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Transforming food, land and water systems under global climate change: A review

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ABSTRACT

Food systems are imperative in ensuring food and nutrition security, livelihoods, and socio-economic conditions. Climate change worsens these challenges, threatening agricultural production vis-a-vis food security through temperature increases and extreme weather conditions. In India, rainfed agriculture makes the country highly susceptible to climate change and even small rainfall decreases can result in crop losses. To overcome these challenges, sustainable intensification and integrated resource management are fundamental to optimizing food production and resource conservation. This demands a multidisciplinary approach, successful adaptation and mitigation measures as well as the emergence of climate-resilient genotypes and better water management systems. Digital agriculture supporting precision technologies can increase productivity and resilience and the incorporation of indigenous knowledge with contemporary ways can lead to international partnerships to improve responses to climate aberrations. Transforming agri-food systems is essential both in India as well as at the global level for sustainable development and ecological harmony.

Key words: Agri-food systems, Climate change, Food security, Sustainability

Agi-food systems are fundamental in ensuring food and nutrition security, while contributing towards livelihoods and socioeconomic upliftment (Bilali *et al.,* 2019). Food systems involve a diverse network of stakeholders and interconnected value chain processes, covering every stage from food production to disposal. They are rooted in sectors like agriculture, horticulture, livestock, fisheries, and the food industry, while being shaped by the broader socio-economic conditions and environmental contexts they are embedded in (FAO, 2018). Food systems are closely linked to undesirable social, health, and environmental impacts. Strengthening resilience and enhancing food security presents a significant challenge for the global community.

The global climate crisis has significantly impacted food, land, and water systems. Rising temperatures, erratic weather patterns, and depleting natural resources are constraining agricultural productivity, food security, and water availability. IPCC (2021) reports suggest an increase in global surface temperatures roughly by 1.1°C from the pre-industrial era, leading to an increase in the frequency of extreme weather occurrences globally. Frequent weather extremities disproportionately affect agricultural systems, especially in tropical and subtropical regions (Vermeulen *et al.,* 2018). India, with its diverse agro-ecosystems and a population exceeding 1.4 billion, relies heavily on agriculture as the foundation of its rural economy.

The nation encounters distinct challenges in aligning development objectives with climate resilience, which has a significant effect on the sustainability of agriculture (Dagar *et al.,* 2012; Dar *et al.,* 2020; Singh *et al.,* 2021). Indian agriculture largely depends on rainfall, making it highly susceptible to climate-related aberrations (Aggarwal *et al.,* 2019). Due to its heavy reliance on the southwest monsoon, rainfed agriculture in India is especially susceptible to erratic rainfall patterns. Minor deviation from annual average rainfall could cause a significant impact on crop production. Moreover, two to four-week dry spells during crucial crop growth phases might result in a large or complete loss of output (Rockström and Falkenmark, 2000). Approximately 27% of India's geography has seen discernible changes in climate zones,

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according to a district-level climate assessment. Climate has changed from dry sub-humid to semi-arid in parts of Madhya Pradesh, Tamil Nadu, and Uttar Pradesh, extending semi-arid zones into these areas. States such as Chhattisgarh, Odisha, Jharkhand, Madhya Pradesh, and Maharashtra have seen a growing shift from moist sub-humid areas to arid sub-humid zones (Raju *et al.,* 2013).

The complexity of agri-food systems coupled with the multifaceted threats they confront, addressing the issues that lie ahead will require transformational change rather than incremental innovation. Transforming food, land, and water systems is critical for ensuring sustainable livelihoods and ecological integrity. As outlined by Rockström *et al.* (2010), the inclusion of integrated resource management and sustainable intensification strategies is vital in addressing the interconnected challenges of enhancing food production and safeguarding natural resources. This transformation requires a multidisciplinary approach that integrates technological innovation, policy reforms, and community engagement. Likewise, expanding the reach of effective adaptation and mitigation strategies poses a major challenge in the transformation of food systems in changing climatic scenarios. Hence, we tried to investigate existing literature on the effects of climate change on these systems, evaluate different approaches implemented worldwide and in India towards agri-food transformation, and outline essential research and policy priorities towards sustainability.

