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The multifaceted impact of climate change on agriculture and biodiversity: An integrative assessment

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Abstract

The 21st century presents formidable challenges, including climate change, energy supply, health and disease invasion, and the need for a sustainable environment. Among these, climate change poses a significant threat, particularly to biodiversity and food security, with narrowly adapted and endemic species being the most vulnerable. India, with its unique geography, history, and culture, is distinguished by its remarkable diversity of natural ecosystems. It is one of the twelve mega biodiversity hotspots globally, reflecting the breadth of its biological diversity. This study offers a comprehensive analysis of the impacts of climate change on four interconnected domains in India: agriculture, land resources, water resources, and biodiversity. Our findings reveal that rising temperatures, altered precipitation patterns, and the increased frequency of extreme weather events are significantly undermining India's agricultural productivity, which in turn poses serious risks to food security. Land degradation and desertification are accelerating in vulnerable regions, while water resources are under increasing pressure due to factors such as glacial retreat, shifting monsoon patterns, and heightened evapotranspiration rates. Furthermore, India's rich biodiversity is at risk, with shifts in species distribution and potential extinctions on the horizon. The study underscores the intricate interplay between these sectors, highlighting the urgent need for integrated adaptation strategies. We conclude by proposing a framework for policy interventions that address these challenges holistically. This framework emphasizes the importance of sustainable resource management, climate-resilient agricultural practices, and ecosystem conservation as essential strategies for mitigating the impacts of climate change on India's natural and agricultural systems.

Keywords: Climate change, India, agriculture, biodiversity, adaptation

1. Introduction

Climate refers to the long-term average of weather conditions in a specific region, encompassing statistical patterns of meteorological elements such as temperature, precipitation, and humidity (WMO, 2006). Climate change (CC) involves alterations in these climatic patterns due to both anthropogenic and natural disturbances, including ozone layer depletion and greenhouse gas effects. The 21st century faces significant challenges including climate change, energy supply, health risks, and environmental sustainability. The rate of climate change is accelerating beyond recent historical norms, with global average surface temperatures increasing by approximately 0.6°C throughout the 20th century. Recent years have seen a rapid rise in greenhouse gas (GHG) emissions from both human activities and natural processes. These gases, which trap infrared radiation and remain in the atmosphere, are expected to significantly influence future climate conditions (Montzka *et al*., 2011) [74]. The broader effects of global warming are extensive, leading to Arctic shrinkage, glacial retreat, and rising global sea levels. Changes in precipitation patterns are expected to cause more frequent and severe floods and droughts. Additionally, agricultural yields may be affected, new trade routes could emerge, and there could be widespread species extinctions and expanded ranges for disease vectors (Mohanty *et al*., 2010) [72].

Asia is particularly vulnerable to the impacts of climate change, with projections indicating a global mean temperature increase of 1.5 °C between 2030 and 2050 if current trends continue (IPCC, 2019). Arid regions in western China, Pakistan, and India are expected to experience significant temperature rises, while the monsoon season will become more erratic and intense. South and Southeast Asia are predicted to face increased aridity due to reduced winter rainfall. These climatic abnormalities are projected to contribute to a 0.1-meter rise in global sea levels by 2100 (IPCC, 2019). Future climate scenarios for Asia include increased heatwaves, hot and dry days, unpredictable rainfall patterns, intensified dust storms, and worsened tropical cyclones (Gouldson *et al*., 2016) [39]. Natural disasters significantly impact agricultural productivity in Asia, with extreme temperatures, storms, and wildfires responsible for 23% of losses, floods for 37%, droughts for 19%, and pest and disease infestations for 9%, totaling approximately 10 billion USD in damages (FAO, 2021) [32]. South Asia, home to 262 million malnourished individuals, is recognized as the most food-insecure region globally. Rural populations in drylands and deserts are particularly vulnerable due to limited natural resources. In India, climate change threatens agriculture, land and water resources, and biodiversity, disproportionately affecting the poorest populations reliant on climate-sensitive sectors like agriculture and forestry (Kumar *et al*., 2020) [58].

Climate change poses a significant threat to sustainable agriculture, food security, and the livelihoods of farmers, especially small and marginal farmers in India who have limited adaptive capacity (Rao *et al*., 2020) [86]. The adverse effects of climate change on rice production—a staple food in the region—are particularly concerning. Factors such as extreme temperatures, droughts, salinity, heavy rains, and floods are negatively impacting rice yields and farmers' incomes (Dabi & Khanna, 2018) [23]. Addressing these challenges requires increasing agricultural productivity and income while ensuring sustainability. The effects of climate change on India's agricultural systems underscore the need for comprehensive assessments and adaptive strategies to protect food security and support farmers' livelihoods (Praveen & Sharma, 2020) [67].

The increasing concentration of atmospheric carbon dioxide (CO_2) is a pressing global environmental issue due to its persistent and irreversible effects on ecological timescales (Doney *et al*., 2012) [28]. Elevated CO_2 levels lead to rising ocean temperatures, resulting in greater ocean stratification, higher sea levels, reduced sea ice extent, and altered ocean circulation patterns. Ocean acidification, another direct impact of rising CO_2, is also a significant concern (Bijma *et al*., 2013) [13].

Climate change affects global biodiversity in complex ways. Animal movement is crucial for ecological interactions and can influence fitness and population survival through foraging, predation, and migration (Nathan *et al*., 2008) [78]. For example, fish may migrate in response to warming temperatures, and global warming can impact the timing of bird migrations. Rising temperatures also lead to physiological changes in animals, such as increased respiration rates and decreased nutrient utilization efficiency, which affect reproductive performance, particularly in dairy cows (Chase *et al*., 2006) [20]. Plants are similarly affected, with changes in climatic conditions altering their phenological phases, growing seasons, and fitness. These impacts highlight the need for effective conservation strategies to mitigate the adverse effects of climate change on biodiversity and the environment.

2. Drivers of climate change

2.1. Emission of green-house gases

Anthropogenic greenhouse gas (GHG) emissions, primarily from carbon dioxide (76%), methane (16%), and nitrous oxide (2%), are the main drivers of climate change. Historically, the Earth's temperature was moderated by the partial reflection of solar radiation. However, the accumulation of GHGs has created an atmospheric layer that traps and re-radiates infrared radiation back to the Earth's surface, enhancing the greenhouse effect. Methane and nitrous oxide are particularly potent, with heat-trapping potentials 25 and 300 times greater than CO2, respectively. Initially, developed nations were the major CO2 emitters, but China now leads with 27% of global emissions, followed by the United States (11%) and India (6.6%), though India ranks ninth in per capita emissions. The combustion of fossil fuels for industry and transportation remains the primary source of GHG emissions. Atmospheric CO2 levels have increased from pre-industrial levels of 280 ppm to 412 ppm as of 2019.

