



Climate-smart cotton (*Gossypium herbaceum*) crop production in Punjab: A comprehensive review of sustainable management practices

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ABSTRACT

The growth and productivity of cotton (*Gossypium herbaceum* L.) crop are greatly influenced by major fluctuations in the local weather. The output of cotton is negatively impacted by extended periods of unfavourable weather, despite the crop's apparent relative resistance to heat and drought. Among various cotton growing states in India, Gujarat often leads as the highest cotton-producing state in the country followed by Maharashtra, Telangana, Rajasthan, Karnataka and Andhra Pradesh. These states collectively contribute more than 65% to India's cotton production. In Punjab, the optimal sowing window for cotton spans from the 1st April to 15th May. Deviating from this recommended time frame, be it through excessively early or late sowing, correlates with compromised crop establishment and reduced productivity. Temperature thresholds dictate progression of the cotton crop's key stages. For germination, a threshold temperature of 16°C is required, while the range of 21 to 27°C is conducive to vegetative growth, and 27 to 32°C supports reproductive development. The diurnal/night time temperature for fostering cotton root growth resides within 30°C/22°C to 35°C/27°C. Elevated temperatures (40°C/32°C), even under adequate water and nutrient conditions, results in the emergence of shallow root systems. Strategic measures encompassing suitable sowing dates, precise plant spacing, favourable row orientations, judicious irrigation techniques and mulching can effectively temper the influence of climate change on cotton output. Furthermore, the application of crop simulation models and access to timely, accurate weather forecasts and agro-advisories equips decision-makers with invaluable insights for short-term operational planning.

Keywords: Climate change, Cotton productivity, Crop simulation, GIS, Microclimatic modifications
Modeling, Remote sensing

Climate change is a long-term, continuous shift in average weather patterns. It is brought on by changes in the environment, the earth's orbit around the sun, or atmospheric alterations made by humans (Kirby *et al.* 2016). Moreover, strong evidence suggests that human driven changes to the atmosphere are to be blamed for the unprecedented rate of temperature rise. Since the world is predicted to reach 1.5°C barrier during the next two decades, the Intergovernmental Panel on Climate Change (IPCC 2021), declared that only the most drastic reductions in carbon emissions going ahead will help to prevent environmental catastrophe. Climate change is an important challenge in the coming decades for sustainable agricultural production, especially in mid-century when the world's food demand is expected to be doubled (Kaur *et al.* 2023a). Enhanced greenhouse effect due to anthropogenic activities has resulted in climatic changes and then adverse impacts on agricultural productivity

(Kingra 2017). Minimum temperature in Punjab is increasing @0.05°C/year in all the agroclimatic regions during both *kharif* and *rabi* (Kingra *et al.* 2017) as well as annually (Kingra *et al.* 2018). As a result, increase in intensity and frequency of extreme weather events in the vacant past, has exerted significant effect on crop productivity (Kingra *et al.* 2019). Cotton is an important rainy (*kharif*) season crop being grown in more than 70 countries around the globe and accounts for 75% of the fibre used in the textile industry with 4% contribution to GDP. India is one of the world's top cotton producers, accounting for around 23% of global cotton output (Anonymous 2022). India encompasses 10 primary cotton-producing states, categorized into three distinct zones: the Northern zone, the Central zone, and the Southern zone. Among these three cotton producing zones, states in central zone i.e. Gujarat, Maharashtra and Madhya Pradesh are the highest cotton producing states in country shares more than 65% India's cotton production (BN_Cotton.pdf (nfsm.gov.in)). Cotton is the second most important *kharif* crop in Punjab after rice widely known as the White Gold or King of fibres and also the most important cash crop in the state's south-western (S-W)

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area. Cotton crop occupied 3.04 lakh ha in Punjab during 2021–22 and produced 11.6 lakh bales of 170 kg along with 652 kg/ha productivity (Anonymous 2022). Many variables impact cotton plant's reproductive cycle, including climate considerations, variety agronomic and pest control measures. Climatic conditions like maximum air temperature, rainfall and relative humidity have a significant impact on cotton flowering and boll production. Plant reproductive activities such as pollen tube development, pollen germination and fruit setting are all influenced by air temperature (Verma *et al.* 2016, Santosh *et al.* 2017). Cotton requires a specific amount of heat to attain different phenological stages in their life cycle, from sowing to the physical maturity stage (Fig. 1).