Climate change and vulnerability of crop production

Agricultural productivity is affected by two primary types of climate-induced impacts. The first consists of direct influences, including alterations in temperature, rainfall patterns, and carbon dioxide concentrations. The second involves indirect effects, such as soil moisture fluctuations, spread, and occurrence of pests and diseases. In India, the warming trend from 1901 to 2007 was recorded at 0.51°C (Krishna Kumar, 2009). The global average concentration of greenhouse gasses in the atmosphere has been steadily increasing over the years (Fig.1). As per Kumar *et al.* (2022), under the business-as-usual scenario, CO_2 levels have been increasing since 1900 and are predicted to surpass 700 ppm by the end of the 21st century.

Climate change is projected to intensify crop yield fluctuations, threatening food security, livestock productivity, and water availability, particularly in states like Punjab, Rajasthan, and Tamil Nadu. By 2050, crop water needs for major staples may increase by 4.7–6.6%. Rising temperatures have been reported to reduce yields of crops like wheat and soybean by 3–7%, with overall productivity potentially declining by 10–40% by 2100 (Ninan and Satyasiba, 2012). They have also reported that, while elevated CO_2 levels may boost yields for some crops, climate risks will require resilient strategies for crops, soil, and water management. Ninan and Satyasiba (2012) suggested that the climate change impacts as evaluated in different climatic zones in crops like wheat, rice, sorghum, brassica, maize, groundnut, chickpea, pigeonpea, soybean suggested potential yield reductions and in certain cases, positive effects of increased CO_2 were nullified by shortened crop growing duration due to increased temperature. Increased droughts and floods are likely to have considerable effects on the livestock and fisheries sector like fish breeding, migration, distress due to heat, etc. (Venkateswarlu *et al.,* 2016)

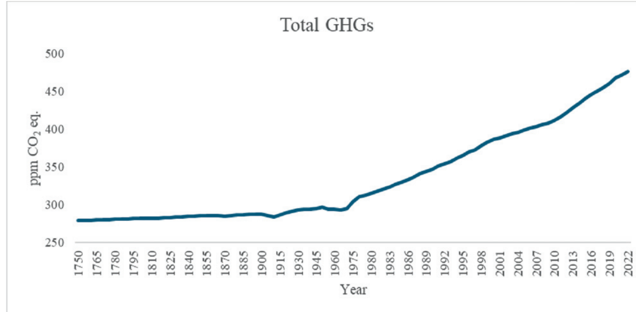

Fig. 1. Trend of the global average concentration of greenhouse gasses

Data source: Greenhouse Gases (NOAA), Netherlands Environmental Assessment Agency (PBL) and AGAGE Data & Figures, Advanced Global Atmospheric Gases Experiment (AGAGE)

Climate change puts food security at further risk, particularly for vulnerable populations. When future climatic pressures make it impossible for current systems to support agricultural livelihoods, new adaptation techniques are crucial. Changing food, land, and water ecosystems to increase long-term resilience and address climate impacts that are substantial enough to drastically change food systems is one such strategy.

Climate change impacts on food, land, and water systems

Global agriculture is being impacted by climate aberrations, which are creating food insecurity for millions of people and lowering crop yields and livestock output. As extreme weather events, increasing temperatures, and water scarcity are increasing in frequency and severity over the next few decades, these effects are expected to get worse. The agricultural sector is particularly vulnerable, accounting for around 26% of global damages and losses caused by climate-related disasters (FAO, 2017). In India, economic growth, urbanization, and shifting lifestyles have significantly altered dietary patterns. This evolving consumption trend adds pressure on the agricultural sector to diversify and meet changing food preferences. The two most important factors influencing food production are arable land and drinkable water supplies. Climate change, population expansion, and usage, however, are putting growing strain on both (Kumar *et al.,* 2012; Kumar *et al.,* 2020). Adopting sustainable land and water management techniques, improving resource efficiency, and putting climate-resilient agricultural strategies into practice are all necessary to address these issues.