The rise in oceanic temperatures and acidity due to atmospheric CO2 absorption not only reduces the ocean's carbon sink capacity but also adversely impacts marine ecosystems. Livestock farming, driven by growing demand for meat and dairy, significantly contributes to methane emissions through enteric fermentation and manure management. Sejiyan *et al*. (2016) highlight methane production by ruminants during digestion, while Pimentel and Pimentel (2003) note the resource-intensive nature of meat production compared to plant-based alternatives. Producing 1 kg of meat requires 7 kg of grain and 5000-20,000 L of water, whereas 1 kg of wheat needs only 500-4000 L of water. Leeming (2021) [62] cites Patrick Brown's assertion that plant-based ingredients can match the nutritional value of meat at a lower cost. Nitrous oxide emissions primarily come from microbial activity in uncultivated soils and wastewater (60%), with agricultural practices, especially nitrogenous fertilizers, contributing significantly to anthropogenic sources. Synthetic fertilizers are more prone to microbial conversion to nitrous oxide than organic alternatives due to their rapid nitrogen release.

Current atmospheric concentrations of CO_2, methane, and nitrous oxide are at unprecedented levels in recent geological history, as noted in the AR6 Climate Change report (2021). Additionally, the thawing of permafrost in Arctic regions due to global warming poses an additional threat, as it may lead to the microbial decomposition of previously frozen organic matter, potentially releasing significant amounts of CO_2 and methane into the atmosphere.

2.2 Deforestation

The early stages of human civilization saw limited deforestation primarily driven by subsistence agriculture, where forests were cleared to cultivate crops for local use. During this preindustrial era, a balance existed between carbon dioxide emissions and absorption, with forests acting as crucial carbon sinks. The industrial revolution marked a pivotal shift, with deforestation accelerating due to urbanization, industrial expansion, and large-scale agriculture.

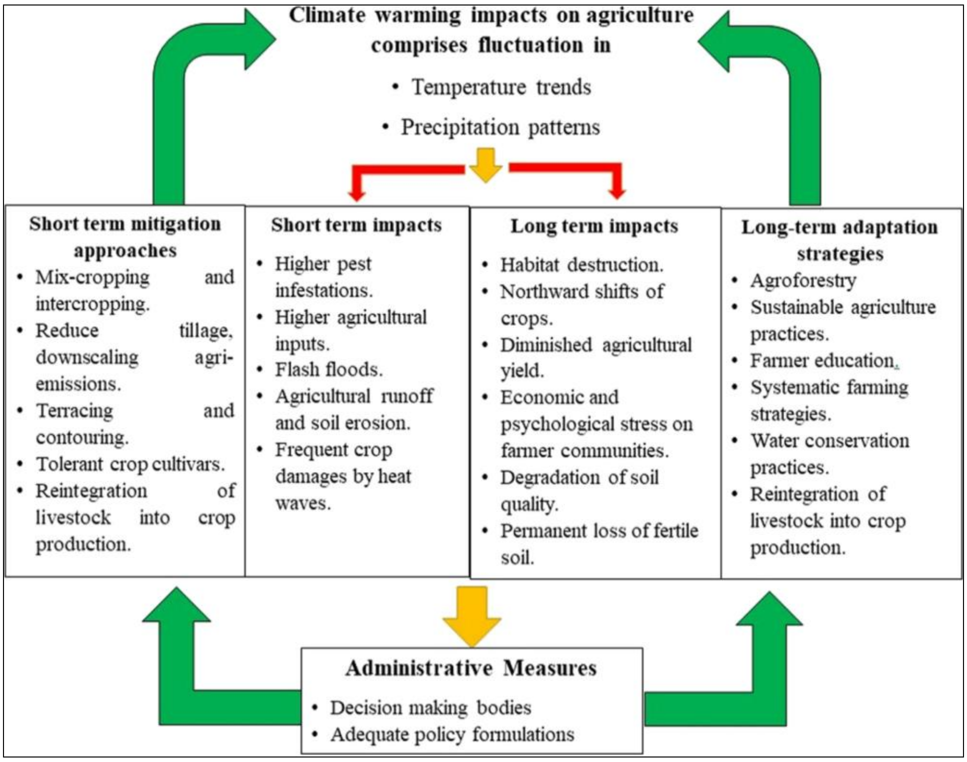
Recent satellite imagery indicates that croplands have expanded by approximately one million square kilometers over the past two decades, with nearly half of this expansion occurring at the expense of forests and other ecosystems (Potapov *et al*., 2021). The demand for plantation crops such as oil palm, coffee, tea, and rubber, along with land for cattle ranching and mining, has significantly reduced global forest cover. According to the World Wildlife Fund (WWF), from 2004 to 2017, over 43 million hectares of monitored forest were lost out of 377 million hectares globally (Pacheco *et al*., 2021).

The Amazon Rainforest, the world's largest tropical rainforest covering more than 5 million square kilometers, has faced unprecedented levels of degradation. National Geographic reports that approximately 17% of the Amazon has been destroyed over the past five decades, with the rate of deforestation accelerating recently, including a loss of over 10,000 square kilometers in the past year alone.

3. Impacts of climate change

The increase in atmospheric temperature due to climate change has profound consequences for biodiversity, ecosystems, and human well-being. The evidence for climate change is well-supported by long-term data on CO2 levels, global temperatures, and weather patterns. Published climate models have been instrumental in predicting these changes, and their reliability is reinforced by their performance over time. Analysis of climate models published between 1970 and 2007 has shown that these models consistently predicted global warming trends and associated changes in surface temperatures with high accuracy. A comparison of these predictions with actual observational data confirms that the models were effective in forecasting the warming trends and associated impacts on weather patterns (Hausfather *et al.*, 2019) [43]. This alignment between predicted and observed data underscores the credibility of climate models in projecting future climate scenarios and their effects on biodiversity and human well-being. As the climate continues to change, the impacts on various aspects of life, including ecosystems, species distributions, and human health, are becoming increasingly apparent. The models' consistent predictions provide valuable insights for planning and implementing adaptation and mitigation strategies to address these challenges effectively.