Long term climate variability analysis in central Punjab has also indicated significant increase in minimum temperature (@0.06°C/year) and decrease in sunshine hours for both *kharif* and *rabi* season (Kingra *et al.* 2016) which can have severe implications on crop productivity in the region. The productivity potential of crops is also significantly affected by intensity and distribution of rainfall especially in the semi-arid regions (Kingra *et al.* 2013). To minimize the adverse effect of weather on cotton, there is a need to develop suitable adaptation strategies. For that, microclimate modifications can be an effective adaptation strategy. An alteration in sowing time, spacing and row

orientation etc. are some of the microclimatic modification techniques that can be applied to make the optimum microclimate for optimum growth and development of cotton crop (Kingra and Kaur 2017, Sharma *et al.* 2018). In addition to microclimatic modifications, simulation modeling is also found to be highly effective for mitigating or adapting to climate change. The Decision Support System for Agrotechnology Transfer (DSSAT) is a broad decision-support tool that includes the Cropping System Model-Crop Growth (CSM-CROPGRO-Cotton) (Hoogenboom *et al.* 2010), which validates crop model outputs and enables users to contrast the simulated outcome with observed effects (Jones *et al.* 2003). CSM-CROPGRO-Cotton is broadly used as a technological tool for strategic decision-making for dryland as well as an irrigated crop to achieve better growth and yield of cotton under a given set of conditions (Jones *et al.* 2003, Hoogenboom *et al.* 2010). The present article provides an overview of recent climatic changes, their impact on cotton productivity, along with adaptation and mitigation measures for sustaining cotton productivity under changing climatic conditions.

Climatic requirements of cotton

Cotton yield is highly affected by rainfall and temperature, among several important weather variables