Impact on food systems

By 2050, agricultural systems will need to supply food for a global population projected to reach around 9.1 billion, surpassing 10 billion by the end of the century (UNFPA, 2011). Developing countries will face the major impact of this population growth and urbanization. Rising populations, increasing incomes, and urban expansion are driving shifts in food and feed demand. To meet these growing needs, the FAO projects that food production must rise by 60% by 2050. As per FAO, all four facets of food security i.e. availability, accessibility, use, and stability—are expected to be impacted by climate change and increasing climate variability (FAO, 2008). Battisti and Naylor (2009) stated that crop yields, farmer incomes, and overall food security are seriously threatened by anticipated changes in the occurrence and severity of climate events especially during crop growth season.

By altering soil fertility, crop yields, nutrient content, pest resistance, and the risk of hunger, climate change upsets food systems. These impacts jeopardize diet quality and food security, especially for groups that are already at risk (Owino *et al.,* 2022). Climate-related phenomena are responsible for a large portion of agricultural losses worldwide (Hay, 2007). About 8% of India's territory is vulnerable to cyclones, 12% to floods, and 28% to drought (Chattopadhyay and Lal, 2007). Climate change impact could result in crop yield changes and shifting agricultural zones, increased vulnerability of smallholder farmers and changes in livestock and fisheries productivity.

Agricultural productivity: Climate change can have both positive and negative effects on crop yields and can influence the alteration of the kinds of crops grown in particular areas (Rao *et al.,* 2008). Crop production may be disrupted and total output may be greatly impacted by long-term climate changes. Because it jeopardizes the achievement of food security, this worries scientists and policymakers. Reduced crop yield, particularly wheat, and rice, legumes under changed climatic scenarios in India was reported by (Avasthe *et al.,* 2022; Aggarwal *et al.,* 2022; Geethalakhsmi *et al.,* 2023)

Food security: Food insecurity and malnutrition are made worse by climate change, with rural communities being particularly at risk (FAO, 2021). In addition to compromising food quality and safety, it compromises food security by restricting food supply, stability, and access (FAO, 2015). From production to consumption, efforts should concentrate on strengthening food systems' ensuring that they prioritize nutrition across the whole supply chain (Kumar *et al.,* 2018; Bryan *et al.,* 2019; Kumar *et al.,* 2022).

Livelihoods: Food is not just a basic need for producers in poverty, but it is frequently their only and most precarious source of income. Economic growth must be inclusive and provide possibilities to enhance the well-being of the impoverished, even though it is essential in lowering undernourishment. With a significant portion of the world's workforce being employed in agriculture, women constitute about 43% of the agricultural workforce (FAO, 2015) in middle- and low-income countries. Achieving the zero-hunger target requires increasing smallholder farmers' income and production.

Impact on land systems

In addition to providing the basis for agricultural output, land is essential for environmental management. It contributes to water transportation and purification within the hydrological cycle, mitigates and filters pollutants, helps recycle nutrients, and carbon sequestration. Unabated land degradation is an issue of increasing concern globally. Land degradation threatens land quality and productivity, water quality, ecosystems, and livelihoods. This problem is further aggravated by climate change. According to the UNCCD, a state where the amount and quality of land resources needed to maintain ecosystem services, functions, and food security either stay the same or get better over a given period and space, is said to be in a neutral state in terms of land degradation (UNCCD, 2016). This explains the deterioration of land conditions brought on by direct or indirect anthropogenic activity.