Figure 1



Source: Abbass *et al.*, 2022

Fig 1: Schematic description of potential impacts of climate change on the agriculture sector and the appropriate mitigation and adaptation measures to overcome its impact.

3.1. Weather pattern and natural disasters

In recent years, one of the most pronounced effects of climate change has been the increase in extreme and unpredictable weather patterns, along with a rise in the frequency and intensity of natural disasters. For example, in 2021, Brazil's south-central region experienced one of its worst droughts, with major reservoirs dropping to less than 20% of their capacity. This drought severely impacted both agricultural production and energy generation (Getirana *et al.*, 2021) [37]. In the past, weather patterns were more predictable, allowing farmers to align their crop cycles with expected conditions, such as the timing of monsoon rains. However, with the current changes in weather patterns, this predictability has significantly diminished, leading to major agricultural losses. The amount and distribution of annual rainfall have also become more erratic. Regions that historically received little rainfall are now experiencing heavy rains, while areas traditionally known for substantial rainfall are seeing reductions. Additionally, the timing and amount of snowfall in temperate regions have become highly variable.

The increased frequency and severity of natural disasters, including floods, droughts, cyclones, hurricanes, typhoons, and wildfires, have become increasingly evident. In 2021, the countries most affected by climate change were Japan, the Philippines, Germany, Madagascar, and India. These disasters have led to extensive loss of life and significant economic damage, affecting both urban and rural populations. In 2020, catastrophic floods and landslides displaced approximately 12 million people across India, Nepal, and Bangladesh. According to a comprehensive report by the World Meteorological Organization (WMO) published in August 2021 (WMO-No.1267), climate change-related disasters have increased fivefold over the last 50 years. Despite this surge, improvements in early warning systems and disaster management have limited fatalities to 2 million and economic losses to US$ 3.64 trillion. However, over 91% of these deaths occurred in developing countries, with the most significant human losses resulting from droughts, storms, floods, and extreme temperatures. The report underscores that the frequency and intensity of weather, climate, and water-related extremes will continue to increase as climate change progresses.

Global warming is also intensifying the drying of organic matter in forests, increasing the risk of wildfires. These fires have become more frequent and severe, particularly in areas like the western United States, southern Europe, and Australia. In India, wildfires have also grown more prevalent, with numerous incidents recorded across several states. According to the European Space Agency, wildfires impact an estimated four million square kilometers of the Earth's land each year. These fires emit large amounts of carbon dioxide, carbon monoxide, and fine particulate matter, contributing to air pollution and associated health risks. In 2021, wildfires worldwide released 1.76 billion tonnes of carbon (European Union's Copernicus Atmospheric Monitoring Service). The 2020 wildfires in Australia alone reportedly killed over a billion native animals, with some species and ecosystems potentially facing irreversible damage (OXFAM International, 2021).

3.2. Sea level rise

Global warming is causing sea levels to rise through two main mechanisms: the melting of glaciers, polar ice caps, and the Atlantic ice shelf, which adds water to the oceans, and the thermal expansion of seawater as it warms. Additionally, the incomplete combustion of fossil fuels, biofuels, and biomass releases fine carbon particles, known as black carbon (< 2.5 μm). These particles absorb sunlight thousands of times more effectively than CO2 while suspended in the atmosphere, thus significantly contributing to global warming. When black carbon settles on snow, glaciers, or ice caps, it accelerates their melting, further contributing to sea-level rise. The global mean sea level has risen faster since 1900 than during any previous century in at least the last 3,000 years. Between 2006 and 2016, the rate of sea-level rise was 2.5 times higher than the average for most of the 20th century (OXFAM International, 2021). Satellite radar measurements show an accelerated rise of 7.5 cm from 1993 to 2017, averaging 31 mm per decade (WCRP Global Sea Level Budget Group, 2018).

In the Arctic, snow remains the primary form of precipitation, but the region is warming four times faster than the global average. As ice melts, it exposes darker land or ocean surfaces that absorb more sunlight, creating a feedback loop of warming. Recent projections indicate even more rapid warming and sea ice loss in the Arctic by the end of the century than previously predicted (McCrystall *et al*., 2021) [69]. The transition from snow to rain-dominated precipitation in the Arctic during summer and autumn is likely to occur decades earlier than expected. This shift has already begun, as evidenced by rain falling at Greenland's highest summit (3,216 m) for several hours on August 14, 2021—the first time on record—while air temperatures remained above freezing for nearly nine hours (National Snow and Ice Data Center, 2021).

At the American Geophysical Union's annual meeting on December 13, 2021, researchers warned of the rapid deterioration of Thwaites Glacier, one of western Antarctica's largest glaciers, often referred to as the "Doomsday Glacier." Roughly the size of Florida, Thwaites Glacier is at risk of collapsing within a few years, which could contribute over 65 cm to global sea levels. Thwaites acts as a barrier holding back the entire West Antarctic Ice Sheet, which could raise sea levels by 3.3 meters if it collapses. The glacier is being undermined by warm water, and its potential failure would have catastrophic consequences for both human populations and biodiversity.

The Himalayan Mountain range, home to the world's third-largest collection of glacier ice after the Arctic and Antarctic regions, is known as the "Asian Water Tower." Meltwater from Himalayan glaciers provide freshwater to nearly 2 billion people living in the surrounding regions. However, these glaciers are melting at unprecedented rates. A study by King *et al*. (2021) analyzed 79 glaciers near Mount Everest and reported a consistent increase in ice loss since the early 1960s. This trend is expected to worsen with continued warming. Another study found a tenfold acceleration in ice loss across the Himalayas in recent decades compared to historical rates (Lee *et al*., 2021) [61]. The melting of these glaciers threatens the flow of perennial rivers during summer, leading to water scarcity for billions of people, animals, and agricultural activities. The resulting sea-level rise and river depletion could drive mass migrations, creating additional socio-economic challenges.

Even if global temperature rise is limited to 1.5 °C, projections indicate a sea-level rise of 1.7 to 3.2 feet by 2100. A rise of 2 °C could be even more devastating, leading to the submergence of many islands, extensive coastal flooding, saltwater intrusion into freshwater sources, and increased soil erosion. The Maldives, where 80% of the land is less than one meter above sea level, would face severe submergence risks. Coastal biodiversity would be at risk of extinction. Countries such as China, Vietnam, Fiji, Japan, Indonesia, India, and Bangladesh are among the most vulnerable. The Sundarbans National Park, a UNESCO World Heritage Site and the world's largest mangrove forest, has already lost 12% of its shoreline over the past four decades and is likely to be fully submerged. Jakarta, Indonesia, is the fastest sinking city globally, having sunk 2.5 meters in the past decade, with projections indicating most of it will be underwater by 2050. In Europe, three-quarters of all cities could be affected by rising sea levels, especially in the Netherlands, Spain, Belgium, Greece, and Italy. The entire city of Venice could be submerged. In the United States, cities like New York and Miami are particularly at risk.