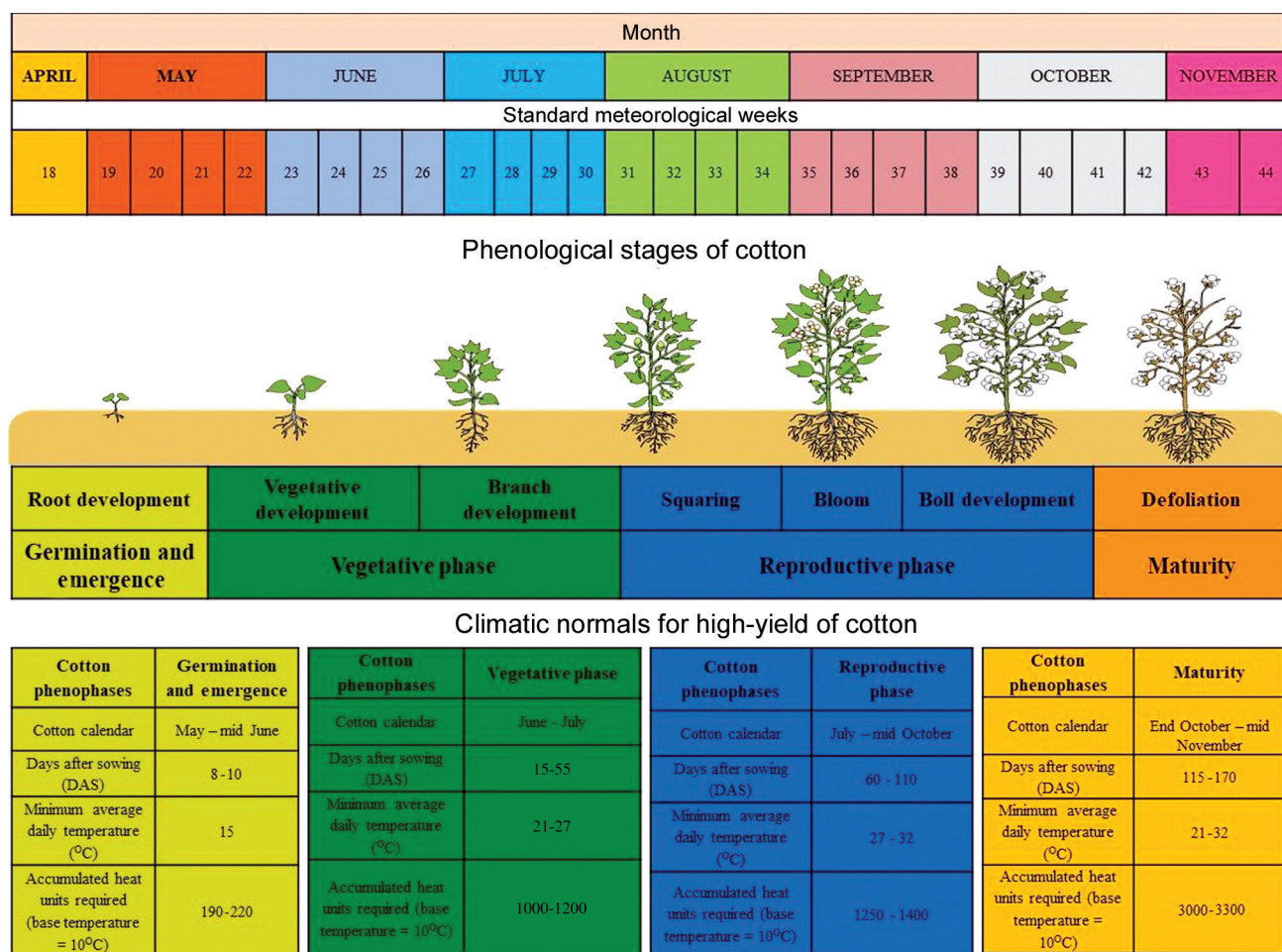


Fig. 1 Phenological life cycle and optimum climate conditions for growth and development of *kharif* cotton.

influencing growth and development (Thakare *et al.* 2014). Freeland *et al.* (2004), found that untimely rainfall, irrigation and humid weather during later stages primarily at the beginning of boll opening may hurdle the defoliation, reduce quality and decline in yield of cotton. Cotton is a crop from tropical and sub-tropical areas that requires a temperature between 21–32°C. The optimum soil temperature at seed depth should be above 18°C. To ensure proper seed germination and crop emergence, cotton needs adequate soil temperature and moisture conditions. The production of cotton flowers and bolls is negatively impacted by climatic variables such as temperature, rainfall and relative humidity. Cotton needs a minimum daily air temperature of 16°C for germination, 21–27°C for vegetative growth and 27–32°C for fruiting (Santosh *et al.* 2017) along with 500–700 mm of rain for the duration of its growth period (Supplementary Fig. 1). Heavy rainfall during flowering stage leads to the fall of flower buds and young bolls. Since the majority of the cotton planted in our country is rainfed, any deviations from ideal meteorological conditions have a significant impact on crop development and quality.

Effect of climate change on cotton productivity

Cotton is highly vulnerable to climatic variations such as increase in temperature, changing precipitation patterns, increased incidences of extreme weather and decreasing water supply etc. which may create the optimum weather conditions for the outbreak of insect-pest and plant diseases which ultimately effect crop growth and production. As a result, large fluctuations have observed in cotton production at the state as well as at the national level during recent decade (Supplementary Fig. 1). Climate change will impact cotton farming by increasing carbon dioxide (CO₂) levels, raising temperatures, lowering humidity and reducing water availability (Cetin *et al.* 2010). Due to the fact that cotton is a C₃ plant, which assimilates carbon dioxide through photosynthesis, higher atmospheric CO₂ levels can have beneficial effects (Verhage *et al.* 2018). The plants may grow bigger leaves by utilizing the greater CO₂ levels, which results in a larger surface area for photosynthetic activities and leads to a greater number of branches, leaves and bolls. However, greater vegetative growth may result in a greater need for pesticides, fertilizers and watering. The stress brought on by water shortage may be somewhat offset by enhanced efficiency of water usage due to the increasing CO₂ concentration (Kumar *et al.* 2019, Kaur *et al.* 2023b).

At different growing stages, cotton has variable water needs. Precipitation aids cotton during planting, germination, and vegetative development, but harms it during boll opening and harvest. An increase in rainfall intensity may cause issues for cotton growing in a changing environment. Although cotton requires a lot of water throughout the flowering season, the fibre becomes extremely sensitive to rain during harvest, which can lead to damaged blooms, buds, and bolls (Thakare *et al.* 2014). The cultivation of cotton in Punjab has been plagued by persistent pest infestations, particularly those caused by

Table 1 State-wise production of cotton (in Lakh bales)

State	2020–21	2021–22	2022–23 (P)
Maharashtra	101.05	71.18	80.25
Gujarat	72.18	74.82	91.83
Telangana	57.97	60.67	53.25
Rajasthan	32.07	24.81	27.12
Karnataka	23.2	19.5	21.04
Haryana	18.23	13.16	17.21
Andhra Pradesh	16	17.08	17.85
Madhya Pradesh	13.38	14.2	15.19
Punjab	10.23	6.47	9.22
Odisha	5.51	6.26	6.82
Tamil Nadu	2.43	3.6	1.87
Others	0.23	0.28	0.26
Total	352.48	312.03	341.91

Source: <https://pib.gov.in>; P, Provisional.

the pink bollworm and whitefly. As a result of these pests' accumulating resistance to chemical pesticides, cotton production in the Malwa region has significantly decreased, and farmers there have suffered large losses. However, overall state-wise production of cotton (in Lakh bales) is detailed in Table 1 (PIB 2022).