About one-third of agricultural land is affected by land degradation desertification, which poses serious risks to farmers' livelihoods, productivity, and overall food security (FAO, 2022). Long-term ecosystem deterioration is particularly likely to affect populations in arid locations, where it is extremely challenging to manage land and water supplies. In dry regions, it is rapidly spreading due to several factors, including land-use competition, climate change, urbanization, and demographic changes. Ensuring increased productivity while maintaining the sustainability of natural resources is a major challenge which is primarily determined by the balance of combined effects of soil, water, vegetation, biodiversity, etc along with human activity (FAO, 2019). As per the Desertification and Land Degradation Atlas of India (2021) report these impacts are evident through shifts in environmental conditions and land productivity which reported, over 96.4 million hectares are degraded due to deforestation, overgrazing, and unsustainable agricultural practices. Certain populations may grow, decline, or go extinct due to climate change impacts. The entire biodiversity of a region may then be impacted by these changes. The geographic range that plants and animals occupy may also shift in response to shifting climatic circumstances. Climate change can also result in desertification, loss of biodiversity, dust storms, sea level rise, changes in land use, etc. Uncontrolled urbanization negatively affects socioeconomic and biophysical systems.

Impact on water systems

Achieving Sustainable Development Goal (SDG) 6 on clean water and sanitation requires improved agri-food systems as water is fundamental to food systems (UN, 2018; Uhlenbrook *et al.,* 2022). India will be especially impacted by climate change in terms of water supply because a significant portion of the nation already experiences water scarcity and relies heavily on groundwater for cultivation. The availability of regional water resources and hydrology may be significantly impacted by the warming atmosphere, increased precipitation, and rising CO_2 concentrations. While an increase in temperature may raise the demand for evapotranspiration, increased precipitation may result in higher runoff. Food security in the nation could be seriously jeopardized by this disparity between water supply and demand, which could have a major impact on food grain production. Visible effects of climate-induced change could be but not limited to declining water availability and quality, groundwater depletion, and climate-induced hydrological imbalances. Water-intensive farming practices are a major contributor to aquifer depletion.

Shaping the future of agri-food systems in India, South Asia, and the Global perspective

Future of Indian agriculture and food systems

For smallholder farm-based economies in Africa, South Asia, and Southeast Asia, India's transformation from a food-deficient country to one that is self-sufficient provides an encouraging example (Gulati *et al.,* 2023). India's food system, however, has many obstacles as it looks to 2030 and beyond (Gulati *et al.,* 2023). India needs to implement a well-balanced policy framework to address these issues, which includes combining price and income policies, increasing agricultural diversity to support the production of more nutrient-dense foods, and moving the emphasis from subsidies to investments.

Future of agri-food system in South Asia

It is expected that by 2050, nutrient and micronutrient availability in South Asia will rise further depicting a significant stride from traditional cereal-based diets to diverse nutritionally rich foods.

Already, the CGIAR initiative foresight South Asian agri-food systems going to play a critical role in sustainable agri-food systems as it is home to over 50% of all agrifood system workers (Nedumaran *et al.,* 2024). At the same time, it is expected that with climate change there will be an increase in the yield of crop commodities. According to Rosegrant *et al.* (2024), there will be a perceptible yield increase of major commodity groups as predicted under IMPACT V3.6 model simulations (Fig. 2).

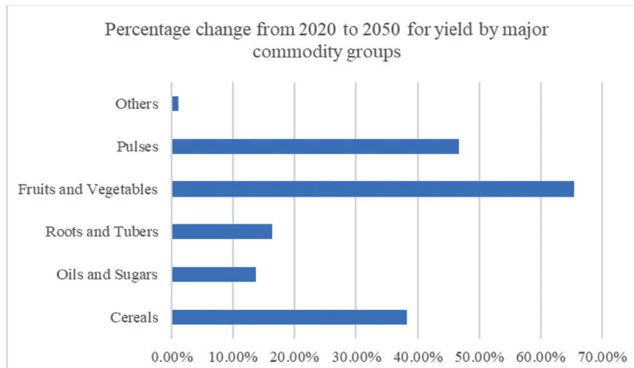

Fig. 2. Percentage change in yield of major commodity groups in South Asia from 2020 to 2050
(Source: IMPACT V3.6 model simulations (Rosegrant *et al.,* 2024).

