# Potential Impact of Changing Climate on the Sustainability of Potato (*Solanum Tuberosum* L.) Production in India

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**Abstract** Potatoes are a large commercial crop and the world's most consumed non-cereal food crop. The crop thrives in cool, but not frosty weather. Potatoes are a cool-season vegetable. Climate change is a serious issue that has the potential to impact the way we produce and handle food. Potato production systems will undoubtedly

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need to adapt to the consequences of climate change and control greenhouse gas emissions and energy from arable land. Frost free and heat free period is essentially required for potato in some critical growth stages. Climate change may alter the climatic condition of a region which may result in drastic yield reduction There is a key differential between locations where potato is grown in a relatively frost-free time and areas where potato is produced in a relatively frost-free period when assessing the effects of climate change on potato and areas where potato is grown in a moderately heat-free period. Higher day temperatures can make some areas unsuitable for potato production due to lower tuber yields and quality. Temperature fluctuations outside of 5–30 °C can severely limit tuber growth and yield. The rate of warming in the last 50 years has been twice that of the previous century. The temperature rises and increases in atmospheric $CO_2$ levels occur concurrently under future climate change and global warming scenarios. If $CO_2$ levels rise to 550 ppm, temperature rises are expected to be 3 °C, with a 13.72% drop in potato production by 2050. Drought, salinity, frost, flooding, and erratic unseasonal weather will negatively impact potato production. It has the potential to reduce seed tuber production, as well as have an impact on the storage facility and potato processing industries. As a result, quantifying regional vulnerability and assessing its impact is critical for developing early warning disease forecasting systems and breeding heat, drought, salinity, and disease-resistant cultivars.

**Keywords** Climate change · Greenhouse gas · Temperature · Drought · Crops

## 1 Introduction

On a worldwide basis, climate change is having a significant impact on agricultural productivity. Climate change is defined as a long-term change in temperature and typical weather patterns in a location beyond the average atmospheric condition caused by both natural and artificial factors such as volcanic activity, the orbit of the Earth's revolution, and crustal movements, as well as an increase in greenhouse gas and aerosol concentrations. Climate change, an average global temperature increase, has emerged as a key issue that will result in substantial future world changes. In reaction to changes in temperature and precipitation patterns, climate change increases the frequency and intensity of floods, droughts, heat waves, typhoons, and hurricanes. Worldwide, climate change considerably impacts agricultural productivity [43]. Climate change is projected to influence India, too [49]. By 2030, temperatures are anticipated to climb by up to 0.5 °C, causing more harsh weather and rainy days [62]. People are becoming more aware of the weather and the effects of climate

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change. If people are unaware of climate change, it will weaken or decrease rural incomes, food security, water storage, and increase the incidence of pests and diseases [55, 56, 67, 75, 80]. Globally speaking India is the world's second-largest producer of potatoes. It is an irrigated crop grown during the winter season, with the Indo-Gangetic plains (IGP) accounting for nearly 85% of the crop's 1.8 million hectares in India. West Bengal and Bihar are the two major Eastern Indo-Gangetic Plains (IGP) states. In India, Uttar Pradesh is the largest producer of potatoes, followed by West Bengal. Potato production is expected to be around 53.69 million tonnes, up from 48.56 million tonnes in 2019–20. India covers 2.13 million hectares for potato production, with annual output reaching nearly 44 million tonnes and an average yield of 20.5 tonnes per hectare [23]. The United Nations estimated in 2017 that the Indian population will increase by 19% by 2050, posing a significant challenge for the production of all food crops, including potatoes, to meet the country's future demand. Climate change is expected to shorten the duration of potato cropping in West Bengal's Indo-Gangetic plains (IGP). In future climates, evapotranspiration (ET) is expected to increase while water use efficiency (WUE) for potato yield is expected to decrease due to lower threshold temperatures for yield reduction than ET. It has been discovered that the upper threshold for ET decrease is 23 °C, whereas the upper threshold for WUE is 15 °C. The optimal temperatures for tuber yield are 17 °C, and thus a decrease in water use efficiency (WUE) in future climates is detectable. Climate change is expected to reduce potato yields in the IGP region by 2.5, 6, and 11% in 2020 (2010–2039), 2050 (2040–2069), and 2080 (2070–2099), respectively.

Rice, mustard, jute, wheat, and a few pulses have significantly contributed to agricultural research on the Gangetic plains of Bengal. Potato is a relative newcomer to this sector. Environmental elements such as temperature, sun radiation, and day length play a major role in the growth of the potato plant and its tubers. The potato feeds on the top layer of the soil. The root system is usually restricted to the top layers of soil (up to 30 cm). As a result, the nutritional content of the uppermost layers of the soil mostly controls the growth of haulm and tuber. Soil temperature affects the uptake of nutrients and water from the top soil layer. After the tuber is planted, potato buds begin to grow, which is mostly reliant on temperature. At 15 °C or higher, the apical sprout grows quicker, limiting the growth of the other buds [33]. Many buds continue to grow for prolonged periods due to climate change and unfavourable conditions. The dominating sprout is maintained by storing the tuber at a favorable and unfavorable temperature. Potato agriculture is mostly limited to a few areas dispersed along both banks of the Ganges in West Bengal's Gangetic plains. In the current scenario, the Leaf Area Index has significantly dropped as the cumulative maximum and lowest air temperatures have increased. The incidence of late blight in potato, the most deadly disease in West Bengal, is determined by rainfall and relative humidity, both of which are significant and destructive variables. Rainfall helps to reduce soil temperature and hydrolysis of starch respiratory losses from potato tubers, resulting in higher potato yields. Monsoon rains arrive late and stay late, making it difficult to prepare potato fields. The temperature does not drop even in December. Climate change is causing rising temperatures and $CO_2$ levels in the atmosphere, and both are predicted to rise at the same time in future climate change and global warming scenarios. Temperature rises of 3 °C are projected if $CO_2$ levels are elevated to 550 ppm, with a 13.72% reduction in potato yield by 2050. Potato output will be harmed by drought, salinity, frost, flooding, unpredictable unseasonal rains, and other conditions. It has the potential to diminish seed tuber output while also affecting the potato storage and processing businesses. As a result, evaluating regional susceptibility and assessing its impact is crucial for developing early warning disease forecasting systems, and breeding heat, drought, salinity, and disease resistant cultivars. The negative effect of climate change on potato productivity can be mitigated to some extent by changing the planting date and/or selecting suitable varieties, which may reduce the yield reduction from 9.7 to 7.1% in 2055.

## 2 General Observations on the Extreme Events of Weather Conditions on Potato

- Unwanted rain during the winter season at the time of planting affects the plant's emergence as well as tuber yield.
- Flooding in the crop field caused by heavy rain during the crop season reduces crop yield.
- Heavy rain at the time of harvesting causes potato rot.
- Cloudy skies and early rain during the cropping season increase the attack of blight disease in potatoes, resulting in a lower yield.
- Relatively warmer winters in 2008 reduced tuber yield in West Bengal, Uttar Pradesh, and Bihar.