Climate variability, area, production and yield of cotton in south-west Punjab during recent decade

Variability in climatic parameters of south-west Punjab for the period 2009 to 2018 indicated that the maximum temperature ranged from 37.0–38.2°C in 2009 and from 35.9–37.1°C in 2018. Similarly, the minimum temperature ranged from 23.2–24.6°C in 2009 and 23.5–24.2°C in 2018. The rainfall in the cotton growing area of the state was observed to range from 100–350 mm in 2009 and from 120–500 mm in 2018. Increase of rainfall was observed in the Month of June and July especially at vegetative as well as square formation stage. Variability in the aforementioned climatic parameters affected the area, production and yield of cotton crop. A decrease in area under cotton has observed during this decade, as a result, the outcomes revealed that the area which was under a range 1–1,53,000 ha in 2011 got decreased to 1–85,000 ha. Production was also found to decrease from 2011 to 2020. However, owing to the introduction of new high yielding and insect and pest resistant cultivars, cotton crop yield was observed to improve from greatest 706 kg/ha in 2011 to 865 kg/ha in 2020 (Fig. 2). These results indicated that adoption of sustainable management practices is crucial for mitigating and adapting to the impacts of climate variability in cotton crop.

Management strategies

Climate change is likely to have a negative impact on cotton productivity. As a result, suitable mitigation strategies need to be adopted to meet the challenges imposed by

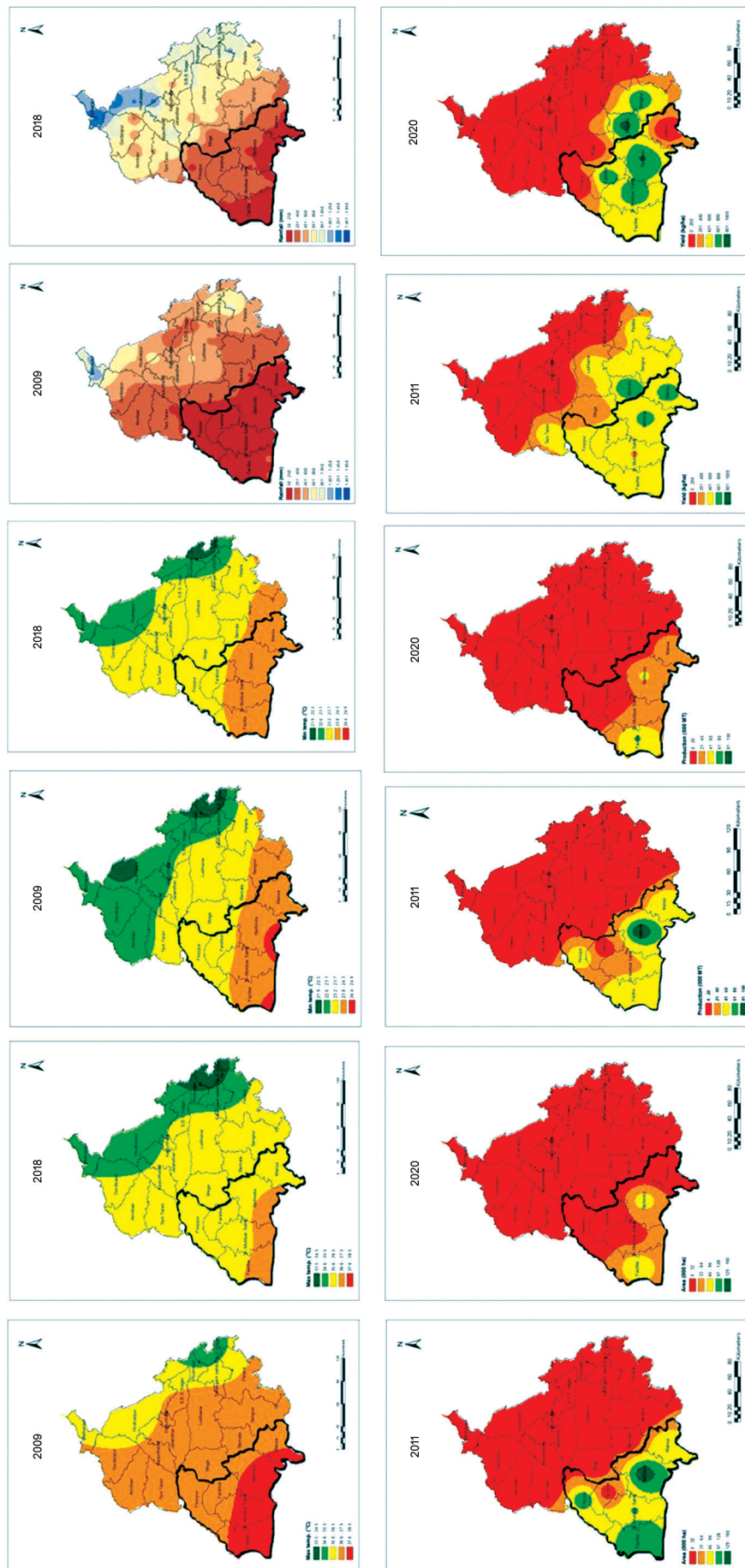


Fig. 2 Variability in maximum temperature (°C), minimum temperature (°C), rainfall (mm), area (000 ha), production (000 mt) and yield (kg/ha), respectively over past decade in Punjab.