3.3. Crop productivity and human health

Many studies have indicated that climate change is driving increasing losses in crop productivity (Zhu *et al*., 2021). The models on global yield loss for wheat, maize and rice indicate an increase in yield losses by 10 to 25% per degree Celsius warming (Deutsch *et al*., 2018). Bras *et al*. (2021) reported that heatwave and drought roughly tripled crop losses over the last 50 years, from − 2.2% (1964–1990) to − 7.3% (1991–2015). Overall, the loss in crop production from climate-driven abiotic stresses may exceed US$ 170 billion year^{-1} and represents a major threat to global food security. Analysis of annual field trials of common wheat in California from 1985 to 2019 (35 years), during which the global atmospheric CO_2 concentration increased by 19%, revealed that the yield declined by 13% (Bloom and Plant 2021) [15]. Apart from crop yield, climate change is reported to result in the decline of nutritional value of food grains. For example, rising atmospheric CO_2 concentration reduces the amounts of proteins, minerals, and vitamins in rice (Zhu *et al.*, 2018). This may be true in other cereal crops also. As rice supplies 25% of all global calories, this would greatly affect the food and nutritional security of predominantly rice growing countries. Climate change would also increase the prevalence of insect pests adding to the yield loss of crops. The prevailing floods and droughts also affect food production significantly. Global warming also affects crop productivity through its impact on pollinators. Insect pollinators contribute to crop production in 75% of the leading food crops. Climate change contributes significantly to the decline in density and diversity of pollinators. Under high as well as low temperatures, bees spend less time in foraging (Heinrich, 1979) [44] adding additional constraints to pollination efficiency of crop species.

The IPCC Third Assessment Report (Climate change 2001: The scientific basis – IPCC) concluded that the poorest countries would be hardest hit with reductions in crop yields in most tropical and sub-tropical regions due to increased temperature, decreased water availability and new or changed insect pest incidence. Rising ocean temperatures and ocean acidification affect marine ecosystems. Loss of fish habitats is modifying the distribution and productivity of both marine and freshwater species thus affecting the sustainability of fisheries and populations dependent on them.

Air pollution is considered as the major environmental risk of climate change due to its impact on public health causing increasing morbidity and mortality (Manisalidis, 2020) [66]. Particulate matter, carbon monoxide, nitrogen oxide, and sulphur dioxide are the major air pollutants. They cause respiratory problems such as asthma and bronchiolitis and lung cancer. Recent studies have indicated that exposure to air pollution is linked to methylation of immunoregulatory genes, altered immune cell profiles and increased blood pressure in children. In another study wildfire smoke has been reported to be more harmful to humans than automobiles emissions. Stubble burning (intentional incineration of stubbles by farmers after crop harvest) has been a common practice in some parts of South Asia particularly in India; it releases large amount of toxic gases such as carbon monoxide and methane and causes serious damage to the environment and health (Abdurrahman *et al.*, 2020) [2]. It also affects soil fertility by destroying the nutrients and microbes of the soil. Attempts are being made to use alternative methods to prevent this practice.

A number of diseases such as zika fever, dengue and chikungunya are transmitted by *Aedes* mosquitoes and are now largely restricted to the monsoon season. Global warming facilitates their spread in time and space thus exposing new populations and regions for extended period to these diseases. Lyme disease caused by a bacterium is transmitted through the bite of the infected blacklegged ticks. It is one of the most common diseases in the US. The cases of Lyme disease have tripled in the past two decades. Recent studies have suggested that variable winter conditions due to climate change could increase tick's activity thus increasing the infections (Pennisi, 2022).

3.4. Impact of Climate Change on Biodiversity

The global climate is undergoing unprecedented changes, leading to far-reaching consequences for the delicate balance of ecosystems and the biodiversity they support. Climate change, driven primarily by human activities such as the burning of fossil fuels and deforestation, poses a grave threat to the survival of countless species worldwide (Montoya & Raffaelli, 2010; Bhattarai, 2017) [73, 12]. As the planet's temperature rises, shifting weather patterns, altered precipitation levels, and the increased frequency and intensity of extreme weather events are disrupting the natural habitats and life cycles of diverse flora and fauna.

The impacts of climate change on biodiversity are complex and often unpredictable. Some species may be forced to adapt to new environmental conditions, while others may struggle to survive, leading to population declines and even extinctions (Debinski & Cross, 2009) [25]. The clearing of land for agriculture and urbanization exacerbates these problems by eliminating wildlife habitats and reducing genetic diversity. Moreover, the interconnectedness of ecosystems means that the loss of one species can trigger cascading effects, disrupting the delicate balance of the entire system and threatening the ecosystem services that support human well-being.

India, known for its rich and diverse natural landscapes, faces a significant challenge as climate change continues to reshape its fragile ecosystems. The country's biodiversity, a vital component of its cultural heritage, is under severe threat from the relentless march of global warming. Climate change presents a multifaceted threat to India's biodiversity, manifesting in various ways. Changing rainfall patterns and rising temperatures have profoundly affected agricultural activities, drastically altering crop yields and the types of crops that can be grown in certain areas. This disruption of traditional farming practices and the loss of arable land have had cascading effects on the country's natural habitats, leading to the displacement of numerous species (Kumar *et al*., 2020) [58].

Climate change is also driving large-scale shifts in species distribution, abundance, and the reorganization of terrestrial and aquatic ecosystems. Geographic range shifts are widespread across taxa and ecosystems. For instance, a recent review of plant and animal species in temperate North America found that 55% have either contracted the warm edge or expanded the cool edge of their range (Wiens, 2016). Documented shifts towards the poles, upslope, and into deeper waters average tens of kilometers per decade (Burrows *et al*., 2011) [18]. In the Northern Hemisphere, birds are experiencing a decrease in abundance along their southern and lower elevational range edges, further illustrating the widespread impact of climate change on biodiversity.