## 3 Climate Change Impacts on Potato Production in India

Climate-related temperature, precipitation patterns, and circular factors such as high intensity and prevalence of pests and conditions all have an impact on potato output. Although climate change forecasts for Indian agriculture are still questionable, some experts anticipate that excessive rains will negatively influence the country [55, 56]. Despite this, due to India's size, there are regional variations in how climate change affects potato production.

Temperatures are not predicted to rise in northern provinces like as Punjab and western Uttar Pradesh, where the current average is the lowest minimum temperature, and some writers predict an increase in rainfall; as a result, potato farming in the region could be profitable. In Punjab, however, farmers employ groundwater sources in addition to the monsoon for irrigation, and there is evidence of over-exploitation of these resources [8]. In addition, rising groundwater depletion may restrict the benefits of rain. Rising temperatures and late blight could wreak havoc in southern states like as Gujarat and Karnataka, where temperatures are already high [78].

Punjab is getting warmer, but rain is on its way, which is great news for potato farmers. Late blight, as well as other pests and illnesses, will be more difficult to combat. A similar pattern would emerge in western Uttar Pradesh. Temperatures are forecast to rise in other parts of the country, putting potato production in peril. This will be especially true in Karnataka, where growing potatoes will become a high-risk endeavour. Minimum temperatures in Bihar are approaching the maximum limit for a number of grain and transplanting varieties [36], [83]. Rising temperatures in Punjab may be compensated for by increased $CO_2$ levels in the environment, resulting in steady potato yields overall [25]. Another issue related to climate change is dwindling rainfall. Rainfall-dependent areas, such as IGP, will be impacted. The states most affected by the increased pressure of low humidity induced by falling rainfall include Bihar and Eastern Uttar Pradesh, Gujarat, and Karnataka, whereas West Bengal and West Uttar Pradesh are predicted to benefit from monsoon rains [35, 48, 55, 56, 83]. A significant dependency on rainfall and a high drought sensitivity in the Northwest Peninsula (which includes Punjab and Gujarat). Guhathakurta and Rajivan [35], on the other hand, expected increasing rainfall in those states, while Mohanty et al. confirmed that rainfall levels in Gujarat have increased [59]. Our research area's comparatively wealthy states have fewer constraints, such as better market access, increased rural electrification, and a lower share of marginal farmers, and are thus better prepared to adapt to climate change [69]. During the Kharif season, most of Karnataka's northern districts are predicted to see more drought, while the Rabi season is likely to see more dryness in the eastern districts [7]. The conditions (e.g., greater temperatures, more variable rainfall) change as the climate changes, allowing germ density and disease severity to rise [31]. In the case of late blight, climate change may increase or reduce the ideal duration of disease development. For example, the number of good days in Punjab is projected to rise, while the number of suitable days in West Bengal is expected to fall [25, 54]. The Indo-Gangetic plains in India account for over 85% of total potato farming land (1.8 MHa). The crop is grown as an irrigated crop throughout the winter season. Climate change would cut potato yield by 2.5, 6, and 11% in the Indo-Gangetic plains by 2020 (2010–2039), 2050 (2040–2069), and 2080 (2070–2099), according to an experiment conducted by Naresh Kumar et al. [61]. Several techniques can be implemented to address this issue, such as shifting crop planting dates, which will boost tuber output by 6% in 2020. In the same way, enhanced potato cultivars can be utilised in addition to nitrogen to boost potato yield by 8% in 2020 and about 5% by 2050.

Climate change caused by global warming has the potential to increase potato production in Punjab, Haryana, and western and central Uttar Pradesh by 3.46–7.11% by 2030. However, potato production in West Bengal and the plateau region may fall by 4–16%. If proper strategies or management are not implemented, potato production in India may decrease by 3.16% and 13.72% in the years 2020 and 2050, respectively, due to climate change and global warming. Potato production is expected to fall by 23–32% by 2050 as a result of climate change and global warming. Dua [25] conducted a simulation study for 13 different locations in Punjab using the WOFOST crop growth model. According to the findings, an increase in temperature will reduce the productivity of potato varieties such as KufriBadshah from +11.6% (Amritsar) to −10% (Fatehgarh) in 2020, KufriJyoti from +11.6% to −11.6%, and KufriPukhraj from +12% to −11.5%. If the $CO_2$ concentration is increased, potato productivity will increase by 3.9–4.5%, depending on the production area and potato variety. Potato varieties may decrease production from 17.9 to 22% if the temperature rises further until 2055. When changes in temperature and carbon dioxide concentration are combined, potato production will be unaffected in 2020 compared to the baseline scenario; however, potato production of various cultivars in Punjab will decrease in the range of 2.62–5.3% until 2055. Venkateswarlu and Rao used the INFOCROP-POTATO model to investigate the effects of global climate change on potato production in India. According to the study's findings, potato production will decrease by 2.61% and 15.32% respectively by the years 2020 and 2050 if proper measures are not taken. However, due to climate change, potato production in Punjab, Haryana, and Western Uttar Pradesh may increase by 7.11% and 3.46% in 2020 and 2050, respectively, while potato production in the rest of India will decrease by 0.52–16.59% and 0.69–46.51% in 2020 and 2050, respectively. Singh et al. (year) demonstrated in his experiments that increasing the $CO_2$ concentration by 550 ppm and increasing the temperature by 10 °C increases potato production by 11.1%, but increasing the temperature to 30 °C has the opposite effect, reducing potato production by 13.7%. If $CO_2$ concentrations rise to 550 ppm, the temperature rises to 3 °C, reducing potato production by 13.72% by 2050. Severe climatic conditions such as drought, frost, flooding, salinity, unseasonal rain, and many other climate changes caused by global warming will negatively impact potato production in India. It will reduce seed tuber production and impact storage facilities and industries related to potato processing.

There is a growing consensus that changes in temperature, precipitation, and atmospheric $CO_2$ levels can have a negative impact on potato production. These effects are difficult to quantify and depend on various assumptions, and the land suitable for potato cultivation will be greatly impacted. Climate change will have different effects on different agro-ecological regions. Some of the regions will have a negative impact on potato cultivation, while others will have a positive impact.

Climate change will, directly and indirectly, affect potato cultivation, affecting food security and livelihood. Changes in agroecological conditions of regions are among the direct impacts, while changes in economic growth and farmer income distribution are among the indirect impacts. The problem will worsen as the quality and quantity of available cropland begins dwindle. Some cropland areas will also suffer from various types of land degradation and soil salinity issues [39].

### *3.1 Impact of Higher $CO_2$ Level and Temperature on Potato*

According to the Intergovernmental Panel on Climate Change [40], atmospheric carbon dioxide ($CO_2$) concentrations have increased from roughly 280 parts per million before the industrial revolution to around 360 parts per million now. Higher

$CO_2$ levels should, in theory, enhance photosynthesis in some plants. This is particularly true for $C_3$ plants like potatoes, because increasing $CO_2$ suppresses photorespiration. When atmospheric $CO_2$ level is higher, Rubisco, the principal enzyme in $C_3$ plant for $CO_2$ fixation, fixes more $CO_2$ and reacts less with $O_2$, resulting in increased photosynthesis and encouraging growth and production [4]. It has the potential, on the other side, to reduce crop duration. Potatoes may be cultivated in a range of climates, but they do best in milder ones. Increased temperature caused by increased $CO_2$ concentration results in a decrease in tuber yield, owing to increased respiration rates. At high temperatures (over 170 °C; [81], tuberization reduces. Reynolds and Ewing [70]. Potato is also frost-sensitive, thus it suffers when the temperature dips below 0 °C [38]. Assimilation and $CO_2$ concentration have a positive relationship. Total biomass grew by 27–66% when $CO_2$ concentrations were increased from 360 to 720 parts per million [18, 24, 37, 58, 65], [87]. Tuber yield increased from 32 to 85%. [19, 28, 92].