Future of food systems at the Global level

The World Economic Forum has analyzed scenarios for the future of global food systems and the goal of this analysis is to create systemic change on global challenges to find How will food systems sustainably and nutrient-densely feed 8.5 billion people by 2030 (WEF, 2017). The same report analyzed four situations viz., 1. Survival of the Richest: A divided society with slow economic growth in which the wealthiest profit from resource-heavy consumption, leading to increasing inequality. 2. Unchecked Consumption: A situation in which global market connection propels rapid GDP growth at a substantial environmental cost. 3. Open-source sustainability is a vision of a future where global collaboration and creativity promote resource efficiency, yet not everyone benefits equally. 4. Local is the New Global: a fragmented environment where countries prioritize resource efficiency and concentrate on local food production (Fig. 3). The results of the analysis revealed that the present food systems are inadequate for sustainably feeding the global population, underscoring the necessity of systemic change to meet the SDGs and redesigning of farming systems will provide a window of opportunity to progress through innovations.

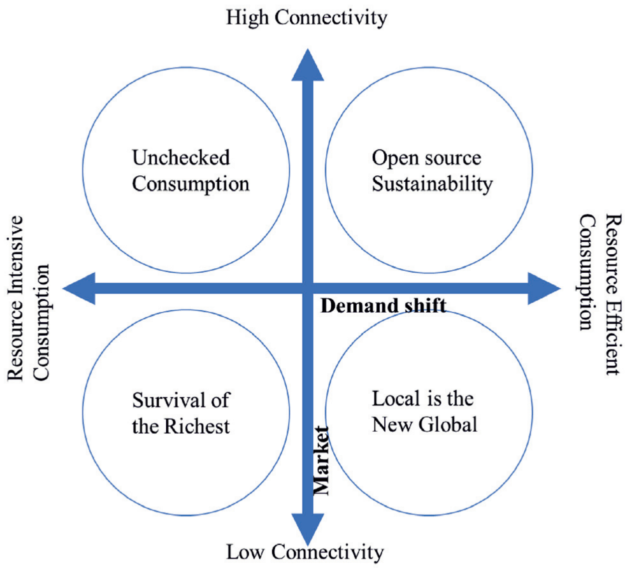

Fig. 3. Four potential future worlds Source: adapted from WEF (2017)

Adaption and mitigation strategies

From tiny farms to the global food network, food production systems must become more robust and efficient to face the pressing issues derived from climate aberrations. In addition to increasing resilience against disturbances and environmental shocks, this entails optimizing resource usage by producing more food sustainably using less land, water, and inputs. Despite the progress that sustainable agriculture has achieved in enhancing resilience, more has to be done. In environmental and territorial management, adaptation and mitigation go hand in hand and are both crucial. To preserve carbon storage and their ability to absorb CO_2, agricultural and forest ecosystems in particular must be resilient (Menga, 2023; Konfo *et al.,* 2024). The goal of adaptation is to make agricultural systems more resilient to the difficulties brought on by climate change. This entails using tactics that support ecosystems, livestock, and crops in surviving climate vagaries (Govindraj *et al.,* 2019; Kipling *et al.,* 2019, Konfo *et al.,* 2024). Conversely, mitigation entails actions that encourage carbon absorption in vegetation and soils, reduced emissions, and efficient land use (Smith *et al.,* 2020; Konfo *et al.,* 2024). Early action and a general focus on sustainability present the strongest opportunities to address climate change which means less food waste, better nutrition, and slower population growth and inequality. Agroecology and other nature-based solutions have a lot of potential to improve adaptation while halting more biodiversity losses and wasteful resource use. However, if the effects of climate change worsen, depending only on such strategies will become riskier. Climate-smart innovations could provide sustainable solutions to tackle climatic challenges in agri-food systems (Konfo *et al.,* 2024).