climate change on crop productivity (Kingra and Singh 2016). To address the issue, adjustments in sowing timing, row orientation, plant spacing, irrigation method, mulch application, intercropping with legumes for minimizing the risk of crop failures, relay intercropping of cotton in between standing wheat or transplanting of cotton plants, ridge planting to avoid waterlogging etc. must be made. Other techniques that might be very helpful includes crop simulation modeling, monitoring weather forecasts and agro-advisory etc. (Fig. 3). Singh *et al.* (2017) suggested *Bt* cotton-groundnut intercropping system for increasing edible oilseeds production in India. Singh *et al.* (2017), concluded that by using new era transgenic or *Bt* cotton production technology there was reduction in the environmental footprint and enhancement in the profitability of cotton production in which there was significant reduction in pesticide use roughly by 40%, and yield advantages of 30–40%. Due to use of cotton-wheat production system, an innovative technology for enhancing productivity and profitability, the net income from the cotton-wheat system was 28.2% higher for the self-propelled relay seeder than with conventional sowing (Buttar *et al.* 2013).

Date of sowing: The date of sowing is a very important adaptation strategy to manage climate change impacts on cotton especially in improving heat use efficiency of crops (Kingra and Kaur 2011, 2012, 2013). Selection of crop duration by optimizing sowing date is of tremendous importance in terms of cotton production (Fig. 3). Many studies have shown higher yield and yield attributes of cotton under earlier sown crop (Kumar *et al.* 2014, Dhir *et al.* 2020). Bilal *et al.* (2015), concluded that as compared to non *Bt* cultivars, *Bt* cotton varieties performed better under early as well as late planting conditions. Correspondingly, late sowing crop takes lesser days to reach at different phenological stages than normal sowing (Ban *et al.* 2015, Herkal *et al.* 2017). Mahmoud *et al.* (2017), revealed that phenological characteristics, yield and yield components were more strongly affected by planting dates than by planting patterns. They came to the conclusion that planting cotton on April 1st was preferable to delayed sowing. Sharma *et al.* (2018), observed that earlier-sown cotton hybrids had greater diurnal variation of temperature profiles than late-sown cotton hybrids. Sunayana *et al.* (2018), found that desi cotton varieties (HD 123 and HD 432) had high mean, regression coefficient near unity and early sowing was best for seed cotton yield and lint yield. Locations and planting dates affected the ultimate seed cotton yield and its attributes (Ullah *et al.* 2017, Bilal *et al.* 2019). Dhir *et al.* (2021a) also found that the highest seed cotton yield was recorded in early sowing i.e. when sown on 30 April (3203 kg/ha at Bathinda and 3370 kg/ha at Faridkot) followed by 15 May, while the lowest with late sowing i.e. crop sown on 30 May. Brar and Singh (2021), observed that more than 40% and 15% of the output was reduced as a result of the late planting and delay in first irrigation from 4 weeks after sowing (WAS) to 6 WAS.

Plant spacing and row orientation: A crucial agronomic

component for crop optimization is maintaining an appropriate spacing between plants and rows (Zaxosa *et al.* 2012). To get high yields, a suitable plant stand must be set up since low plant densities waste resources while high densities restrict the growth of individual plants (Brodrick *et al.* 2013). Singh *et al.* (2018), concluded that appropriate row orientation is highly effective in improving heat use efficiency of crops under changing climatic scenarios. In addition to radiation absorption, moisture availability, wind speed and humidity, plant density directly affects crop maturity, branching pattern, fruiting behaviour and yield (Fig. 3). Jahedi *et al.* (2013), determined that cotton grown in narrow rows had lint yields equal to or higher than those attained in the 70 cm spacing. Sylla *et al.* (2013), observed that the number of bolls per plant grew along with the increase in the space between the plants and the experiment showed that the maximum yield was achieved with a combination of 70 cm between the rows and 20 cm between the plants, with a total density of around 71400 plants/ha. Blaise *et al.* (2020) stated that compared to the other treatments (1523–2051 kg/ha), the seed cotton output was considerably higher with spacing treatments of $0.30 \times 0.15 \text{ m}^2$ (2430 kg/ha), $0.45 \times 0.15 \text{ m}^2$ (2306 kg/ha), and $0.30 \times 0.10 \text{ m}^2$ (2212 kg/ha). Singh and Ahlawat (2014), explained plant growth behaviour of transgenic cotton with peanut intercropping system and integrated use of manure and fertilizer for simultaneously enhancing lint and oilseed production.