For every 100 ppm rise in $CO_2$ content, the increase in tuber production is expected to be around 10% [58]. These beneficial impacts are: ascribed to a 10–40% increase in photosynthesis [18, 44, 65, 73, 89]. Young leaves showed the greatest improvement in photosynthesis [44, 89]. This is due to a phenomenon known as photosynthetic acclimation. It occurs later in the growth season, especially in older leaves [50, 73, 89]. There are racial disparities in how people react to increased $CO_2$ levels [65]. Under increasing $CO_2$, the number of tubers remained unaltered, but mean tuber weight rose mostly due to an increase in the number of cells in the tuber. Tubers without affecting the volume of the cells [17, 18, 24]. However, there has been a rise in the number of tubers [19, 58]. When $CO_2$ levels are high, evapotranspiration (ET) is reduced, resulting in water savings of 12–14% [65]. Increased $CO_2$ concentration promotes tuber start and blooming [58], but accelerates leaf withering [58, 86]. Reduced chlorophyll content in leaves, especially later in the growth season after tuber start, is one of the few detrimental impacts of high $CO_2$ concentration [11, 50].

Potatoes are a temperature-sensitive crop. Cumulative maximum and lowest temperatures have a substantial impact on potato growth rate. The leaf area index decreased dramatically as the cumulative maximum and minimum temperatures rose. As the temperature rises throughout the growing season of the crop year after year, the greenhouse effect will reduce potato output in dry and semi-arid regions compared to northern India. Temperature and $CO_2$ levels in the atmosphere rise in lockstep, and $CO_2$ enrichment does not appear to compensate for the negative effects of increasing temperatures on tuber yields. The potato crop yield varies with temperature variations and is somewhat dependent on the current temperature in that location. Reduced tuber initiation and growth, reduced starch partitioning to tubers, physiological damage to tubers (e.g. brown patches), shortened/non-existent tuber dormancy, and tuber sprouting too early are all detrimental consequences of temperatures exceeding 30 °C on potato output. They will limit the crop's output by reducing the number and tuber of the potato crop. As a result, areas where the temperature is close to the maximum temperature for the potato crop will undoubtedly suffer in the future. The yield of the crop has been lowered. The growth and development of the potato crop is hampered in tropical areas by high temperatures. Potato crop growth is impossible at temperatures below 2 °C and impossible at temperatures beyond 30 °C [88]. The optimal (16–25 °C), lowest (0–7 °C), and maximum (40 °C) temperatures for net photosynthesis are presented [45]. Tuberization of potatoes requires a chilly night temperature [15, 21, 46]. Although high temperatures reduce photosynthesis in potatoes [46], tuberization and the partitioning of photosynthates to tuber [71]. Under high temperatures, the radiation use efficiency (RUE) is lowered [3]. Tuber number and size are reduced when the temperature is too high [26]. High temperatures cause aberrant morphological changes in the plant, such as white yellow spots and smaller leaves and leaflets, lowering the LAI [26, 29], as well as a reduction in tuber quantity and size [26, 29, 67]. Long day conditions and high temperatures, prevalent in the spring season in Punjab state on India's plains, encourage leaf growth and increased tuber processing quality [57]. Potato tuberization requires a cold night temperature, which is disrupted by even modestly high temperatures [26, 46]. Temperature had the greatest impact on tuber start [32].

### *3.2 Temperature and $CO_2$ Interaction Effect on Potato*

As a result of the current global warming situation, temperature and $CO_2$ levels are becoming increasingly intertwined. This will be a source of concern in the following days, and it will have economic implications in terms of crop growth, output, and quality. The impact of rising $CO_2$ and temperature on potato output in India was assessed using the INFOCROP-POTATO simulation model [76, 77] without adjustments and assuming that the area under the crop remains constant at current levels in future climatic scenarios (1.2 m ha). Experiments have shown that a 550 ppm rise in $CO_2$ content will boost potato yield by 11.12% However, the future climatic scenario for India suggests that if $CO_2$ concentrations rise by 550 ppm, temperature rises by 30° [40], reducing potato output by 13.72% by 2050. The 1 °C increase in temperature is projected to be connected with just 400 ppm of $CO_2$ in 2020 [40], resulting in a 3.16% decrease in potato yield.

### *3.3 Elevated Precipitation Due to Increased Temperature and Its Impact on Potato*

Rainfall in India and extreme rainfall events are expected to increase steadily in the future. By the 2030s, mean warming over India is anticipated to be in the range of 1.7–2.0 °C, and 3.3–4.8 °C by the 2080s, compared to pre-industrial times. As a result, precipitation over India is projected to rise by 4–5% significantly in comparison to 1961–1990, between the 2030s and 2080s, the annual growth rate will be 6–14%. Increased precipitation will result in a delayed monsoon and undesired rains throughout the winter season, delaying crop planting and inviting several crop diseases. The effects of climate change are diverse in different sections of the nation. Extreme occurrences are more likely to hit western Rajasthan, southern Gujarat, Madhya Pradesh, Maharashtra, northern Karnataka, northern Andhra Pradesh, and southern Bihar [55, 56]. Wheat, soybean, mustard, peanut, and potato yields are predicted to fall by 3–7% for every 1 °C increase in temperature [2]. High rainfall may have a deleterious effect on tuber bulking, but it also has a beneficial effect in that it reduces the need for irrigation water, lowering the cost of cultivation. The presence of moisture in the soil also inhibits the hydrolysis of the starch in the tuber, resulting in a reduction in respiration loss and an increase in yield, despite the increased moisture content in the soil being a challenge during crop harvesting.

## 3.4 The Impact of Increased $CO_2$ Levels and Temperatures on Soil and Water Availability, as Well as the Consequences for Potato

The soil carbon and nitrogen stocks are substantially negative and positively connected to the ratio of mean annual precipitation to potential evapotranspiration, meaning that they are equally vulnerable to rising temperatures and decreasing water availability. Acidic soils with pH levels ranging from 5.0 to 6.5 are ideal for growing potatoes. As a result of rising temperatures and lower precipitation, water quality is deteriorating day by day. Soil acidity in north east India could develop further under a business-as-usual scenario, due to rising temperatures and $CO_2$ concentrations in the atmosphere. Repeated experimental observations of increased $CO_2$ creation in soil as a result of greater root and soil microbial respiration in rising $CO_2$ environments tend to confirm this notion. $CO_2$ can exacerbate carbonic acid leaching and thus exacerbate the already severe problem of soil acidity in north east India [47].

