., 2016). The impact of eCO_2 on yield attributes on different legumes are summarised in Table 1. Inarguably, grain legumes are by far the most climate smart crops but, to achieve it legumes require optimum supply of primary nutrients such as N, P and K and soil moisture. Meta-analysis from several FACE experiments showed the complex relationship between crop performance, eCO_2 and applied inputs (Kimball, 2016). Results indicated that in presence of N and water, C_3 legumes (soybean and clover) showed up to 25% increase in shoot biomass whereas, the respective response from C_3 cereals (wheat, rice, and barley) was 19% and it was almost negligible in C_4 crops viz. sorghum and maize. Interestingly, in absence of N, the C_3 cereals showed only 10% increase in shoot biomass whereas legumes due to BNF showed positive growth rate without any yield penalty (Kimball, 2016). Previous work by Thomas et al. (2006) also highlighted the importance of innate traits like BNF, rhizobial or mycorrhizal infection in sustaining crop performance and alleviating photosynthetic down regulation under eCO_2. Further, it was hypothesized that dilution of tissue nutrient concentration increase use efficiency of major nutrients (Lam et al., 2012). Generally, performance of dicots (legumes) was better than monocots (cereals) under eCO_2, but, later are more prone to water stress as compared to formers particularly during reproductive stage (Newton et al., 1996). Under eCO_2 gain in shoot biomass was more in wheat (55%) than fieldpea (36%) (Butterly et al., 2015). Though, extensive studies have been conducted to show influence of N-fertilisation on legume growth under eCO_2 few of them focuses on other nutrients like P and K. The

Table 1
Effect of eCO_2 on legume growth and yield.

Crop	Experimental site	Experimental condition	Concentration of CO_2	Yield response (over ambient CO_2)	Refs.
Pea	Pamplona, Spain	controlled environment chambers	Ambient (360 ppm) Moderately elevated (700 ppm) Elevated (1000 ppm)	↑ (60% in biomass)	Cabrerizo et al. (2001)
Kabuli Chickpea	New Delhi, India	Open Top Chambers	Ambient Elevated (580 ppm)	↑ (44% in stem biomass)	Saha et al. (2011)
Pigeon Pea	New Delhi, India	Open Top Chambers	Ambient Elevated (580 ppm)	↑ (41% in biomass)	Saha et al., 2011
Black gram	Hyderabad, India	Open Top Chambers	Ambient (390 ppm) Elevated-1 (550 ppm) Elevated-2 (700 ppm)	↑	Sathish et al. (2014)
Lentil	University of Plymouth, UK	Tightly sealed ventilated chambers	Ambient (400 ppm) Elevated (700 ppm)	↑ (35% in biomass)	Nasser et al. 2008
Mungbean	Varanasi, Uttar Prdesh, India	Open Top Chambers	Ambient (400 ppm) Elevated (700 ppm)	↑ (20–34% in biomass)	Mishra and Aggarwal (2015)
Pigeonpea	Hyderabad, India	Open Top Chambers	Ambient (380 ppm) Elevated-1 (550 ppm) Elevated-2 (700 ppm)	↑ (33% in biomass)	Srinivasarao et al. (2016)
Mungbean	Hyderabad, India	Open Top Chambers	Ambient (390 ppm) Elevated-1 (550 ppm Elevated-2 (700 ppm	↑ (34% in pod yield)	Bindumadhava et al. (2018)
Pea	Denmark	Growth chamber	Ambient (380 ppm) Elevated (700 ppm)	↑	Gavito et al. (2000)
Soybean	Japan	Hydroponic culture	Low CO_2: CO_2-free air, Medium CO_2: 3 dm^3 m^{-3} CO_2 air High CO_2: 25 dm^3 m^{-3} CO_2 air	↑	Yamakawa et al. (2004)
Pea	Horsham, Victoria, australia	Free air CO_2 enrichment	Ambient (390 ppm) Elevated (550 ppm)	↑ (26% in grin yield)	Bourgault et al. (2016)
Mungbean	Changping, Beijing, China	Free air CO_2 enrichment	Ambient (400 ppm) Elevated (550 ppm)	↑ (14% in yield)	Ji et al. (2015)
Lentil	Horsham, Victoria, Australia	Glasshouse	Ambient (500 ppm) Elevated (700 ppm)	↑ (16% in biomass)	Delahunty et al. (2018)
Cowpea	New Delhi, India	Free air CO_2 enrichment	Ambient (400 ppm) Elevated (550 ppm)	↑	Dey et al. (2017a)

Table 2
Effect of eCO_2 on legume growth and yield attributes under P supplementation.

Crop	Experimental site	Experimental condition	Concentration of CO_2	Yield response (over ambient CO_2)		Refs.
				+P	-P	
Chickpea	Horsham, Victoria, Australia	Free air CO_2 enrichment	Ambient (390 ppm) Elevated (550 ppm)	↑ (5.9 fold in shoot biomass)	↓	Jin et al. (2012)
Fieldpea	Horsham, Victoria, Australia	Free air CO_2 enrichment	Ambient (350 ppm) Elevated (550 ppm)	↑ (6.8 fold in shoot biomass)	↓	Jin et al. (2012)
Chickpea	Horsham, Victoria, Australia	Glasshouse in Rhizobox	Ambient (380 ppm) Elevated (700 ppm)	↑ (19%and 49% higher shoot and root biomass respectively)	↓	Jin et al. (2013)
Chickpea	Melbourne, Australia	Growth chamber	Ambient (350 ppm) Elevated (700 ppm)	↑ (32% and 70% higher above ground biomass and yield respectively)	↓	Lam et al. (2012)
Fieldpea	Melbourne, Australia	Growth chamber	Ambient (350 ppm) Elevated (700 ppm)	↑ (24% and 21% higher above ground biomass and yield respectively)	↓	Lam et al. (2012)
Mungbean	New Delhi, India	Free air CO_2 enrichment	Ambient (400 ppm) Elevated (550 ppm	↑ (31% higher above ground biomass)	↓	Dey et al. (2017b)
Green gram	New Delhi, India	Open top chamber	Ambient (390 ppm) Elevated (550 ppm)	↓	↑ (Biomass increased 0.3 fold)	Pandey et al. (2016)

role of P in growth and yield attributes of different grain legumes are shown in Table 2.