3.4.1. Climate Change Impact on Indian Biodiversity

India is renowned for its rich and unique flora and fauna, a natural heritage that is celebrated worldwide. The country is home to an estimated 45,000 species of plants and 65,000 species of animals. Among the flowering plants, approximately 15,000 species have been identified, with several hundred (5,000-7,500) being endemic to India. The animal diversity includes more than 50,000 species of insects, 4,000 molluscs, 6,500 other vertebrates, 2,546 fishes, 197 amphibians, 408 reptiles, 1,224 birds, and 350 species of mammals. This extraordinary wealth of biodiversity places India among the world's mega biodiversity centers, with hotspots in regions such as the Western Ghats and Eastern Himalayas (MoEF, 2000; Myers *et al*., 2000) [71, 78].

However, the impact of climate change on India’s water resources is particularly alarming. The country faces significant challenges related to water scarcity and the uneven distribution of rainfall, which have severe consequences for its diverse flora and fauna. The depletion of water bodies and the salinization of groundwater have devastated aquatic ecosystems, leading to the decline and displacement of numerous species (Goyal & Surampalli, 2018) [40].

The threats to Indian biodiversity extend beyond the direct effects of climate change to include secondary impacts on human systems and regional agriculture. Climate change exacerbates issues such as food security and the livelihoods of those dependent on agriculture and forestry. The resulting social and economic pressures have the potential to further destabilize the delicate balance of India’s natural ecosystems (Kumar *et al*., 2020) [58].

In the face of these daunting challenges, there is a pressing need to develop and implement comprehensive strategies to mitigate the impact of climate change on Indian biodiversity. This will require a multifaceted approach, including the adoption of sustainable agricultural practices, the restoration and protection of natural habitats, and the development of innovative solutions to address the challenges posed by water scarcity and resource depletion (Khandekar & Srivastav, 2014) [52].

The threats posed by climate change to India's biodiversity extend far beyond the realm of agriculture and water resources. Extreme weather events, such as heatwaves, droughts, and floods, have become increasingly frequent and intense. The effects of climate change on India's biodiversity extend far beyond the realm of agriculture and water resources. The increasing frequency and intensity of extreme weather events, such as heatwaves, droughts, and floods, have wreaked havoc on the country's natural habitats, triggering the loss of critical species and the disruption of delicate ecological balances (Goyal & Surampalli, 2018) [40]. In a case study of the southern Indian state of Kerala, Achanta *et al*. (1996) [3] link the precipitation effectiveness index to net primary productivity of teak plantation. Results indicate that under the climate scenarios generated by the ECHAM3 climate model, the soil moisture is likely to decline and, in turn reduce teak productivity from 5.40 m3/ha to 5.07 m3/ha. The study also shows that the productivity of moist deciduous forests could decline from 1.8 m3/ha to 1.5 m3/ha predict that the Montane forests of western ghats would change into grasslands and further in the absence of management of these grasslands it is envisaged that exotic of C3 photosynthetic type would establish themselves.

Table 1: Biological diversity of Himalayan region

Taxonomic group	Species	Endemic species	% Endemic of (SI)
Plants	10,000	3,160	31.6
Mammals	300	12	4
Birds	977	15	1.5
Reptiles	176	48	27.3
Amphibians	105	42	40
Fresh water fishes	269	33	12.3

Source: (Myers *et al.,* 2000 and Gadgil, 2008) [78, 34].

The impact of climate change on rice, a staple crop that is central to India's food security and cultural identity, is particularly alarming. Extreme abiotic factors like high and low temperatures, droughts, salinity, osmotic stress, heavy rains, floods, and frost damages are posing serious threats to rice production, jeopardizing the livelihoods of millions of farmers who depend on this crop (Dabi & Khanna, 2018) [23]. The consequences of these changes go beyond the immediate impact on food production and economic security. The disruption of natural ecosystems and the displacement of species can have far-reaching implications for the intricate web of life that sustains the country's biodiversity. As the effects of climate change continue to unfold, it is crucial for India to prioritize the protection and conservation of its natural heritage, and to adopt comprehensive strategies that address the multifaceted challenges posed by this global crisis.

The alteration of climatic conditions poses a significant threat to the survival of numerous flora and fauna species, potentially leading to their extinction. While not all species are directly impacted by changes in environmental conditions, they can still be indirectly affected through their interactions with other species. Assessing the response of plants to climate change requires giving equal consideration to these indirect impacts. Climate change can cause shifts in the distribution of certain species, potentially leading to their invasion into the ranges of other species. This may establish novel competitive relationships between them. Additionally, climate change is likely to influence both minimum and maximum temperatures, increasing the frequency of severe rainfall events and storms. Projections for the Indian sub-continent suggests a decrease in winter precipitation by 10–20% and a reduction in summer monsoon precipitation by 30% by 2050.

According to Kumar Ajay *et al*. (2017) [56], the ecological impact of biodiversity loss is substantial and primarily driven by environmental changes. The function and distribution of organisms are significantly influenced by environmental conditions in conjunction with other factors. Environmental changes have historically had a profound impact on biodiversity patterns and are expected to continue shaping these patterns in the future. The study of environmental changes includes not only alterations in climate but also those resulting from overpopulation, overexploitation of natural resources, and deforestation. Mitigating carbon emissions and greenhouse gases from the industrial, energy, and transportation sectors is essential, and this can be achieved through reduced fuel consumption and the increased use of renewable and sustainable energy sources.

The protection of natural habitats is a crucial component of climate change strategies as nations seek to implement measures for both mitigation and adaptation. Enhanced support for protected areas and the broader adoption of sustainable resource management techniques are vital approaches to safeguarding biological resources and ecosystems. Addressing the interconnected crises of climate change and biodiversity loss requires a comprehensive and coordinated approach. Drastic reductions in greenhouse gas emissions, the protection of multi-use landscapes and seascapes, and equitable policies for access to natural resources are crucial steps in mitigating negative impacts and ensuring the resilience of our planet's biodiversity. As we work to overcome these intertwined challenges, it is essential to recognize the fundamental role that biodiversity plays in sustaining the health and well-being of our planet and its inhabitants.

3.5 Impact of climate change and variability on agricultural productivity

3.5.1 Impact of climate change and variability on rice-wheat crops

In many parts of Asia, crop productivity has significantly declined due to reduced availability of water and rainfall, alongside increasingly erratic and intense rainfall patterns over recent decades (Aryal *et al*., 2019) [7]. Although the Green Revolution led to increased crop production, sustaining this level of production, and improving food security for impoverished rural populations in Asia poses a substantial challenge, especially under the looming threat of climate change (Ahmed *et al*., 2019) [5]. In the least developed countries, climate-induced damages could jeopardize food security and weaken national economic productivity (Myers *et al*., 2017) [77]. The impacts of climate variability on crop yields, such as rice and wheat, have varied across regions, reflecting the diversity in climate patterns. While CO_2 fertilization might enhance crop productivity in C3 plants and mitigate some of the adverse effects of elevated temperatures (Obermeier *et al*., 2017) [79], it does not fully counteract the negative impacts of increased temperatures (Arunrat *et al*., 2018) [6]. Rising temperatures and rainfall variability have adversely affected crop growth and development (Asseng *et al*., 2019) [8].