Because climate change occurs often and swiftly, it has an impact on the ecosystem, particularly the soil system. Soil formation is impacted by a variety of soil forming elements and processes such as gas exchange, temperature, solar radiation, and other factors that are directly influenced by climate change [14]. Changes in global climate have an impact on soil erosion rates, which are determined by rainfall intensity and total number of wet days. Soil erosion affects soil fertility and water availability, which is a primary factor causing a fall in agricultural output and degrading environmental quality. The quantity and intensity of rainfall directly influence soil erosion, which fluctuates as the amount and intensity of rainfall changes [64, 90]. Soil deterioration is mostly caused by water erosion (82.6 Mha), followed by chemical degradation (24.7 Mha). There are 5.34 billion tonnes (Gt) of soil in the world degraded at a rate of 16.3 t $ha^{-1}$ $yr^{-1}$ on average in India. Temperature rises will enhance potential evapo-transpiration while decreasing surface runoff, infiltration, water storage, and groundwater recharge, especially if there is little precipitation. Climate change poses a danger to potato availability, access, and use owing to changes in climatic factors such as temperature, precipitation, $CO_2$, and so on. It is also predicted that soil salinity would rise in many parts of the world, reducing the appropriateness of potato farming on such soils. Furthermore, changes in environmental conditions may affect the availability of water for this vital crop's production.

According to the IPCC Working Group II report and a few other worldwide studies [1], crop production in India might drop by 10–14% by the year 2080–2100. This would result in more frequent heat waves, floods, droughts, cyclones, and glaciers' slow retreat, resulting in increased food production instability [1]. Looking at this statistic on temperature changes through time, it appears that the classifications of land suitability in terms of climatic region, with specific reference to mean temperature during the growing season, will continue to shift, and areas classified as very appropriate may become less so up to 2080, moderately appropriate will shift to marginally suitable class, while marginally suitable class will transition to unsuitable class.

## 4 Impact of Maximum and Minimum Temperature on Growth Parameter

The influence of cumulative minimum and maximum temperatures on LAI is nearly identical, with 36.4% of the variance in LAI explained by changes in cumulative minimum temperature. The CGR is inversely proportional to the cumulative maximum temperature, meaning that when the cumulative maximum temperature rises, the CGR rises up to a certain point. The fluctuation in cumulative maximum temperature might account for 32.3% of the variance in CGR of potatoes. When the cumulative maximum and lowest temperatures approached 350 and 150 °C, respectively, the CGR dropped considerably. Temperature has a significant impact on respiration [5]. Solar radiation, temperature, LAI, canopy design, and single leaf photosynthetic rate all influence canopy photosynthesis [52]. Potatoes are mostly farmed in north India during the winter months, when there is little rain. However, owing to the effects of global warming, the temperature is expected to rise the most in northern India, affecting potato output directly or indirectly. Today, we may witness unpredictable weather conditions such as unseasonal rain, floods, and icing, all of which impact crop development and productivity.

## 5 Indirect Effects of Climate Change and Global Warming

### *5.1 Drought*

The shallow root structure of the potato need optimal water delivery. The potato plant's roots are usually 40–50 cm deep [10]. Potato tuber beginning is quite susceptible to dryness, and drought under this scenario will result in a drop in tuber output.

As a function of development stage (DS) and root:shoot ratio, drought stress impacts dry matter partitioning to root, shoot, leaf, and stem. Drought reduces dry matter production, resulting in an increase in the root:shoot ratio, indicating that root development is favoured. Drought-stricken plants' roots are also often thinner. Both reactions allow drought-stricken plants to better use the existing soil moisture [91]. Under drought stress, tuber initiation and maturity are accelerated [10].

### *5.2 Salinity*

Despite low residual sodium carbonate (RSC) levels, potato is particularly vulnerable to salt and irrigation with saline water [79].

### *5.3 Frost*

Potatoes have a high level of frost sensitivity. When the temperature drops below 2 °C for 2–3 nights in a row, foliage is reported to be completely gone. It will take about 4–5 h. Even one night of exposure to temperatures below 1 °C can cause 50% leaf loss. The timing of frost in relation to the crop's growth stage determines the crop's yield loss. The degree of agricultural yield loss is also determined by when the frost occurs; for example, if the frost occurs 80–90 days after planting (DAP). The yield loss will be 10–15%, however if it occurs 50–60 days after planting (DAP), the yield loss will be 30–50%.

### *5.4 Flooding*

Even a few days of flooding during the active vegetative phase has an impact on growth and productivity. Flooding during harvest affects physical appearance and marketable quality due to rotting and rupture of tuber lenticels, whereas flooding before emergence diminishes emergence due to rotting seed tubers and the production of soil crusts. Erratic Rainfall that is out of the ordinary. Rainfall of even 10–15 mm during or immediately after planting hastens emergence due to the formation of a soil crust, delaying planting and reducing yield. Rains during the active vegetative period can worsen late blight disease.

## 5.5 Production of Seed Tuber

The use of disease-free, high-quality seed tubers as planting material in a vegetatively propagated potato crop is of particular importance. When tuber is utilised as seed material, it contains several fungal, bacterial, and viral pathogens that induce disease infestation in subsequent generations of the crop, resulting in a loss in crop production. Seed tubers, in particular, account for half of the cost of inputs in potato cultivation, and seed quality significantly impacts the cropping operation's profitability. Aphids and other vectors disseminate viral diseases that induce rapid degradation of planting materials in the potato crop. The 'seed plot approach' was developed to produce seed tubers in normally aphid-free seasons in the plains during the winters and terminating vines by dehaulming before the aphid population reaches a threshold, preventing viral disease infection. For every 1 °C increase in mean temperature, the arrival of the potato peach aphid (Myzuspersicae) is claimed to accelerate by two weeks, and population expansion is connected to highest temperature and lowest relative humidity [12]. Aphids have appeared earlier and in greater numbers as a result of climate change and global warming. The population is expected to reduce the amount of time that seed tubers are free of aphids, lowering seed tuber quality and quantity, and reducing potato output in India. In certain locations, warming may completely destroy seed tuber production, while in others, it will increase the cost of herbicides and insecticides, as well as the cost of seed, resulting in a drop in profitability.

## 5.6 Storage

Potato harvesting in India's plains corresponds with the start of the scorching summer season. To keep the tuber from decaying and losing weight, it is kept in the refrigerator. The tuber is kept in cold storage until the end of October, when it is harvested for eating. The potato may be kept in farm storage for up to 80 days in certain areas with chilly meteorological conditions. The operating cost of the potato grew while it was held in cold storage; as a result, the market cost of the potato as well as the seed cost of the potato increased. A greater number of cold storage facilities should be available around the region of production and consumption to keep the manufacturing, storage, and supply chains running efficiently, especially during the summer months (March–October).

## 5.7 Industry of Potato Processing

Potato tubers kept in cold storage at 4 °C are not suitable for processing because of a rise in decreasing sugar content in the stored potato, which is not viewed as a desirable attribute for many processed commodities. Potato tubers are kept in low-temperature storage at 10 °C or in farm country warehouses for processing. Tubers stored in low-temperature and remote storage, on the other hand, sprout and lose weight once the dormancy is broken, making them unsuitable for processing. As a result of global warming, the 'time window' of accessible potato appropriate for processing will be decreased, raising the expense of chemically treating tubers to avoid sprouting. In terms of raw material supply, this has ramifications for the potato processing industry's long-term viability.