In an irrigated row crop of cotton, Agam *et al.* (2012), observed that ground heat flux was larger in the N–S direction field at the beginning and the end of the growing season. Dhir *et al.* (2021a) found that yield components of *Bt* cotton hybrid were highest when the crop was sown early (April 30th) at wider row spacing (75 cm) and in E–W row orientation in south-west Punjab region. Higher yields in early sowing were because of better crop macro-climatic conditions, while wider row spacing and E–W row orientation presumably provided better crop micro-climate for optimum crop growth under these conditions.

Irrigation method and mulch application: Choudhary *et al.* (2016) found that yield attributes of all cotton cultivars have higher values in the drip irrigation method followed by furrow and sprinkle drip irrigation. Li *et al.* (2013) revealed that the overall soil temperature was higher in drip irrigation and mulch application than traditional cultivation from mid-April to July which is good for vegetative as well reproductive growth. Brar and Singh (2021) revealed that pre-sowing heavy irrigation to early sown cotton crop and first irrigation at 4 WAS attains maximum growing degree days (GDD), photo thermal units (PTI) and helio thermal units (HTU) during all pheno phases which had a significant positive correlation with seed cotton yield. Singh and Singh (2021) examined the effects of alternate furrow method and drip irrigation on cotton yield and physical water productivity and found that, the drip method produced higher crop yield and physical water productivity during normal rainy years and drought years. Nalayini *et al.* (2011)

observed that the entire yield attributes and seed cotton yield were maximum under mulched as compared to non-mulched crop. Dong *et al.* (2009) concluded that soil temperature was more under early mulching (EM) and conventional mulching (CM) with no significant difference from 15–30 days after sowing (DAS). Similarly, soil moisture was maximum under EM and CM with no significant difference during 10–30 DAS. Nalayini (2007) revealed that silver poly-mulching gives best results as compare to black and no mulching for weed control in cotton crop. According to Jayswal *et al.* (2022), there was a 33.15% rise in net profit and 29.01% increase in average gross return when using plastic mulch, respectively. These findings demonstrated the advantages of using plastic mulch in cotton crops for farmers. Zong *et al.* (2021) found that the highest cotton yield and water use efficiency (WUE) were observed in polyethylene (PE) film mulching (5480.59 kg/ha and 1.35 kg/m³) in comparison to other used mulch types.

Crop simulation modeling: The modeling techniques used in agricultural practices have advanced rapidly. For any given place and time period, even if it is location-specific and not resilient, it can produce findings that are far more effective than those of process-based models. When compared to physically based models, it has the ability to predict when the number of variables is lower. By classifying and processing various plant images taken by remote sensing satellites, UAVs, Android phones, etc., it can possibly be utilised for agricultural yield forecasts, crop water, nutrient status, disease, and growth detections (Gupta *et al.* 2022). Thorp *et al.* (2014) evaluated the seed cotton yield of 105 to 1107 kg/ha was simulated by a CROPGRO-cotton model within 3 to 28% of root mean square error (RMSE). Wajid *et al.* (2013) simulated days to anthesis with a mean per cent difference of 1.20% and days to maturity, leaf area index, total dry matter and seed cotton yield with 1.16, 7.80, 3.96 and 4.38% mean per cent difference (MPD) by using the CROPGRO-cotton model. Pal *et al.* (2016) determined that elevated/downscaled units of mean temperature had a greater effect on simulated seed cotton yields than did solar radiation. According to Dhir *et al.* (2021b), the crop sown on April 30th at Bathinda and Faridkot had a significantly higher simulated seed cotton yield (3053 and 3274 kg/ha) than the crop sown on May 30th (2392 and 2511 kg/ha) and was in good agreement with the observed yield. Mishra *et al.* (2021) determined that phenological events like anthesis and physiological maturity were reasonably predicted with high d-index values of 0.83 and 0.89 and low root mean square error (RMSE) i.e. 2.27 and 4.98, respectively. Additionally, the aboveground biomass and seed cotton production also showed great accuracy, with RMSE's of 126 kg/ha and 706 kg/ha, respectively.