Rice and wheat are critical to food security in Asia, but there is an enormous challenge to increase wheat production by 60% by 2050 to meet the growing food demand (Rezaei *et al*., 2018). In arid and semi-arid regions, decreased crop productivity is largely due to rising temperatures in lower latitudes. In China, droughts and floods have led to reductions in the yields of rice, wheat, and maize, and these problems are expected to become more severe in the future. Rice is particularly sensitive to gradual increases in night-time temperatures, which can cause yield and biomass reductions of 16–52% if temperatures rise by 2 °C above the critical threshold of 24 °C (Yang *et al*., 2017). Semi-arid and arid regions in Asia are especially vulnerable, already experiencing drought stress and low productivity. The quality of wheat, in terms of protein content, sugars, starch, and grain yield, has declined due to the negative effects of rising temperatures and increasingly erratic and intense rainfall (Yang *et al*., 2017). In the North Nile Delta in Egypt (up to 17.6%), as well as in India and China, climate variability has significantly decreased wheat yields, a decline attributed to rising temperatures, erratic rainfall, and increasing insect pest infestations (Arunrat *et al*., 2018) [6]. In South Asia, rain-fed rice yields have already decreased and are projected to decline further by 14% under the RCP 4.5 scenario and by 10% under the RCP 8.5 scenario by 2080. High temperatures and drought have reduced rice yields due to their detrimental effects during the booting and anthesis stages, particularly in Pakistan and China (Ahmed *et al*., 2019) [5]. Heat stress remains a significant threat to rice, reducing productive tillers, causing grain shrinkage, and ultimately decreasing grain yield (Wang *et al*., 2019). Climate change in Asia is expected to have a significant impact on upland rice (10 million hectares) and rain-fed lowland rice (over 13 million hectares).

3.5.2 Impact of climate change on livestock

The livestock sector in arid and semi-arid regions is particularly vulnerable to the challenges posed by increased temperatures and reduced precipitation (Balamurugan *et al*., 2018) [68]. Domestic livestock thrive within a temperature range of 10–30 °C, but for each degree rise above this range, there is a 3–5% decrease in feed intake. Conversely, lower temperatures increase feed requirements by up to 59%. Drought and heat stress are projected to have severe impacts on livestock production under climate change scenarios. Climate variability also influences the occurrence and transmission of various livestock diseases. For example, increased precipitation has led to the spread of Rift Valley Fever (RVF), while rising temperatures have intensified the prevalence of tick-borne diseases (TBDs), both of which have become epidemic among sheep, goats, cattle, buffalo, and camels.

Different livestock breeds respond differently to higher temperatures and water scarcity. In India, thermal stress negatively impacts animal reproductive traits, leading to poor growth and high mortality rates, particularly in poultry. In Asia's dry regions, extreme rainfall variability and drought stress are expected to result in severe feed scarcity (Arunrat *et al*., 2018) [6]. Moreover, elevated CO2 levels are known to reduce the quality of fodder, leading to decreased levels of protein, iron, zinc, and vitamins B1, B2, B5, and B9 (Ebi and Loladze, 2019) [29]. Future climate scenarios predict significant impacts on pastures, grasslands, and the quality and quantity of feedstuffs, as well as biodiversity. These changes will affect livestock productivity and challenge the sustainability of rangelands, including their carrying capacity, ecosystem buffering capacity, grazing management, feed selection, and greenhouse gas emissions (Nguyen *et al*., 2019).

3.6. Climate change and food security

Considering the Sustainable Development Goal 2, which aims to achieve Zero Hunger by 2030, global food insecurity remains a significant challenge. Currently, between 720 million and 811 million people are undernourished, and approximately 2.3 billion people suffer from malnutrition (FAO *et al*., 2021) [32]. When distinguishing between chronic and acute food insecurity, the Integrated Food Security Phase Classification (IPC) reports that around 200,000 people are experiencing catastrophic levels of food insecurity. Additionally, 32.3 million people are at the emergency level, 112.3 million are in a crisis stage, and 210 million are in a stressed stage of food insecurity (IPC, 2022). The IPC classifications rely on first-level outcomes (e.g., changes in food consumption and livelihoods), second-level outcomes (e.g., nutritional status and mortality), and contributing factors such as food availability, access, utilization, stability, hazards, and vulnerability (IPC Global Partners, 2021). For instance, catastrophic food insecurity is characterized by an extreme lack of food and other basic needs, leading to starvation, death, destitution, and critical levels of acute malnutrition (IPC, 2022).

Climate change is expected to further intensify food insecurity and malnutrition risks. The extent and timing of these impacts will depend on greenhouse gas (GHG) emissions and shared socioeconomic pathways (SSPs). While the severity of climate-related food security and nutrition (FSN) risks is projected to increase modestly until 2050, stronger escalations in risks are anticipated between 2050 and 2080 (Bezner Kerr *et al*., 2022) [11].

The factors driving increased hunger and malnutrition due to climate change include declining agricultural productivity, reduced incomes in climate-sensitive livelihoods, emerging food safety concerns, and disruptions in food distribution networks (Bezner Kerr *et al*., 2022) [11]. The severity of these risks is closely linked to atmospheric CO2 levels, which, while potentially boosting crop yields, are moderated by other climate-related risk factors (Zhu *et al*., 2018).

3.7. Risk to hunger

Climate change negatively impacts the productivity of crops, livestock, fisheries, and aquaculture by altering water availability and quality, inducing heat stress, shifting phenological patterns, and changing the environment for pests and diseases, including the accelerated spread of mycotoxins and pathogens. The increased frequency and intensity of floods, droughts, storm surges, and other extreme events disrupt food supply chains through harvest failures, infrastructure damage, and heightened competition within food production systems (Cottrell *et al*., 2019) [22]. For instance, Europe, a net food exporter, is experiencing more frequent, co-occurring, and persistent climate extremes.