## 6 Effect of Elevated $CO_2$ on Disease of Potato:

$CO_2$ levels that are too high can affect the host and the pathogen in various ways. The faster growth of leaves and stems in plants grown in high $CO_2$ environments has been related to thicker canopies and more humidity, both of which favour disease (www.Climate-and-forming.org). Increased $CO_2$ levels (400–700 ppm) and/or ozone levels (ambient or two-fold ambient) impacted the susceptibility of potato plants infected with P. infestans, according to Osswald et al. [66]. The most important conclusion was that raising $CO_2$ made the sensitive potato cultivar 'Indira' far more resistant to P. infestans, whereas ozone had no effect. The impact of N-fertilization in combination with $CO_2$-treatment on potato resistance to P. infestans was also investigated because $CO_2$ caused a rise in resistance linked to an increased C/N-ratio in potato leaves. The lower C/N ratio, which was generated by higher N concentrations, lowered resistance to P. infestans. Similarly, Plessl et al. [68] discovered that after exposure to 700 ppm $CO_2$, the potato cultivar Indira, which was vulnerable to P. infestans under normal conditions, developed resistance. Ywa et al. [93] discovered that tomato plants planted at higher $CO_2$ levels were more resistant to Phytophthera root rot. Higher $CO_2$ increased the pathogen load of C3 grass, possibly due to increased leaf lifetime and photosynthetic rate.

## 7 Effect of Elevated Temperature on Disease of Potato

Temperature and exposure time are crucial factors in understanding the impact of climate change on disease severity. Changes in temperature have resulted in the emergence of novel disease races that are currently inactive but may become pandemic in nature in the future. Temperature changes directly impact a pathogen's capacity to infect, reproduce, disperse, survive, and other important phases of its life cycle. When soil temperatures rise, several soil-borne illnesses may become more common. Pathogens will follow their hosts if climate change causes a progressive shift in farming zones. In the epidemiology of the disease, the susceptible host is critical. Epidemiological factors have a significant impact on climate change. At higher temperatures, P. infestans had a short incubation time, with the shortest Incubation

Period (IP) occurring at 28 °C [9]. According to Mizubuti and Fry, with increasing temperature, IP reduced exponentially but Lesion Area (LA) increased exponentially (1998). Indirect germination (5–10 zoospore/sporangium) is favoured at temperatures below 20 °C, with an ideal of 1213 °C, whereas direct germination (5–10 zoospore/sporangium) is favoured at temperatures above 20 °C, with an optimum of 24 °C (one sporangium gives rise to a germ tube). Even at ideal temperatures, direct germination is typically much lower than indirect germination [20, 34].

Late blight's destructive capacity may alter abnormally in India as well as the rest of the world as the climate changes. Previously, late blight was not a serious problem in Punjab, Haryana, and parts of Uttar Pradesh due to sub-optimal temperature regimes in December and January. The sickness epidemic was exacerbated by increased temperature mixed with high RH. Such scenarios have occurred during warmer years, such as 1997–98 and 2006–07, when average crop losses in this region neared 40%. The severity of late blight has lately grown as a result of increased rainfall during advanced stages of crop growth. Under the current climate, states like Madhya Pradesh, Gujarat, and Central Uttar Pradesh, which are comparably less affected by late blight, may see regular outbreaks of the disease.

## 8 Effect of Rainfall/High Humidity on the Disease of Potato

When rainfall and high humidity increase at the same time, disease outbreaks in potatoes such as late blight (Potato infestans) become more likely, especially when extended growing seasons are combined. In Upper Great Lakes region of the US, the late blight of potato causes huge loss of the yield of potato due to this reason economic loss occurs this thing happens when there is an increase in precipitation as well as number of rainy days' increases. In India, the Lahaul valley of Himachal Pradesh, which had previously been free of late blight due to a lack of precipitation, has suddenly been hit by late blight as a result of rainfall [75]. Summers that are hotter and drier, as they are predicted to be in the UK, may lessen the importance of late blight, while early disease onset may negate this benefit. An empirical climate disease model has suggested that with the increase in temperature by 1 °C with the decrease in the amount of precipitation by 30% will reduce the chances of Late blight of potato in Germany by 16% from the current scenario. With the rise in temperature in India's North-Western plains, late blight attacks are anticipated to grow. The disease is expected to decline in the Eastern Plains, especially West Bengal. With the increase in temperature and decrease in precipitation, hilly locations may have a shorter late blight assault.

## 9 Climate Change Effect on Rainfall:

Precipitation is influenced directly by global warming. Increased temperature leads to increased evaporation and, as a result, surface drying, increasing the severity and duration of the drought. The ability of air to store water increases by about 7% as the temperature rises by 1 °C. (This causes an increase in atmospheric water vapour, according to the Clausius-Clapeyron (C–C) equation.) Additionally, every decade, global warming produces a 0.14 °F increase in mean sea surface temperature (https://www.epa.gov/climate-indicators/climate-change-indicators-sea-surface-temperature). With increased moisture, extratropical rain or snow storms produce more powerful precipitation episodes, which leads to more storms (Fig. 1).

In India, the highest rainfall in June was received in 2008 (445.8 mm), and the highest rainfall in July was received in 2007 (638 mm), while the highest rainfall in August was received in 1996 (494.7 mm), and the highest rainfall in September was received in 1995 (482.2 mm). The years 1990 and 1999 saw the highest annual rainfall of 2384.5 mm and the maximum southwest monsoon rainfall of 1814.2 mm, respectively (IMD). Southwest monsoon rainfall (June–September) accounts for 77% of yearly rainfall in India. And West Bengal receives the most rain in July (30% of SW monsoon rainfall), followed by August (26% of SW monsoon rainfall) (IMD). Due to climate change, monsoons begin with modest rainfall but end with increasing rainfall, with torrential rains triggering fatal floods in many states. The number of days with heavy rainfall has increased as a result of climate change, making weather forecasting more difficult.

The monsoon in India retreated several days later than usual in 2019. The monsoon usually withdraws from extreme northwest India, i.e. west Rajasthan, on September 1 and from the entire nation by September 15. Because of various circumstances, the