Under eCO_2, P plays crucial role in plant growth and development because of its integral role in synthesizing adenosine-tri-phosphate (ATP) and other cellular bio-chemical components (Veneklaas et al., 2012). Different FACE experiments showed that eCO_2 with high P resulted in 6–7 fold increase in shoot biomass in crops like chickpea and fieldpea, due to higher photosynthesis and biomass accumulation rate (Jin et al., 2012, 2013; Zhang et al., 2014). The compensatory impact of eCO_2 under lower P dose was also reported in greengram in terms of 14% increase in above ground biomass (Pandey et al., 2015, 2016). Nevertheless, still there was no consistent correlation observed between P-dynamics and above ground shoot biomass under changing climate (Lam et al., 2012). One of the reasons that could explain inconsistency in results regarding impact of eCO_2 on grain legumes may be the variable duration of exposure. As discussed earlier under prolonged exposure to eCO_2, photosynthetic down regulation nullifies the positive impact of climate change (Aranjuelo et al., 2014; Rogers et al., 2006). The two probable reasons for this down regulation are: (i) poor stomatal conductance under eCO_2 and (ii) scaled down activity of ribulose-1, 5-bisphosphate carboxylase/oxygenase (rubisco) due to excess carbohydrate accumulation in the leaves (Rogers et al., 2009; Rosenthal et al., 2014). Rogers et al. (2009) hypothesized the reason behind this photosynthetic down regulation are: (i) C sink limitation hypothesis (ii) N limitation hypothesis (Rogers et al., 2009). According to, C-sink limitation theory plants needs to generate additional sinks to translocate photosynthates or C to the associated microbes; otherwise this excess of C could negatively impact plant hormones like Rubisco (Sulieman et al., 2015). Whereas, as per N-imitation theory legumes can substantiate additional N-requirement by improving nodule mass and nitrogenase activity resulted overall increase in BNF (Sulieman et al., 2015). For example, mycorrhizal infection found to be highly beneficial in alleviating photosynthetic acclimation by acting as a C-sink and consequently supply nitrogen to legumes (Goicoechea et al., 2014).

Consequently, other probable hypothesis states that poor stomatal conductance along with lower rubisco activity, and imbalanced source-sink ratio might be the reason of unsatisfactory response under sub-optimal P nutrition and eCO_2 (Duchein et al., 1993). Above ground parameters like secondary and tertiary fruiting/podding branches and other components of plant growth should be thoroughly investigated in light of plant physiological response and metabolic changes to understand the plant response under climate change. Although, the intricacy related to nutrient uptake, dynamics and the reasons behind the uncertain performance as found in some cases must be unravelled through more exhaustive studies.

2.2. Impact on yield and yield attribute

Elevated CO_2 mediated changes like higher photosynthetic response significantly impact yield and associated attributing characters. Higher relative growth rate (RGR), biomass, pod number and seed yield of soybean under eCO_2 (1250 ppm) increased by 12, 37, 24, and 19% over ambient CO_2 (350 ppm) observed in a meta-analysis (Ainsworth et al., 2002). Intrinsic physiological responses like increase in photosynthetic rate, canopy temperature and C-partitioning are rationale behind this constructive response. A multiyear FACE experiment under eCO_2 (concentration: 550 ppm) in Australia confirmed higher grain yield and biomass by 26 and 28%, respectively in fieldpea and by 60 and 62% in lentil (Bourgault et al., 2016, 2017). Better synchrony between source and sink, lower harvest index, indeterminate growth habit and moreover larger reproductive organs facilitate legumes to perform smartly under changing climate and come out to be a crop of the future (Ainsworth et al., 2006). In case of greengram, an increase in biomass by 20–34% was recorded under eCO_2 (700 ppm) (Mishra and Agrawal, 2015). Indistinguishable response on yield was also reported in different grain legumes such as lentil (Bourgault et al., 2017; Nasser et al., 2008), blackgram (Sathish et al., 2014), pigeonpea (Vanaja et al., 2010), desi chickpea (Bhatia et al., 2021), kabuli chickpea (Saha et al., 2011), soybean (Drag et al., 2020; Lenka et al., 2020). Unlike eCO_2, high temperature (eT) had deleterious impact on productivity of grain legumes (Prasad et al., 2008; Wang et al., 2006). The extent of damage due to eT depends upon the growth stage and magnitude of temperature. Higher temperature reportedly deflate the sink size, relocate carbohydrates from the grains and subsequently as post-stress trauma, seeds won't get sufficient time to develop (Wang et al., 2006). The deleterious impact of eT can be seen in different legumes like lentil, where with each degree increase over 32°C, number of seeds decreased by 0.10–0.20% (Delahunty et al., 2018). The reasons behind the heat stress in legumes are stomata closure, flower and pod abortion and hindrance in normal physiological functions like respiration or electron transport (Saha et al., 2016). Whereas, recent study showed that high temperature tolerant greengram cultivars had higher total biomass (25%) and seed yield (31%) under eCO_2 condition (Bindumadhava et al., 2018). As a climate smart crop, legumes can recover from heat stress of 10 days without significant yield deduction. Indeterminate growth habit and great plasticity in crop phenology makes them perfect for the coming days (Liu et al., 2003). Hence, the procedure of selecting resilient genotypes in legumes should also consider all the mentioned factors. Apart from breeding, precision agronomic practices should be in place to achieve the yield goals and sustainable management of natural resources.

Table 3
Effect of eCO_2 on root attributes on legumes under P supplementation.