Exposure to heatwaves, droughts, and floods jeopardizes food security, health, nutrition, and productivity, ultimately impacting livelihoods and incomes, particularly for those working in climate-sensitive sectors or outdoors (De Lima *et al*., 2021) [24]. Such impacts are especially severe for vulnerable low- and middle-income countries, regions reliant on rainfed agriculture, and specific social and economic groups like smallholder farmers, low-income households, the elderly, women, and children (De Lima *et al*., 2021; Kuhla *et al*., 2021) [24, 55].

Projections from the Agricultural Model Inter-comparison and Improvement Project (AgMIP) show significant declines in maize productivity under different climate and socio-economic scenarios. For example, under SSP1 and RCP2.6, maize yields may decline by 5%, while under SSP5 and RCP8.5, yields could drop by 23% (Jägermeyr *et al*., 2021) [49]. Rising temperatures are also projected to reduce the production of fruits and vegetables, decreasing their consumption. By the end of the century, nearly one-third of the land currently suitable for major crops and livestock may become unsuitable under SSP5-8.5 (Kummu *et al*., 2021) [60]. Simultaneous yield losses in key maize-producing regions are expected to escalate as global temperatures rise from 1.5 °C to 2 °C (Gaupp *et al*., 2019) [36] and 4 °C (Tigchelaar *et al*., 2018) [27]. Disruptions in storage and distribution, combined with lower food productivity, will further diminish food availability and diversity (Bezner Kerr *et al*., 2022; Rivera Ferre, 2014) [11].

Global warming has already led to a 4% decline in marine fisheries productivity, with some regions experiencing declines of up to 35% (Free *et al*., 2019) [34]. Each 1 °C increase is projected to reduce average global ocean animal biomass by 5% (Lotze *et al*., 2019) [63] and decrease fisheries catch potential by 5.3–7% by 2050 (Cheung *et al*., 2019) [21]. Warming is also driving poleward shifts in marine and freshwater species, altering species composition and abundance within exclusive economic zones, which poses risks for tropical low-income countries (Bindoff *et al*., 2019). Similar poleward shifts in mariculture species and habitats are being observed and are expected to continue, leading to reductions in species and habitats in tropical and subtropical regions (Oyinlola *et al*., 2020; Weatherdon *et al*., 2016).

3.8 Risk to nutrition

The relationship between climate change and human nutrition extends beyond the issue of caloric availability. By 2050, ensuring access to nutritious and affordable diets will become a significant challenge. The increasing frequency and intensity of extreme weather events heightens the risk of acute food insecurity and malnutrition (Bezner Kerr *et al*., 2022) [11]. Climate change is expected to negatively impact factors contributing to micronutrient deficiencies, especially in terms of availability and accessibility to fruits and vegetables (Springmann *et al*., 2016). It is projected that climate change will worsen child undernutrition and stunting, increase childhood mortality due to undernutrition, exacerbate diet-related diseases, and result in greater disability-adjusted life years lost, with the most severe impacts likely in Africa and Asia. Childhood stunting has lifelong health consequences, including intergenerational effects where stunted mothers are more likely to give birth to low-birth-weight infants (Fanzo *et al*., 2018) [31].

Rising atmospheric CO2 levels also reduce the protein and mineral content of staple crops, diminishing food quality and increasing the prevalence of micronutrient deficiencies (Mbow *et al*., 2019) [67]. Concentrations of essential micronutrients like phosphorus, potassium, calcium, sulfur, magnesium, iron, zinc, copper, and manganese could decline by 5–10% under atmospheric CO_2 levels of 690 ppm (associated with a 3.5 °C temperature increase). This decrease in zinc content alone is expected to result in an additional 150–220 million people suffering from zinc deficiency, exacerbating existing deficiencies among over 1 billion people (Myers *et al*., 2017) [77]. Similarly, a reduction in protein and micronutrient content in rice due to increased CO2 levels (568–590 ppm) could put 600 million people who rely on rice as a staple food at risk of micronutrient deficiency by 2050 (Zhu *et al.*, 2018). Additionally, the decline in protein content from elevated CO2 levels (above 500 ppm) could lead to 150 million more people suffering from protein deficiency by 2050, adding to the estimated 1.4 billion people already at risk in scenarios without increased CO2 levels (Medek, 2017) [69].

4. Conclusion and future perspectives

The stability of socio-agricultural, socio-economic, and physical systems is integral to psychological well-being, and disruptions in these systems due to climate change (CC) are likely to have severe consequences. Climate variability, compounded by other anthropogenic and natural stressors, directly impacts the sustainability of both human and environmental health. Food security is a particularly pressing concern, as climate change threatens to degrade food quality, inflate prices, and destabilize distribution systems. Global forests face a dual challenge from climate-related stressors like storms, droughts, flash floods, and intense precipitation, alongside accelerated deforestation driven by human activities. While the degree of vulnerability varies across regions, appropriate mitigation and adaptation strategies are crucial for policymakers to formulate effective responses. Modern societies have evolved within relatively stable climatic conditions; thus, adapting to significant climatic shifts is vital. Rapid changes in climate will intensify the difficulty of adaptation, underscoring the urgency of addressing this global challenge at all levels—from local communities to international organizations. Although substantial progress has been made, ongoing research, effort, and commitment are essential, as this is a critical juncture. Policy measures targeting the most vulnerable sectors, particularly agriculture, are essential to mitigate the impacts of climate change.

4.1. Seasonal variations and cultivation practices

Plant physiology has been greatly influenced by climate variability by several means. Environmental extremes and climate variability enhanced the chances of numerous stresses on plants (Thornton *et al.*, 2014). Boyer reported that the climate changes have reduced the crop yield up to 70% since 1982 (Boyer 1982). According to the study of FAO 2007 (http://www.fao.org/home/en/), all cultivated areas in the world are affected by climatic changes and only 3.5% of areas are safe from environmental limitations. Drought and high temperatures are key stress factors with high impact on cereal yields (Barnabás *et al.*, 2008) [9], and *Rubisco*, the central enzyme of photosynthesis, is disrupted if the temperature increases from 35 °C, and stops the photosynthetic process (Griffin *et al.*, 2004) [40]. Warming may extend the growing season in frost-prone regions, such as temperate and arctic zones, enabling the cultivation of longer-maturing seasonal crops with improved yields. This extended growing period could facilitate multiple crop cycles annually. However, in cases where warming results in frequent high temperatures that exceed critical thresholds, a split-season approach with a brief summer fallow might be considered for short-duration crops like wheat, barley, cereals, and various vegetables. In tropical and subtropical regions, where planting seasons are typically limited by precipitation or where farming takes place year-round, the potential to extend the growing season may be more constrained and highly dependent on changes in precipitation patterns (Wu *et al.*, 2017).