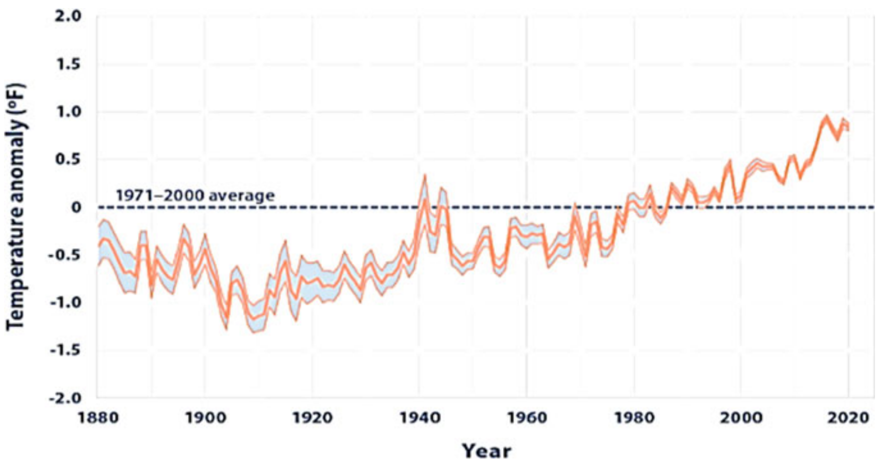


**Fig. 1** Average global sea surface temperature (1880–2020). *Source* NOAA [63]

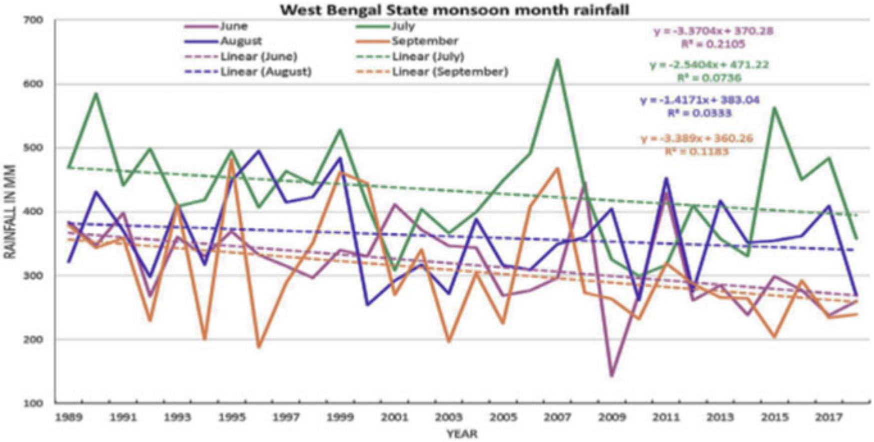


**Fig. 2** Annual rainfall trend over the years in whole India. *Source* Exploratory data analysis on Indian rainfall (1901–2017)

monsoon has been very active in September. One key element is that low-pressure systems that developed over the Bay of Bengal proceeded towards Rajasthan, causing an east–west-directed low-pressure zone. The monsoon was able to continue for a long time as a result of this (https://medium.com/@vighneshutamse/analysis-on-indian-rainfall-1901-2017-49224557278c).

The graphical representation of rainfall for last 100 years has been presented in Fig. 2.

In West Bengal, the monthly rainfall in June and seasonal and annual rainfall indicate a substantial declining trend, whereas the remaining months show no such pattern (Fig. 3).

**Due to climate change variation of rainfall and associate factors over West Bengal has been presented below (Figs. 4, 5, 6 and 7, Table 1): (from 1989 to 2018)**

Heavy rainfall days have increased significantly during the year in the districts of Alipurduar, Bankura, Birbhum, Jalpaiguri, Purulia, PurbaMidnapore, Pashchim-Midnapore, North 24 Parganas, South 24 Parganas, and Kalimpong. High rainfall days have decreased significantly in the Malda, Nadia, Birbhum, and Murshidabad districts.

(From 1989 to 2018) There has been a notable increase in the number of rainy days in the districts of Kalimpong, Jalpaiguri, PaschimMidnapore, PaschimBurdhman, PurbaBurdhman, Bankura, and Nadia during the months of June to September. Rainy days have decreased significantly in Cooch Behar, Malda, Hoogly, PurbaMidnapore, and Murshidabad districts. The number of rainy days in Purulia, Kalimpong, Jalpaiguri, PaschimMidnapore, PaschimBurdhman, PurbaBurdhman, and Nadia

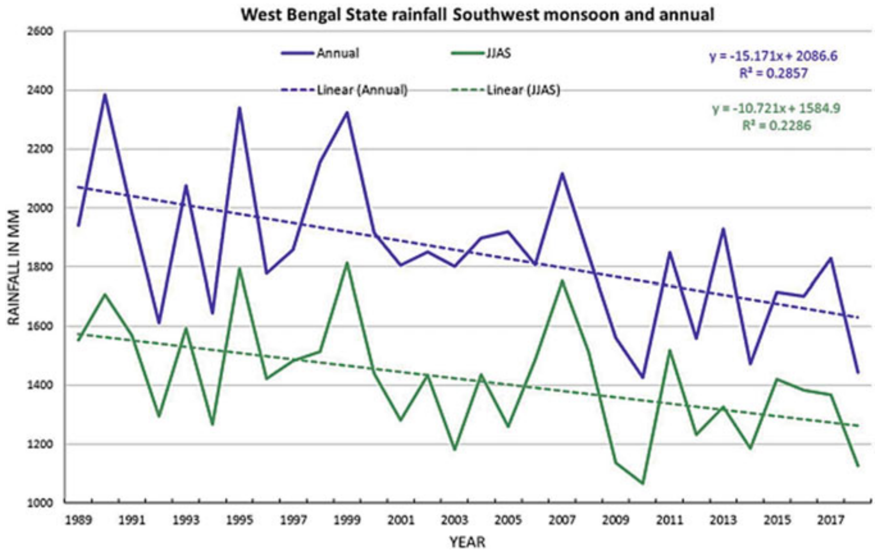


**Fig. 3** Variation of rainfall in West Bengal in different year. *Source* Observed rainfall variability and changes over West Bengal state

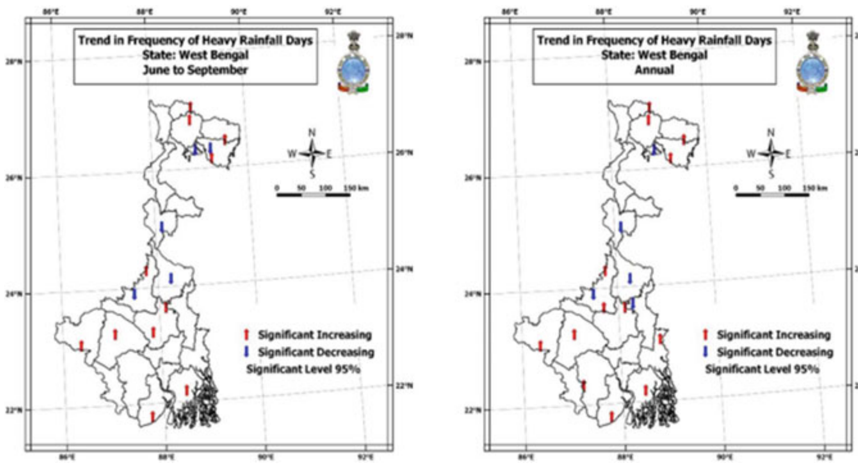


**Fig. 4** Trend in frequency of heavy rainfall days over West Bengal. *Source* Observed rainfall variability and changes over West Bengal state

districts has increased significantly over the year. Rainy days have decreased significantly in the districts of Cooch Behar, Malda, Hoogly, PurbaMidnapore, Darjeeling, Birbhum, DakshinDinajpur, and Murshidabad.

Mean rainfall amount with respect to month and year and corresponding CV% in WB has been given in Table 1.