Crop	Experimental site	Experimental condition	Concentration of CO_2	Root morphology (Root length and root biomass)		Refs.
				Without P (–P)	With P (+P)	
Chickpea	Horsham, Victoria, Australia	Free air CO_2 enrichment	Ambient (390 ppm) Elevated (550 ppm)	↓	↑ (14% in root length)	Jin et al. (2012)
Fieldpea	Horsham, Victoria, Australia	Free air CO_2 enrichment	Ambient (350 ppm) Elevated (550 ppm)	↓	↑ (12% in root length)	Jin et al. (2012)
Chickpea	Horsham, Victoria, Australia	Glasshouse in Rhizobox	Ambient (380 ppm) Elevated (700 ppm)	↓	↑ (50% in root biomass)	Jin et al. (2013)
Chickpea	Melbourne, Australia	Growth chamber	Ambient (350 ppm) Elevated (700 ppm)	↓	↑ (28% in root biomass)	Lam et al. (2012)
White lupin	Toronto, Canada	Control growth chamber	Low (200 ppm) Medium (410 ppm) High (740 ppm)	↓	↑ (3.5 cm more root length)	Campbell and sage (2002)

Table 4
Effect of eCO_2 on root attributes on legumes.

Crop	Experimental site	Experimental condition	Concentration of CO_2	Response on root system (over ambient CO_2)	Reference
Pigeonpea	Hyderabad, India	Open Top Chambers	Ambient (380 ppm) Elevated-1 (550 ppm) Elevated-2 (700 ppm)	↑ (22% in root biomass)	Srinivasarao et al. (2016)
Blackgram	Hyderabad, India	Open Top Chambers	Ambient (380 ppm) Elevated-1 (550 ppm) Elevated-2 (700 ppm)	↑ (15% in root biomass)	Srinivasarao et al. (2016)
Groundnut	Hyderabad, India	Open Top Chambers	Ambient (380 ppm) Elevated-1 (550 ppm) Elevated-2 (700 ppm)	↑ (27% in root biomass)	Srinivasarao et al., 2016
Pea	Horsham, Australia	FACE	Ambient (390 ppm) Elevated (550 ppm)	↑	Butterly et al. (2015)
Pea	Denmark	Growth chamber	Ambient (380 ppm) Elevated (700 ppm)	↑	Gavito et al. (2000)
Chickpea	New Delhi, India	Open Top Chambers	Ambient Elevated (580 ppm)	↑ (32% in root dry weight) ↑ (28–34% in root volume weight)	Saha et al. (2016)
Pigeonpea	New Delhi, India	Open Top Chambers	Ambient Elevated (580 ppm)	↑ (51% in root surface density)	Saha et al. (2011)

Harvest index (HI) is affected by eCO_2 depending upon the time of exposure, nutrient-level, water availability. Mostly, the impact of eCO_2 on HI is either non-significant or negative. Several authors reported poor response ofeCO_2 on legumes like greengram (Dey et al., 2017a; Mishra and Aggarwal, 2015), fieldpea (Bourgault et al., 2016) and soybean (Bishop et al., 2015). However, pigeonpea and lentil showed 9% and 60% increase, respectively in HI upon exposure to eCO_2 (Bourgault et al., 2017; Vanaja et al., 2010). Increase in WUE and more specifically higher water availability in the pod filling stage may be the reason behind higher HI in some legumes. It can be concluded that impact of eCO_2 and eT on biomass and yield were completely reverse. However, proportionate increase in total biomass and partitioning of photosynthates, indeterminate growth habit and flexibility to cope up from abiotic stresses makes pulses as suitable option for the future.

3. Below-ground response

3.1. Impact on root growth

Elevated CO_2 increased C assimilation that had considerable effect on root morphology and architecture, symbiotic relationship with mycorrhizal fungi, modification in pH and redox potential in rhizosphere (Haling et al., 2013; Shen et al., 2011; Zhang et al., 2010). Below ground parameters like (root growth, nodulation and plant-microbes interaction) responded variably with eCO_2 and eT. Promising impact on nodule size, number and biomass reported in different legumes under eCO_2 however, benefits could only be expected under optimum management conditions (Bertrand et al., 2011; Haase et al., 2007; Nuruzzaman et al., 2006). The OTC experiment by Srinivasarao et al. (2016) reported that, root biomass was higher by 27, 15, and 22% under 500 ppm and 56, 43 and 112% under 700 ppm of CO_2 than ambient condition in groundnut, blackgram and pigeonpea, respectively. However, they highlighted factors like increased root length, weight, diameter and volume all together promoted root biomass. Similar promising impact of eCO_2 in other legumes like chickpea (Jin et al., 2013; Saha et al., 2015), pigeon pea (Saha et al., 2011), cowpea (Dey et al., 2017a), greengram (Bindumadhava et al., 2018) were already present. Adaptation strategies like allocating more photo assimilates in the below ground and root proliferation in greater depths to utilise nutrient pools made pulses outperform others in changing climate (Idso and Kimball, 1992; Nie et al., 2013; Rogers et al., 1992). Thus, legumes could easily get access to the non-labile pool of nutrients and solubilise with the help of root mediated secretions. As, discussed in the previous section adequate nutrition was the key to get potential benefit in eCO_2. Phosphorus plays a critical role in promoting root growth and strengthening the symbiotic relationship between roots and microbes. The importance of P in assisting better root growth was reported in chickpea by Lam et al. (2012) (increased by 28%) and Jin et al. (2013) (increased by 34%). The impact of eCO_2 on root growth with or without P is shown in Tables 3 and 4, respectively. Different experimental evidences reported 2–2.5 times more proteoid root and 3–3.5 cm more increase in lateral root of white lupin in growth chamber under higher eCO_2 with sub-optimal dose of P (Campbell and Sage, 2002; Wasaki et al., 2005). Additional C improves specific uptake capacity by promoting the activity of membrane transporters and secreting more chelators while, at the same time legumes produce additional roots to harness the nutrients stored in non-labile sites and appear to be the smartest crop for the future climatic conditions (Campbell and Sage, 2002). Interestingly, Veneklaas et al. (2012) reported higher photosynthetic response was likely to be linked with phosphorus use efficiency because the rate of transformation from