Weather forecast and agro-advisory services

Farmers can make better decisions and reduce associated agricultural risks by using accurate weather and climate information and advisory services (Fig. 3). Vashisth *et al.* (2013) reported that by advising farmers

on the best management techniques based on the weather, weather forecasts and agro-advisories assist farmers increase their economic advantage and concluded that mobile-based advisories can be a powerful tool in enhancing farm productivity (Prabha and Arunachalam 2021). According to Dudpal *et al.* (2021), economic impact of agro advisory services (AAS) revealed that there was a 12 to 33% increase in profit for AAS farmers as compared to non-AAS farmers. Sharma *et al.* (2021) revealed that the costs of cultivation for rice showed that non-AAS farmers spent ₹4495/ha more as compared to AAS farmers by not following agro-advisories, and the benefit-cost ratio for AAS farmers and non-AAS farmers was 3.24 and 2.57, respectively. Therefore, AAS farmers benefited by 29% more than the non-adopters. Studies conducted by several workers in the country also reported the good response by the farmers towards adoption of agro-advisory services in scheduling of the farm operations as per their individual needs (Kumar *et al.* 2021). Singh *et al.* (2022) revealed that the medium range weather forecast has an overall seasonal success rate of 87–98%, 65–75%, 51–72%, and 56–67% for rainfall, cloud cover, maximum and minimum temperatures and 44–83% for wind speed in south-west Punjab. Moreover, farmers who adopted agro advisory services showed higher net profits by 17% and 21% for cotton as compare to non AAS followers by following advisories on sowing time and genotypes sown.

Remote sensing and GIS

Remote sensing (RS) has been used for improving understanding of the climate system and its changes. Satellite-based remote sensing data can offer spatial information on the extent and distribution of the crops during the growing season (Fig. 3). Geospatial technology can be used for crop discrimination, acreage estimation, stress detection, site specific management and yield prediction etc. (Kingra *et al.* 2016). A growing number of agricultural applications integrate remote sensing with unmanned aerial vehicles (UAVs), including disease diagnosis, yield prediction, and production management (Westbrook *et al.* 2016). Ramarao (2009) combined remote sensing (RS), Geographic Information System (GIS) and crop models to match the distribution of the cotton in respect to its appropriateness based on the soil parameters and to produce data on the potential output of cotton crop, which is beneficial in yield gap analysis. Mamatkulov *et al.* (2021) reported the application of GIS and RS in real-time crop monitoring and yield forecasting in low (3.5 ha) and highly productive (8.3 ha) farmlands through Sentinel 2 satellite images. Melandri *et al.* (2021) demonstrated that over the two years of the field trial, different stress severity levels were quantitatively and qualitatively correlated with the extent of metabolic responses to drought, which had an influence on fibre characteristics. Kingra *et al.* (2018) also concluded spatio temporal analysis of crop productivity in Punjab using GIS and observed substantial variations in crop yield, rainfall and temperature across the state with