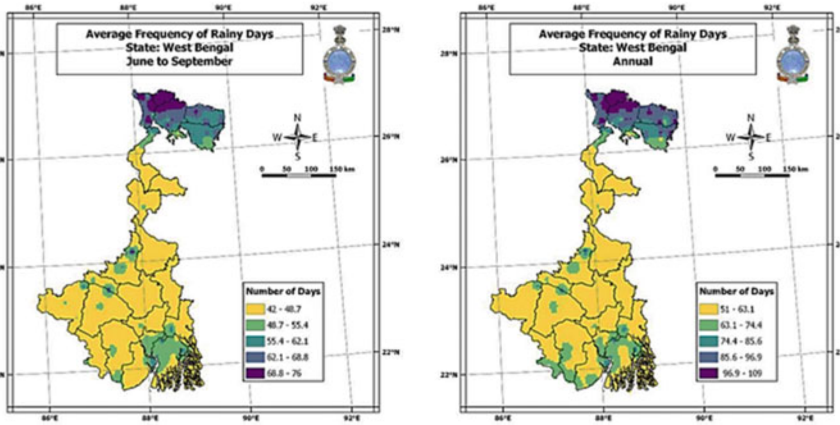


**Fig. 5** Average frequency of rainy days over West Bengal. *Source* Observed rainfall variability and changes over West Bengal state

**Table 1** The state's mean rainfall (mm) and coefficient of variation for monsoon months, the southwest monsoon season, and the annual

| | June | July | August | September | JJAS | Annual |
|---|---|---|---|---|---|---|
| Mean | 318 | 431.8 | 361.1 | 307.7 | 1418.7 | 1851.4 |
| cv | 20.3 | 19.1 | 18.9 | 28.2 | 13.9 | 13.5 |

*Source* Observed rainfall variability and changes over West Bengal state

CV% of annual and seasonal rainfall for different districts of WB has been diagrammatically presented in Fig. 6.

Almost all 26 districts, with the exception of Uttar Dinajpur, Darjeeling, Jhargram, and Hoogly, see a considerable rise in dry days from June to September. Almost all districts, with the exception of Uttar Dinajpur, Jhargram, and DakshinDinajpur, see a considerable increase in dry days during the year. However, in the districts of Birbhum and Murshidabad, the number of dry days has decreased significantly (Fig. 7).

## 10 Climate Change Effect on Water Resources

India now has a water stress of 1,588 cubic metres of water per person per year (India-WRIS, 2012), which is higher than 1000 cubic metres per year and qualifies the country as a water-scarce country. India now has 18% of the world's population, yet it only has 4% of the world's renewable water resources. Only roughly half of the accessible water sources are useable. There will be tremendous strain on our current water resources as a result of population expansion and the predicted rise in demand for water resources, particularly to meet the country's food demands. More

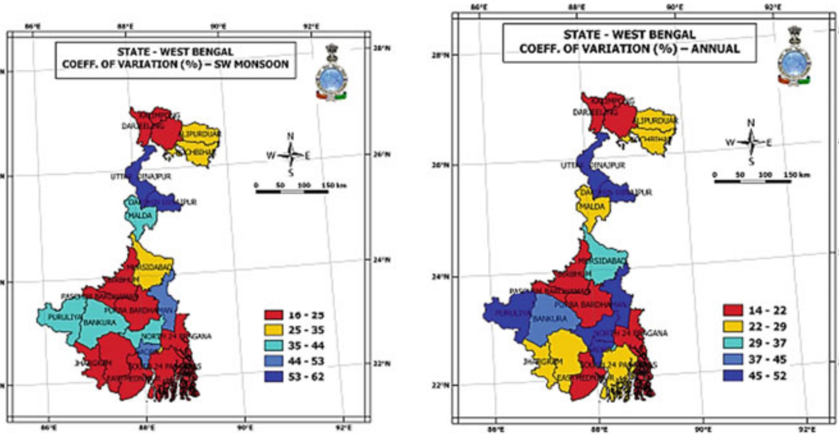


**Fig. 6** CV% of annual and seasonal rainfall for different districts of WB. *Source* Observed rainfall variability and changes over West Bengal state

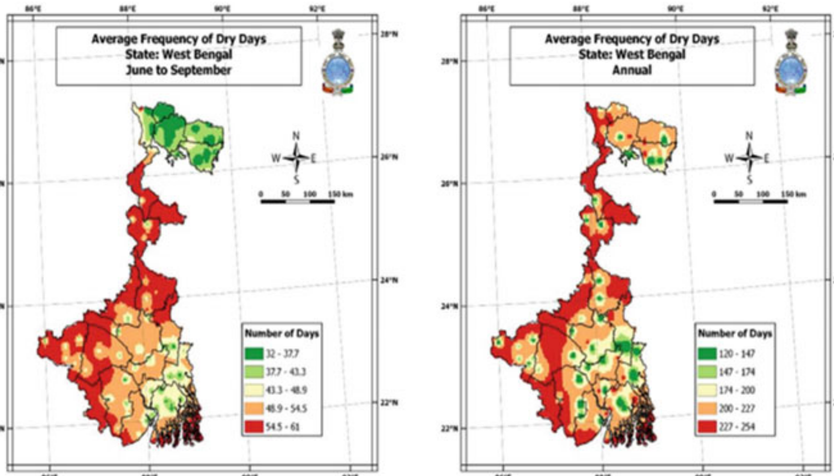


**Fig. 7** Average frequency of dry days over West Bengal. *Source* Observed rainfall variability and changes over West Bengal state

than 54% of the country is now experiencing acute water scarcity. Adopting proper conservation standards, encouraging replenishment, sustainable management, and preserving the quality of current resources are all critical steps in preventing future water shortages in our nation. Apart from conservation, the reuse and recycling of current water resources and the creation of new water resources to satisfy future demands should be prioritised.

### 10.1 Surface Water Sources

The Central Water Commission divides India's surface water resources into 12 main districts and eight composite basins (CWC). Various government agencies (e.g., CGWB, NCIWRDP, ISRO, India–WRIS) create classifications. Surface water provides 37% of irrigation demands, with 29% coming from canals, 4% from higher tanks, and some from other sources. To understand water loss, these figures must be compared to the overall irrigation efficiency of canals, which is 38–40%. [22]. Canal irrigation is widespread in India's northern and northwestern plains, whereas tank irrigation, one of the most popular and long-lasting irrigation technologies, is common on the peninsula's rocky terrain.

## 11 Potential Impacts of Climate Change

The increased frequency of climatic extremes projected as a result of global warming [60] may further diminish the capacity of usable surface water sources. High-intensity precipitation within the catchment regions of storage reservoirs exceeds their capacity, causing shutters to open, resulting in higher flows downstream of rivers and water waste. Flood-prone areas such as Kerala, Chennai, Gujarat, Hyderabad, Uttarakhand, and others are examples of surface water being squandered without being able to retain and maintain it for future use, particularly during droughts. Flash floods are caused by excessive temporal precipitation variability in urban and rural locations. L lengthy droughts mostly affect the south Indian basins, with seasonal flow adding to the water stress in these areas.

GCMs (global climate models) were used to forecast future weather anomalies over a period of time. Despite a forecast rise in precipitation practically everywhere on the planet, even in parched places, all representatives oppose it. The expected temperature in Himalayan and Sub-Himalayan regions and northern India in general shows a better growth. Another significant hazard to the floor water resource is pollution from both point and non-point sources. Climate change contributes significantly to the deterioration of pollutants in water resources. Floods in cities can cause sewage and industrial waste to mingle with surface water sources. The high degree of groundwater extraction in Rajasthan and Gujarat has resulted in uranium contamination of groundwater. Because of the decreasing water levels in such aquifers, the uranium-rich granite undergoes oxidation, resulting in uranium contamination of the groundwater [82].