inorganic P (Pi) to organic P (Po) increased substantially to sustain the production of Rubisco and greater portion of P was utilised for photosynthetic assimilation and metabolism. However, additional factors like management conditions, temperature, genotype and micro-nutrient supplementation also determine crop growth to a great extent under climate change (Gavito et al., 2000; Butterly et al., 2015). According to recent findings, certain set of genes govern the complex relationship between climate change (eCO_2) and P-utilisation in legumes (Ainsworth et al., 2006; Jin et al., 2015). For example, 327 candidate genes responsible for persisting growth under eCO_2 in soybean were reported (Ainsworth et al., 2006). Auxin-responsive promoters like transport inhibitor response 1 (TIR1) and auxin transport genes act as a precursor to initiate elongation of root hairs particularly under eCO_2 with P deficiency (Jin et al., 2015). Hence, altered genetic expression under a particular environmental situation had immense importance on promoting molecular, physiological and cellular processes that contribute to root architecture of plants (Gilroy and Jones, 2000; Santelia et al., 2005). Physiological study regarding amount of root promoting hormones generated with pericyclic cell division needs to be studied across different legumes. Novel approaches like imaging technologies in the visible and near infrared regions, statistical tools and principal component analysis (PCA) and partial least squares regression (PLSR)-coupled machine learning models enables scientists to get deep insights of the roots to understand the physiological changes happening under eCO_2 and assess the genotype (G), environment (E) and management (M) (G*E*M) interactions more scientifically. Moreover, molecular technologies like gene editing and pyramiding/introgressing of genes/quantitative trait loci (QTLs) associated with unique below ground characteristics along with suitable agronomic management practices will capacitate scientists to bring climate smart legumes for a nutritionally secure future.

3.2. Impact on root-shoot ratio

As mentioned in the previous sub-section, positive response of eCO_2 on root growth has been well researched. However, an optimum balance in root-shoot ratio is important to have an equilibrium partitioning of photosynthates to different plant parts under changing climate. There is an ambiguous response related to root-shoot (R: S) ratio amongst different legumes under eCO_2. Jin et al. (2013) reported that neither eCO_2 (700 ppm) alone nor in combination with P nutrition had any significant impact on R: S ratio. A varied R:S ratio between legumes and non-legumes could be due to their differences in C-sink capacity as the legumes divert more C for root growth and further symbiotic processes (Minchin and Witty 2005; Niu et al., 2012). In contrary, results of significantly higher R: S ratio was seen throughout the growth stages as compared to ambient condition under eCO_2 (550 ppm) in greengram (Pandey et al., 2016). Srinivasarao et al. (2016) reported 14% increase in R: S ratio in blackgram in eCO_2 (700 ppm) over ambient (390 ppm). Butterly et al. (2015) showed differential response of eCO_2 on R: S ratio depending upon growth stages. In the vegetative phase, eCO_2 showed significantly positive impact on R: S ratio; whereas, in the later stage, the effect was obscured. Exposure of plants to eCO_2 could significantly modify C-allocation to the roots and below ground C-sink capacity thereby changing the activity/metabolism resulting significant reduction in the R: S ratio (Erice et al., 2007). As an adaptation to changing climate, legumes under eCO_2 drastically modify the root architecture, morphology, biomass, length, and size with possibilities to explore additional soil volume for nutrients and moisture (Pritchard, 2011). Hence, differential response on R: S ratio could be discussed in legumes with regard to biomass allocation, above ground crop growth, availability of major nutrients and management practices.

4. Impact of climate change on nodulation

Substantial attention has been given over the years to decipher the impact of climate change on above and below ground legume physiology; although, relatively less interest has been shown on nodule growth and performance. Nodule formation and subsequent nitrogen fixation process involves multiple steps; but, the impact of eCO_2 on individual step is very hard to assess. In general, eCO_2 has positive response on nodule growth and physiology which has been documented for multiple legumes. Climate change majorly impact nodulation or nodule growth by two ways: 1. alteration in nodule physical parameters (nodule biomass and nodule number per plant) and 2. Change in nodule biochemical characteristics (nitrogenase activity, leghaemoglobin content and N_2 fixation) (Almeida et al., 2000; Rogers et al., 2009; Thomas et al., 2006). Nonetheless, the impact of eCO_2 on nodulation is highly linked with crop species, bacterial symbiont, plant nutritional status, physicochemical conditions of soil and environmental conditions (Bertrand et al., 2011; Hasse et al., 2007; Rogers et al., 2006).