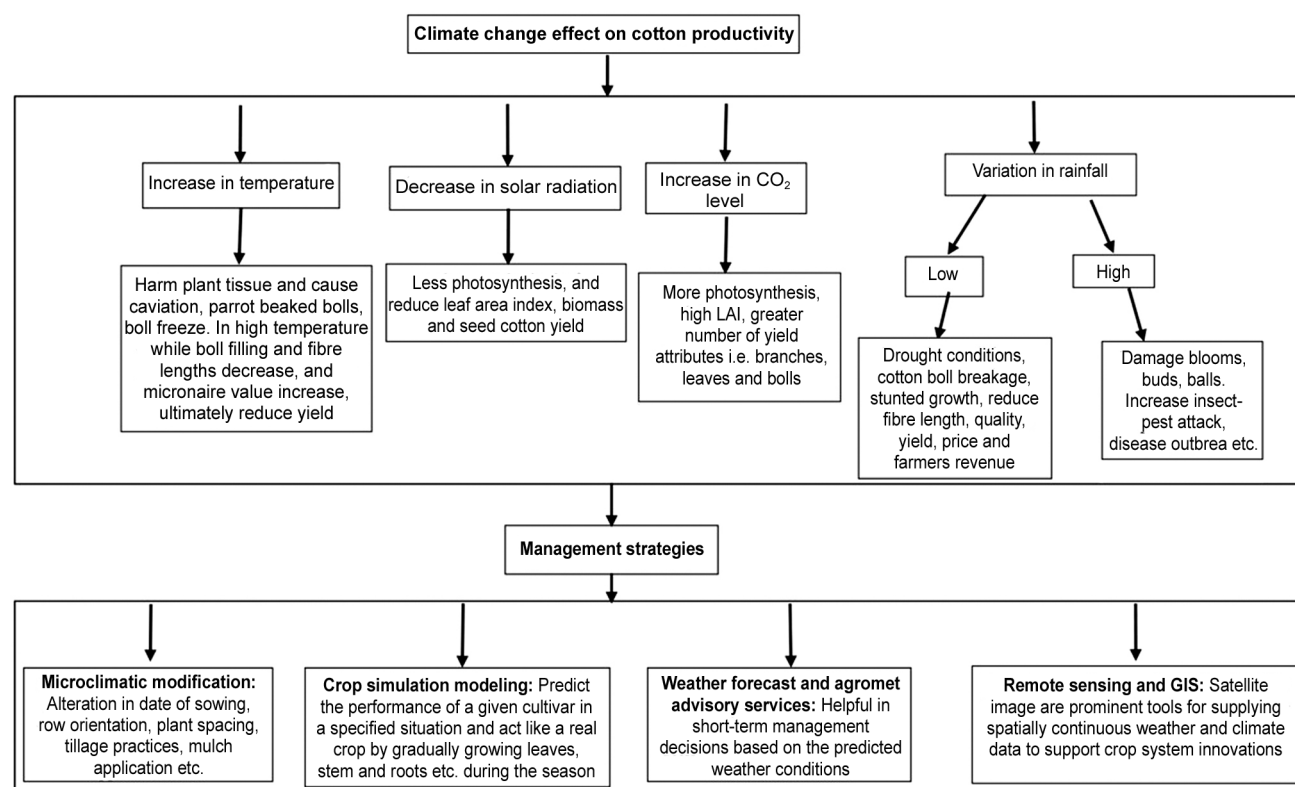


Fig. 3 Schematic illustration of climate change effects on cotton productivity and its management strategies.

important consequences of food security, and indicated the need for region specific technologies.

Way forward for policy-makers, farmers and other stakeholders:

- Grow just the recommended cotton kinds and hybrids, and finish sowing by May 15. To prevent the accumulation and transmission of pests and diseases to cotton at the same time, avoid cultivating bhindi, moong, arhar, castor and dhaincha in and surrounding cotton fields.
- For successful germination and early establishment of plants, heavy pre-sowing irrigation is essential. Depending on the soil type, the first irrigation should be applied 4–6 weeks after sowing. September has to be the last irrigation month.
- A good management technique for mealybug, pink bollworm and whitefly is routine monitoring. Prior to September 15, refrain from using synthetic pyrethroids to reduce the comeback of whiteflies.
- Utilize only the recommended dose of nitrogenous fertilizers and recommended pesticides to prevent the spread of insect pests; avoid tank mixing and the use of pre-made insecticidal combinations.
- To encourage climate smart production in Punjab's cotton-growing regions, the government should create necessary measures for the processing and careful distribution of certified cotton seed among farmers at their doorstep. Progressive farmers can be enlisted to help produce and distribute certified seed locally at a fair price.

- In cotton-growing regions, an awareness campaign on the advantages of climate smart production practices and technology needs to be launched using print, electronic, and smartphone apps. It is important to showcase and share the success stories that demonstrate all the necessary steps for climate smart production-based sustainable farming. Government can set up a farmer's field school and provide farmers, NGOs, with the necessary training for using energy-smart, carbon-smart, and knowledge-smart practices and technology.
- Lack of access to farm services, including easier access to markets, loans, and agricultural extension services, is a significant factor in the low adoption rate of climate smart production. For small and marginalised farms in particular, having access to the aforementioned agricultural services can be a big motivator for climate smart production adoption.
- There is a need to improve the learning opportunities for all stakeholders, agricultural service providers, progressive farmers, community representatives, and public regarding climate change, climate smart production practices and technologies.

Conclusion

The investigation underscores the escalating menace that changing climate scenarios pose to cotton productivity. Distinct climatic factors, notably temperature and moisture, hold pronounced sway over cotton's growth phase, particularly during its reproductive stage. The repercussions of marked deviations in these parameters, stemming

from the specter of global warming and shifting climate patterns, are poised to deliver detrimental blows to cotton productivity, especially in tropical and sub-tropical regions. Strategic interventions in the form of diverse management practices, including prudent selection of planting dates, optimal plant spacing, judicious row orientations, efficient irrigation systems, and effective mulching techniques, wield substantial sway over cotton yield. Concurrently, they exhibit the potential to curtail the emission of greenhouse gases (GHGs). Given the geographical nuances in climate variations, simulation modeling studies have surfaced as a preeminent approach for mitigating or adapting to the throes of climate change. In a realm of real-time decision-making, the timely accessibility to precise weather prognostications and expert agro-advisories emerges as a valuable asset. The integration of geospatial technologies, encompassing the prowess of remote sensing and Geographic Information Systems (GIS), is now an exigency. These technologies assume a pivotal role in the holistic evaluation and proficient management of the regional-scale impacts precipitated by climate change.

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