Snow and glacier melt play a critical role in improving water resources in Himalayan rivers. Glacier melt is significant because it delivers a significant amount of water mostly during drought years and a little amount of water at times during flood years, balancing and sustaining water availability in the basin [55, 56]. Since the mid-nineteenth century, glaciers in Himalayan areas have been retreating and demonstrating negative mass stability, and the rate of loss has doubled in recent years due to temperature rises, according to a large body of evidence [13].

## 12 Groundwater Resources

Groundwater resources are mainly used by the agricultural sector for up to 90% of the groundwater draft, leaving the remaining 10% for domestic and industrial use. Groundwater serves 62% of irrigation needs, 85% of rural water supply systems, and 45% of urban water supply systems [16].

## 13 Potential Impacts of Climate Change

Climate change affects soil moisture, groundwater recharge, and groundwater level in various places by changing climatic extremes' frequency. As the world's population grows, so does the demand for ground water, which limits the real recharge time of aquifers and worsens water levels [55, 56]. The north-west and north-central parts of India experience low-intensity rainfall due to El Nino, which negatively impacts recharging alluvial aquifers. Southern India, on the other hand, receives high-intensity precipitation due to the Atlantic Ocean's warm sea surface temperature, which favours groundwater recharging [6].

On the recent fluctuations in groundwater levels, there is a wealth of information accessible. The analyses based on the Gravity Recovery and Climate Experiment Mission (GRACE) data between 2002 and 2008 produced some contradictory conclusions. Some studies exaggerated depletion rates in north-west India, estimating them to be 17.7 4.5 BCM/year on average [72], which is higher than the Ministry of Water Resources' estimate of 13.2 BCM/year. Long et al. [53] validated GRACE's overestimation of groundwater depletion in north-west India, and he recalculated the depletion to 140.4 BCM/year, in line with Ministry of Water Resources statistics. The high rate of groundwater abstraction for agriculture in Northern India's Gangetic basin causes resource depletion at a rate of 549 $km^3$/year from 2002 to 2008 [84]. The study by Asoka et al. discovered a 1–2 cm/year increase in storage level in southern India from 2002 to 2008 [6]. During the same time span, however, the storage level in northern India fell at a rate of 2 cm/year. Their research also discovered that groundwater withdrawal increases when there is a lack of precipitation in India.

According to Asoka et al. climate change is more significant than manmade factors in determining a region's groundwater table [6]. About 40% of the land area in the north Indian plains and Saurashtra region is irrigated by groundwater; positive precipitation trends have resulted in an increase in groundwater table in the Saurashtra region, In the north Indian plains, negative precipitation patterns have resulted in a drop in groundwater table.

## 14 Effect on Agriculture

The agricultural sector consumes the majority of the country's water resources, accounting for around 83% of total accessible water resources. Sprinkler and drip irrigation systems have an impact on irrigation efficiency. India's Water Resources in a Changing Climate: An overview irrigation system, as well as the total removal of flood irrigation, is crucial for reducing the expanding needs of the agriculture sector. The government's 'per drop, more produce' project is a praiseworthy attempt to improve water efficiency. To minimise groundwater consumption for irrigation, effective and efficient irrigation technology must be implemented by water regulations that incentivize conservation measures such as water price and de-subsidizing pumping costs [30]. Irrigation penetration in the nation is now less than 50%. More penetration is unavoidable in order to secure food security in the face of climate change. Increased irrigation penetration will quadruple water demand for agriculture at current irrigation efficiency. For developing countries like India, obtaining high water and land productivity is critical to ensuring future food security. We must evaluate variables such as green and blue water and their proportional participation in our agricultural goods and agro-exports to optimise water consumption [27]. Water demand is increased by inefficient irrigation practises and an unscientific cropping pattern adopted in the country, where water-intensive crops are produced in critically challenged areas. Since the green revolution, paddy cropping in northern India has resulted in the indiscriminate draining of groundwater resources in the north Indian plains. India is a net water exporter, meaning that it exports water-intensive crops while importing less water-intensive products, increasing the amount of virtual water in our economy. Water-intensive crops such as cotton, rice, sugar, and soybean are exported, resulting in a net water export of 1% of total available water per year [22].

## 15 Future Projections

India's population is expected to reach 1.7 billion people by 2050, as the country changes from an agrarian to a service-oriented economy, the demand for water resources is likely to skyrocket. Rapid urbanisation and industrialisation not only strain food security but also increase demand for water resources, exacerbating the problem. India's water consumption is estimated to increase by more than 70% by 2025, and the country is expected to face serious water scarcity by 2050. The rate of groundwater depletion is at an alarming level and the harsh reality of our country's water crisis is being observed under uncertain and variable precipitation caused by climate change, inefficient irrigation water use. On the one hand, water demand is rapidly increasing while water quality is getting degraded.

According to recent estimates, at least 21 Indian towns may have zero groundwater levels by 2020, and over 40% of Indians may not have enough water to drink by 2030 [74]. Our available resources are both insufficient in quantity and quality. India is ranked 120th out of 122 nations in terms of water quality by the United Nations. Only 20% of municipal and industrial water in India is treated, resulting in 70% of the supply being polluted [42].

## 16 Conclusion

Global warming directly impacts agricultural output, and it has now become a severe challenge for our country in terms of food security. The planting period will vary due to global warming, and the crop's maturity will be delayed. The location of potato production will alter as a result of global warming. In many parts of India, agricultural output will decline in smaller quantities, which will be difficult to notice now but would result in a big loss in the future. Shifting planting time or location is more difficult at lower elevations, and global warming may have a substantial negative influence in these places.

Climate change and global warming will majorly impact India's potato growth storey, affecting all part of the perishable vegetatively propagated crop, including seed multiplication, storage, marketing, and processing. Unless adequate adaptation strategies are developed and implemented in a timely manner, potato growth estimates in India may be halted or even reversed due to future climate change scenarios.

## 17 Recommendation

Recommendations for addressing the impacts of global warming on potato production in India in the context of a research paper could include:

**Assessment of Climate Change Vulnerability**: Conduct comprehensive assessments to identify the regions and specific potato-growing areas in India that are most vulnerable to the impacts of global warming. This will help prioritize adaptation strategies and allocate resources effectively.

**Development of Climate-Resilient Varieties**: Invest in research and breeding programs to develop and promote climate-resilient potato varieties that can withstand higher temperatures, changes in precipitation patterns, and emerging pests and diseases. These varieties should have improved heat and drought tolerance, shorter maturity periods, and high yield potential.

**Implementation of Climate-Smart Practices**: Promote the adoption of climate-smart agricultural practices among potato farmers, such as precision farming, improved irrigation techniques, and conservation agriculture. These practices can enhance resource-use efficiency, water management, and soil health, reducing the vulnerability of potato crops to climate change.

By implementing these recommendations, India can mitigate the adverse impacts of global warming on potato production, ensure food security, and sustain the livelihoods of potato farmers.

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