Exposure time of eCO_2 is having manifold impact on nodule growth and development Generally, short-term exposure promotes nodule functions like nitrogenase activity, N_2 fixation, and whole-plant N status, whereas prolonged exposure modifies the nodule development namely, nodule biomass and nodule number per plant. Experimental studies in FACE and OTC manifested positive response of eCO_2 in different grain legumes. For e.g. OTC studies [eCO_2 (580 ppm)] in chickpea by Saha et al. (2016) showed respective increase in nodule number and biomass by 39 and 76% over control in chickpea. Pandey et al. (2016) reported that fresh nodule weight of green gram increased by 38% under eCO_2 (550 ppm) over ambient conditions. Nodule number and biomass of several leguminous plant species, such as soybean, bean, field pea, alfa-alfa and lentil remarkably increased at eCO_2 exposure (Guo et al., 2013; Haase et al., 2007; Nasser et al., 2008; Prévost et al., 2010). Like above and below ground plant parts, nodule biomass is also positively influenced by P-supplementation. The FACE study Jin et al. (2012) reported that, under eCO_2 (550 ppm) with addition of P, nodule biomass significantly increased by 46 and 49% in chickpea and field pea, respectively over ambient (350 ppm). The differential response of eCO_2 on nodule growth and development and distinctly with P-application are summarised in supplementary Tables 1 (S1) and 2 (S2), respectively. However, results are not always significant and the extents of change in different legumes are hard to ascertain (Yamakawa et al., 2004). To discuss the climate smart adaptive strategies by legumes, Aranjuelo et al. (2013) showcased the concept of higher photosynthetic rate and allocation of C-in the roots due to eCO_2 eventually boosted the nitrogenase (N_{ase}) activity and SNF. Biochemical parameters like leghaemoglobin content and N_{ase} activity were influenced positively with rise of gaseous concentration. Saha et al. (2016) reported 66% higher leghaemoglobin under eCO_2 (580 ppm) in OTC as compared to ambient condition. Positive results were also found in field pea (Cabrerizo et al., 2001) and in greengram by Pandey et al. (2016), with 1.6 fold higher N_{ase} activity under eCO_2 (550 ppm). In addition, higher rhizosphericN_{ase} activity was also observed in other grain legumes under eCO_2 condition (Guo et al., 2013; Srivastava et al., 2002; Sanz-Sáez et al., 2011). As discussed in the earlier sections, eCO_2 have favourable impact on root exudates secretion that significantly aided rhizobium to infect and colonise and form nodule. Like, legume-rhizobium interaction, eT possesses serious threat on nodule metabolism and bio-chemical characteristics. The eT disrupts the nodule metabolism by regulating C-allocation, upscaling the risk of oxidative stress, preventing normal N-metabolism and lastly exposing the bacteroids to oxygen (O_2) which all together prevents N_{ase} to perform smoothly (Aranjuelo et al., 2014; King and Purcell, 2005; Pla et al., 2003). Also, eT depletes the photosynthetic rate by forcefully closing guard cells, diminishing the total soluble protein content in leaves, impeding carboxylase activity and inducing water stress (Aranjuelo et al., 2014). However, Aranjuelo et al. (2014) reported that there was no consistent correlation between photosynthesic down regulation and N_{ase} activity which needs further study before drawing conclusion. High temperature stress is likely to impact gene regulations related to nodulation and rhizobium infection. The activity of rhizobia is highly temperature

sensitive and optimum at 20–25˚C. So, minor fluctuation in soil temperature even by <2 ˚C can ravage the symbiotic relationship by hampering root growth and rate of infection (Aranjuelo et al., 2014). Further, under eT conditions, accumulation of toxic nitrogenous compounds and inappropriate carbohydrate supply to the root system hamper normal root hair growth, degenerates the *nod* gene activity and sooner or later the delicate symbiotic relationship between crop-microorganism becomes fragile (Aranjuelo et al., 2014). Experiments showed that temperature higher than 39˚C alters the gene functioning related to flavonoid production in beans and soybean thereby impeding the normal infection process and also restricts the growth of root hairs considerably (Hungria, 1995). Results were also found showing the inactivation of N_{ase} and reduction in the number of *nif* H genes transcripts per nodule (Cabeza et al., 2014; Watanabe et al., 2013). The process of nodulation and BNF are highly inter-related and modification of a single step will drastically impact the process as a whole. Even the impact of eCO_2 is positive for nodulation; but, the positive impacts are likely to be modified by edaphic conditions like temperature stress, soil N-status and moisture availability. Experimental reports revealed that, legumes can cope up to 1000 ppm of eCO_2 and to sustain nodule growth and N_{ase} activity by balancing the carbohydrate level through subsequent allocation in the form of sucrose and store in the form of starch. Apart from starch mobilisation, increased protein synthesis likely aided legumes to adapt perfectly in the changing climate. Thus in a nutshell it can be said that, apart from natural adaptations like carbohydrate allocation, developing climate resilient agro-technologies for a suitable agro-ecosystems will help legumes adapt and fulfil the grain demand for the mankind.

5. Impact on crop water use

5.1. Vapour pressure deficit (VPD) and evapo-transpiration rate (ET)

Climate change and rise in CO_2 and temperature have heterogeneous impact on crop water use efficiency. As different climate models predicted rise of global temperature by 2˚C- 4˚C by the end of the century, which likely to change weather parameters like vapour pressure deficit (VPD), pan evaporation, wind speed and solar radiation (Vadez et al., 2012). Vapour pressure deficit (VPD) can be defined as difference in moisture content of air at a specific time and at the time of saturation and the typical value for VPD is between 0.8–0.95 KPa (Vadez et al., 2012). VPD and ET are of immense importance for valuating water-use-efficiency in crops. Under ample atmospheric moisture condition with higher VPD, moisture from plant gets depleted through transpiration resulting in over consumption of soil moisture (Vadez et al., 2012). Therefore, huge amount of water has to be transpired to sustain the biomass accumulation rate of the crop under changing climate; however, it is neither economical nor environmentally sustainable. Hence, legume genotypes with sufficient biomass and with lower transpiration rate particularly when VPD is high should be screened to increase the water use efficiency under temperature stress conditions Sinclair et al. (2008). from their experimental evidences reported constant or non-significant change in transpiration rates in drought tolerant soybean genotypes over VPD of 2 KPa. Basically, the strategy is to preserve water for the consequent grain filing stage. Unlike VPD, the importance of ET on water-use-efficiency is still unclear. There are many reports from the scientific community those enumerate the increase of ET with elevated temperature and resulted change in WUE in grain legumes (Roderick et al., 2007; Szilagyi et al., 2001). Reduced ET caused 5–10% of water saving and saved precious soil moisture in number of crops, but on the other side it increased the chance of soil erosion (Rogers et al., 2009). Another important climate resilient strategy is identifying legume genotype those could utilise water depending upon soil moisture status and non-limiting to crop plants. Recently, advanced molecular and physiological tools are being used to screen legume genotypes for drought tolerance such as urdbean (Gurumurthy et al., 2020), mungbean (Kumar et al., 2020), lentil (Biju et al., 2018), cowpea (Munjonji et al., 2018), chickpea (Shah et al., 2020), fieldpea (Mohapatra et al., 2020). Comprehensive datasets from field as well as controlled environments are required to avoid confusion and understand clearly the effect of climate change on crop biophysical parameters and water-use-efficiency. Modern technologies (crop simulation modelling, geographic positioning system and artificial intelligence) simulating future climate conditions along with amalgamation of several disciplines are need of the hour to exploit potential genotypic variability and identifying novel traits of legumes for withstanding abiotic stress on top of higher WUE.