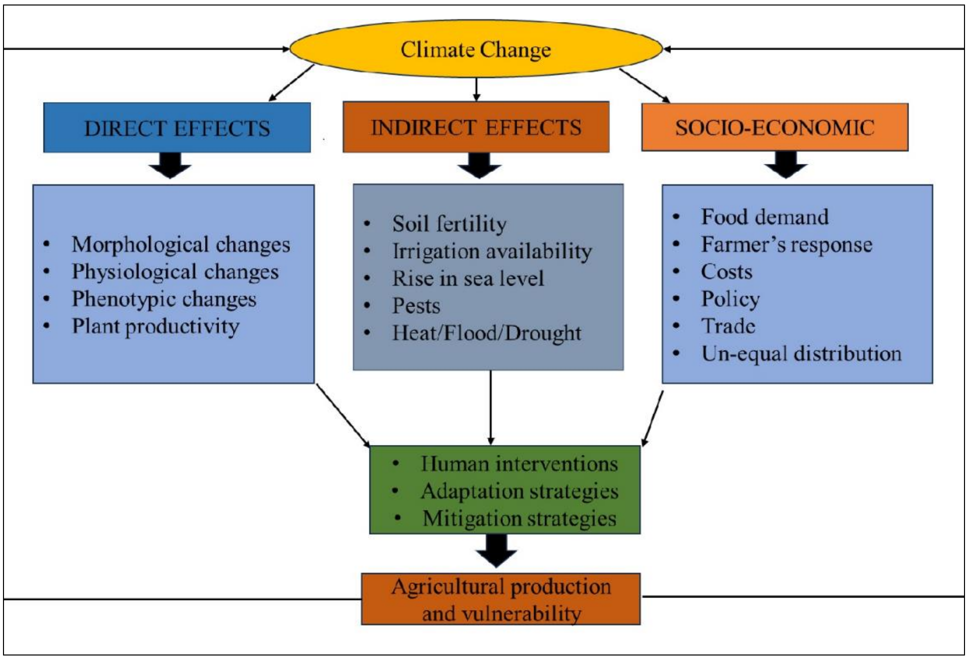


Fig 2: Direct, indirect, and socio-economic effects of climate change on agricultural production -(adapted from Raza *et al.*, 2019)

4.2 New varieties of crops

The genetic basis for yield improvements is well-established for many crops but remains limited for certain species, such as kiwi fruit. Ali *et al.* (2017) examined the response of emerging crops to climate change, identifying potential benefits such as increased resistance to heat, drought, insects, and salinity, alongside improved crop productivity and quality. Genetic mapping and engineering offer the possibility of introducing a wider range of desirable traits. However, the widespread adoption of genetically modified cultivars has been hindered, particularly in initial projections, by challenges in consistently expressing these traits across the entire plant, consumer concerns, economic viability, and regulatory barriers (Davidson *et al*., 2016).

4.3 Changes in management and other input factors

Maximizing the benefits of elevated CO_2 levels in agriculture would necessitate increased use of nitrogen and other fertilizers. However, any nitrogen that is not absorbed by plants can leach into groundwater, run off into surface water, or be released from soil as nitrous oxide when large quantities of fertilizer are applied. Elevated nitrogen levels in groundwater have been linked to chronic human health issues and can negatively impact marine ecosystems. Studies have thoroughly investigated the effects of cultivation, grain drying, and other field practices in this context (Barua *et al*., 2018) [10].

4.4 The technological and socio-economic adaptation

The policy implications of this analysis suggest that biofuel production significantly contributes to oil price volatility, separate from broader international macroeconomic factors. Although biofuel production is still in its early stages in some countries, the global demand for feedstock to fuel industrial growth, especially in China and the USA, creates a direct link between food prices and global oil prices. In response, oil-exporting nations could incentivize increased food production by providing farmers with financial support, seedlings, fertilizers, and equipment. However, with declining global oil prices reducing revenue from oil exports, these countries may struggle to subsidize food imports even in the short term. Thus, enhancing the agricultural value chain through research and development, value-added processing, and correcting exchange rate misalignments could boost export income.

Moreover, diversifying away from oil dependence is essential, given the high volatility of global oil prices. Countries rich in resources and oil exports could transition to non-food renewable energy sources like solar, hydro, wind, and tidal energy. Such a shift would protect global food and oil supplies from disruption. According to IRENA's modeling, a well-structured policy framework could drive economic activity, job creation (offsetting losses in the fossil fuel industry), and welfare gains during the energy transition. However, countries heavily reliant on fossil fuel income must implement structural reforms to seize these opportunities.

Governments currently offer extensive support for fossil fuel extraction through tax incentives, infrastructure investments, and regulatory exemptions. Most major oil and gas producers are focused on expanding production, with some also maintaining or increasing coal output. While some nations are beginning to address a just transition away from fossil fuels, these efforts have yet to meaningfully influence the plans of major producers. Enhanced transparency through the disclosure of production goals in climate commitments under the Paris Agreement is crucial for bridging the production gap.

Achieving the Paris Agreement targets is unlikely without a global transition to renewable energy (Zhao *et al*., 2022). Policy instruments play a central role in driving investment in renewable energy technologies. This study explores the effectiveness of various strategies across multiple countries, noting that while renewable portfolio standards are particularly impactful in established markets, they remain valuable policy tools. Although renewable energy production costs are still higher than those of traditional energy sources, government incentives for research and development can drive innovation and reduce costs. Countries can also export these technologies and share policy insights by forming networks among renewable energy-focused organizations. Ultimately, all policy measures should aim to lower production costs while increasing the share of renewables in the energy mix. Long-term contracts with renewable energy providers, sustained government commitment, and clear goals can support developing nations in integrating renewable technologies into their energy sectors.

Conclusion

The interplay between climate change and human nutrition is multifaceted, extending far beyond mere caloric availability. By 2050, the challenge of ensuring access to nutritious and affordable diets will become increasingly pronounced. The rising frequency and intensity of extreme weather events pose significant risks of acute food insecurity and malnutrition, particularly affecting vulnerable populations in regions such as Africa and Asia. The expected decline in the availability of micronutrient-rich foods, such as fruits and vegetables, alongside the detrimental impacts of elevated atmospheric CO2 levels on staple crops, further exacerbates the looming crisis of malnutrition.

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