5.2. Stomatal opening and root conductance

Stomatal activity, specifically conductance reduce the water requirement under eCO_2 depending upon plant size, canopy and leaf temperature, plant water balance and soil condition (Rasul and Sharma, 2016). Hence, ideal plant type under climate change should have better adaptation, marginal leaf conductance, and water-saving capacity particularly in the early growing phase. Meta-analysis study by Kimball et al. (2002) reported that, legumes in general maintain higher transpiration rate by decreasing the stomatal conductance and transpiration by 42 and 24%, respectively. Legumes due to their inherent capability of raising CO_2 concentration in the sub-stomatal cavity maintains low transpiration rate and increases the rate of photosynthesis thereby saving valuable water and wane the chances of photosynthetic down-regulation. Therefore, eCO_2 is expected to have a positive plant water balance and productivity as reported by multiple authors (Serraj, 2003). But, on the other side, chances of high leaf and canopy temperature may be expected due to reduced transpiration rate; though, reports on this is still lacking. Besides, the complex interaction between root hydraulic properties and channel proteins like aquaporins must be explored for higher water-use-efficiency (Vadez et al., 2012). Molecular interventions in the post- transcriptional level can modulate the aquaporin activity resulting in higher water-use-efficiency (Vadez et al., 2012). Also, eCO_2 regulates the guard cell activity by moderating the rate of photosynthesis and leaf water balance (Kimball et al., 2002) Parent et al. (2009). described the role of aquaporins in maintaining hydraulic conductivity in root and leaves. Surprisingly, abisssic acid found to play highly pertinent role in maintaining optimum hydraulic conductivity and regulating genetic expression of aquaporins. Therefore, apart from basic capabilities of legumes to adjust perfectly in the eCO_2 conditions, more physiological and molecular interventions must be considered to understand the physiology behind aquaporins and hydraulic conductivity to achieve higher WUE. Lastly, there are discrepancies regarding comparative efficacy of WUE amongst C_3&C_4 crops which depend upon diverse set of conditions (Morgan et al., 2011; Bishop et al., 2015). A possible intervention to avoid confusion is to consider the VPD always while assessing WUE irrespective of any crop type. On that account, legume genotypes capable of maintaining high level of VPD besides high WUE should always be considered for coming days.

6. Impact of climate change on insect-pest and diseases incidence

Insects are cold-blooded organisms having body temperature approximately the same as that of the environment (Newbery et al., 2016). Therefore, temperature is probably the single most important environmental factor that influences insect behaviour, distribution, development, survival and reproduction. Generally, climate change impacts on insect population covering phenology, distribution, community composition and ecosystem dynamics that finally leads to extinction or resurgence of species (Vitousek et al., 2017). Climate change may alter insects' physiology and behaviour because of modification in the host plant resistance, natural enemies and interactions with the other insects (Delcour et al., 2015). The infestation of lepidopteron podborers and coleopterous defoliators could intensify under eCO_2 conditions (Sharma, 2010). Furthermore, the sucking pests such as aphids and jassids infestation were increased under eCO_2 condition in case of

grain legumes (Ryalls et al., 2017). As eCO_2 favours canopy growth and form a favourable micro-climate for pathogen to multiply and undergo evolution, ultimately affect virulence. Soil moisture dynamics is highly critical for inception of a particular type of disease under global climate change scenario. Survey reports across the different south Asian countries showed under moisture deficit and eT conditions, dry root rot (*Rhizoctonia bataticola*) in chickpea increased by 2–3 times especially in the reproductive phase (Sharma et al., 2010). Variation in temperature and humidity not only increases the risk of pest's damage but also, alters the survival mechanism. Different climatic models (using long term temperature and rainfall data) indicated rise of *Ascochyta* blight, anthracnose, collar rot, wet root rot, and stunt diseases in chickpea, Phytophthora blight and Alternaria blight in pigeonpea particularly in south Asian countries (Newbery et al., 2016; Rehman and Kumar, 2018). To overcome such challenges, it is very important to understand dynamics and behavioural changes in pests, distribution of pests in different ecosystems, pathogen virulence and infection rate and lastly host vigour and susceptibility with changing climate. Understanding host plant resistance and impact of climate change on natural enemies needs to be thoroughly investigated to have an eco-friendly approach for pest control. New age integrated pest management (IPM) technologies like spinosads and avermectins produced by fungi, nuclear polyhedrosis viruses and Bt toxins that are effective against new pathogens must be introduced along with conventional chemical control methods. Besides plant protection technologies, one of the important points to reconsider is sustainable agronomic management practices. Reports said climate changes have monumental impact on insect feeding behaviour as insects have to feed more (> 40%) in order to obtain adequate nitrogenous substrate under climate change (Vadez et al., 2012). So, climate smart strategies must be developed to counter the problem and to do that, in one side breeders need to select ingrained legume genotypes which can maintain optimum C:N ratio in the new environment and on the other side, advanced site specific real time N-management or recommendation strategies specific for the grain legumes need to be formed to uphold optimum tissue N concentration. As mentioned in the earlier sections, legumes are best adaptor in changing climate and the same is true in case of biotic stresses too. As per reports, legumes develop different plant defensive chemicals [peroxidase (POD), polyphenol oxidase (PPO), phenylalanine ammonia lyase (PAL) and tyrosine ammonia lyase (TAL)] in the leaves upon exposure to eCO_2 which prevent pest severity and increase host resistance (Palit et al., 2020). Sharma et al. (2016) reported pod borer infested chickpea plants under eCO_2 (750 ppm) have higher oxalic acid, malic acid and hydrogen peroxide (H_2O_2) content than ambient with higher pest resistance. In nutshell, it can be said that harnessing the potential of natural enemies and selecting legume genotypes resistant to biotic stresses is the urgent necessity in accordance with the contemporary management practices.

7. Conclusion

Climate change has a profound impact on crop production and the risk is likely to aggravate in the near future. Not only elevated CO_2 or temperature, but also other elements like water, nutrient level in the soil and abiotic stresses will define the response of legumes to future climate. It is likely that grain legumes being a C_3 crop avail the benefits of climate change more especially eCO_2 but, it is very important to rethink the importance of P-fertilisation as more P would be required for harnessing the optimum "CO_2 fertilisation effect" on legume growth and development. Hence, in the future multidisciplinary research encompassing plant physiology, crop improvement, soil science, crop management and agrometeorology must be integrated to have better understanding. Crop simulation models could be of great importance in this regard. There is an urgent need for harnessing the genetic potential of the grain legumes, screening and identifying germplasm or breeding materials as donors for adaptive traits and ultimately improving or introgressing traits that impart the climate resilience in high-yielding popular cultivars (Kumar et al., 2019). Despite the narrow genetic base, adoption of innovative approaches like transgenics, gene editing and epigenetic adaptive trait variations can be generated and introgressed to modern grain legume cultivars to mitigate climate change effects (Kumar et al., 2019). Experimental approaches like optimising nutrient dose for grain legumes, photosynthetic ^{13}C tracing to understand the C-allocation in different plant parts, gene mapping and expression studies enable scientists to conclude that grain legumes are actual climate smart crops having both ecological and social implications (Kumar et al., 2019).

8. Future research and recommendations

Some of the important researchable areas and recommendations with enormous opportunities for improvement are as following (Fig. 1).

8.1. Development of climate smart management practices for grain legumes

Climate smart management is the gateway to address the challenges faced by growing demand of food, fibre and fuel. The various management practices starting from selection of suitable drought resistant and high yielding varieties or the varieties well adopted to changing climate, conservation agriculture practices, crop rotations, adoption of soil and water conservation technologies, integrated tree-crop-livestock system, using non-conventional energy source (e.g. solar power drip irrigation), using resource conservation technologies, integrated nutrient and pest management practices to deal with new emerging insect pests are crucial for better adaptation. Establishment of multi-stakeholder innovative platforms is also crucial for capacity building and generating awareness for adopting climate smart management practices. Complexities in socio-cultural, political, economic and ecological spheres might invite challenges for adoption of such management practices. Such problem can be gradually addressed by appropriate government and private sector interventions to promote climate resilient management practices.

8.2. Developing improved varieties suitable for inclusion in the new niches

High yielding varieties with genetic manipulation is needed to resist new emerging insect pests and to tolerate the adverse climate. Maintaining plant genetic resources, identifying locally available genetically compatible hardy species to perform genetic manipulation for incorporating suitable trait at local level is much needed.

8.3. Breeding for terminal heat and drought stress especially in winter grain legumes

A systemic screening of terminal heat and drought tolerance is necessary for a vast range of genetic material available in each grain legume. It is advocated that wild species and distant relatives of each species are to be screened for potential sources of tolerance (Kumar et al., 2019). It is also customary to workout genetics of these traits in source germplasm or breeding populations. Use of molecular markers may further help to detect and follow the particular gene or QTL of interest in breeding population during the course of introgression. Such faithful introgression of heat or drought tolerance loci or QTL into high yielding genotypes in grain legumes will definitely widen their adaptation in a vast area of cultivation.

8.4. Breeding for varieties those yield higher under eCO_2 and eT scenarios

Due to the gradual increase in global average temperature and increase in atmospheric CO_2 concentration, there is a need to breed grain legume cultivars with higher photosynthetic capacities or higher C-conversion abilities. The target CO_2 concentration and temperature range should have a bearing on the climate change models.

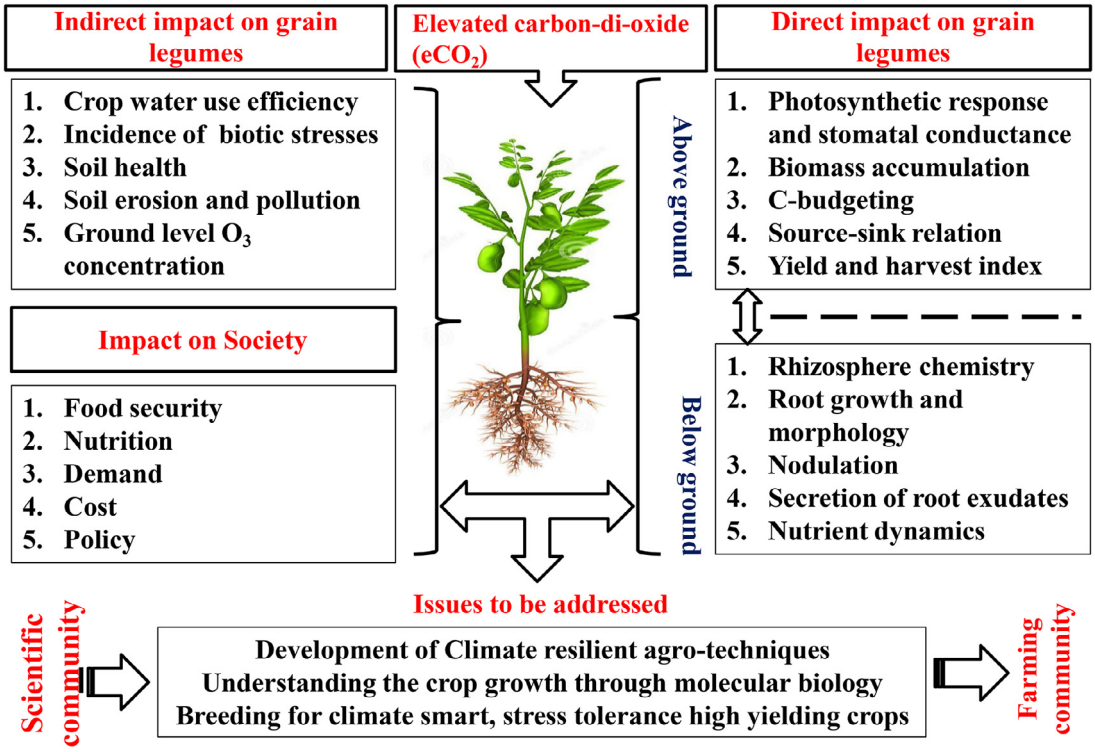


Fig. 1. Direct and indirect impact of grain legumes and future recommandations.

Table 5
Effect of eCO_2 on nodule attributes on legumes under P supplementation.

Crop	Experimental site	Experimental condition	Concentration of CO_2	Nodule attributes		Refs.
				Without P (–P)	With P (+P)	
Chickpea	Horsham, Victoria, Australia	Free air CO_2 enrichment	Ambient (390 ppm) Elevated (550 ppm)	↓	↑ (49% nodule biomass)	Jin et al. (2012)
Fieldpea	Horsham, Victoria, Australia	Free air CO_2 enrichment	Ambient (350 ppm) Elevated (550 ppm)	↓	↑ (46% nodule biomass)	Jin et al. (2012)
Chickpea	Melbourne, Australia	Growth chamber	Ambient (350 ppm) Elevated (700 ppm)	↓	↑ (50% nodule biomass)	Lam et al., 2012
Fieldpea	Melbourne, Australia	Growth chamber	Ambient (350 ppm) Elevated (700 ppm)	↓	↑	Lam et al. (2012)
Green gram	New Delhi, India	Open top chamber	Ambient (390 ppm) Elevated (550 ppm)	↓	↑ (38% in nodule fresh weight)	Pandey et al. (2016)

8.5. Breeding for biotic stress resistant varieties aggravated due to climate change

Many minor diseases are becoming major one and many insects-pests are causing epidemic conditions which were otherwise endemic or pandemic in nature due to the climate change. Different biotic stresses like diseases and insects-pests reaction should be taken into consideration while breeding for elevated CO_2 and temperature. Screening of genetic materials under artificial ephiphytotic or field condition with high load of natural incidence is required while breeding against climate factors.

8.6. Application of crop models

Crop models are important tools to understand the impact of specific crops under climate change scenarios. Crop models include every aspects of climate change, these also integrate present knowledge assisting grain legumes to adapt in changing scenario. Often, the biotic stresses infuriated under abiotic stress conditions need integrated approach to solve the complexity. Along with models modern statistical tools, artificial intelligence and machine learning software's are in use to predict the future climatic conditions and redesign management practices accordingly. Recently, modelling approach to point out region specific constraints limiting crop productivity particularly in the context of climate change (Azadeh and Tarverdian, 2007; Feng and Zhang, 2012; Hajjarpoor et al., 2018). Models also help to manage resources properly, understand nutritional status in plants which ultimately leads to sustainable food production (Tables 5, 6).

8.7. Key policies and recommendations

As climate change manipulates the environmental and socio-economic drivers of food security, time has come to rethink and orientate policies to sustain the grain legume production to achieve long-term benefits for all the communities across the globe. The major policy orientated recommendations are discussed point wise:

i. Integrating food security and sustainable food grain production in global and national policies along with simultaneous reduction of GHG emission
ii. Implementing specific programs and policies to assist small and marginal farmers or those who are highly vulnerable to climate change;
iii. Altering the food consumption habit and inclusion of grain legumes in diet to fight against malnutrition;
iv. Curtailing the loss of grain legumes by improving the storage facilities, avoid any post-harvest losses or developing pulse based processing sectors;
v. Development of comprehensive and shared information system to have a better understanding about the eco-system;

Table 6
Effect of eCO_2 on nodule attributes on legumes.

Crop	Experimental site	Experimental condition	Concentration of CO_2	Response on nodule system (over ambient CO_2)	Refs.
Cowpea	New Delhi, India	Free air CO_2 enrichment	Ambient (400 ppm) Elevated (550 ppm)	↑ (23% nitrogenase activity)	Dey et al. (2017a)
Lentil	University of Plymouth, UK	Tightly sealed ventilated chambers	Ambient (400 ppm) Elevated (700 ppm)	↑ (52% higher active nodule number)	Nasser et al. (2008)
Soybean	Japan	Hydroponic culture	Low CO_2: CO_2-free air, Medium CO_2: 3 dm^3 m^{-3} CO_2 air High CO_2: 25 dm^3 m^{-3} CO_2 air	↓ (22% nodule number)	Yamakawa et al. (2004)
Mungbean	New Delhi, India	OTC	Ambient (350 ppm) Elevated (600 ppm)	↑ (87% nitrogenase activity)	Srivastava et al. (2002)
Pea	Pamplona, Spain	controlled environment chambers	Ambient (360 ppm) Moderately elevated (700 ppm) Elevated (1000 ppm)	↑ (38% leghaemoglobin content)	Cabrerizo et al. (2001)
Soybean	Québec City, Canada	controlled-environment conditions	Ambient (390 ppm) Elevated (800 ppm)	↑ (63% nodule biomass)	Prévost et al. (2010)
Alfa –alfa	Pamplona, Spain	Temperature gradient greenhouses	Ambient (392 ppm) Elevated (700 ppm)	↓ (43% nodule number)	Sanz-Sáez et al. (2011)
Chickpea	New Delhi, India	OTC	Ambient Elevated (580 ppm)	↑ (76% nodule biomass)	Saha et al. (2016)

vi. Allocation of national budget for scientific capacity building and reflect the same on production systems or subsidies commodities which can strengthen farming community;
vii. Development of knowledge of best practises and disseminate the success stories in cross community basis;
viii. Formation of common platforms at national and global levels to share ideas, transfer knowledge and respond the feedbacks coming from farming community.

Declaration of Competing Interest

I declare no conflict of interest and all the authors significantly contributed in gathering information and drafting the document.

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Supplementary materials

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