Climate-smart technology and techniques have been adopted in the agrifood industry recently to reduce climatic impacts while enhancing incomes (Zougmore, 2021). These developments improve agricultural systems' resilience, productivity, and resource efficiency. Agroforestry, which increases soil fertility and decreases evaporation (Fahad *et al.,* 2022); crop varieties designed to withstand extreme weather, withstand pests, and sustain high yields (Hafeez *et al.,* 2023); and vertical farming techniques like hydroponics and aeroponics (Maurya *et al.,* 2023) are important climate-resilient technologies. Furthermore, precision agriculture uses technologies like remote sensing, smart irrigation, crop rotation, pest control, and conservation tillage to maximize productivity, while regenerative agriculture supports soil health and biodiversity (McLennon, 2021; Schreefel, 2020). The adaptation options to cope with the water scarcity situation under climate change must consider both supply and demand side management strategies along with local needs to determine the irrigation water management adaptation plan. To enhance water productivity, the adaptation strategies could be: promotion of crops that use less water, effective irrigation techniques, such as piped networks for water transportation, and solar photovoltaic pumping systems for groundwater pumping to reduce carbon emission, conjunctive use of rain, surface, groundwater, and marginal quality water resources.

By preventing, reducing, and reversing land degradation, sustainable land management (SLM) fosters resilience and sustainability. It entails utilizing land to support changing human requirements, including infrastructure, forestry, and agriculture, while preserving its long-term ecological and socioeconomic roles (Montanarella *et al.,* 2018). SLM incorporates methods for preserving, repairing, and safeguarding land resources, such as biodiversity, soil, and water. To balance productivity, lower production risks, and improve soil resistance against degradation, it combines technologies, regulations, and actions. Furthermore, SLM guarantees social justice, economic sustainability, resource preservation, and access to the advantages of better land use (Noe, 2014; Global Environment Facility, 2011).

Global perspectives and initiatives on transforming food, land, and water systems

To solve the climate change-related systemic issues about food, land, and water systems, international organizations and institutions have played a crucial role. Through programs like Climate-Smart Agriculture (CSA), the Food and Agriculture Organization (FAO) has highlighted the significance of sustainable agricultural intensification (FAO, 2010). Similarly, the Paris Agreement's global climate action plans are supported by the United Nations Framework Convention on Climate Change (UNFCCC, 2015). The Consultative Group on International Agricultural Research (CGIAR) has also led studies on climate-resilient crops and innovative water management practices, particularly in developing countries (CGIAR, 2020). Additionally, the World Bank has launched programs such as the "Transforming Landscapes for Resilience and Development" initiative, focusing on integrated land management to reduce degradation and enhance food security (World Bank, 2021). These initiatives underscore the collective global effort to mitigate the negative impacts and build resilience towards livelihoods and environmental sustainability.

Transformative strategies

It is anticipated that there will be a significant reduction in arable and suitable land for the major crops and farmers will need to adjust to these changes by switching to different crops or completely new activities (transformative adaptation) or by adopting improved crop varieties that are more tolerant of the new climate (incremental adaptation) (Loboguerrero *et al.,* 2019). For food and nutritional security to be guaranteed, sustainable soil management techniques must be used in a variety of geographies. Achieving different SDGs should be the focus of the overall systems-transformation strategy for the food, land, and water systems. Through improvements in genetics, resilient agri-food systems, and systemic change to create better food systems, future innovations should focus on lowering emissions and tackling climate change (Ngaiwi, 2024; Kumar *et al.,* 2024). By encouraging robust, sustainable, and diverse agricultural systems, agroecological techniques such as integrated farming systems are essential to maintaining steady food production. Panwar and Ravisankar (2022) reported region specific integrated farming system models suiting local needs could be the probable solutions to address climatic vulnerabilities and revealed promising prototype farming systems models have the potential to enhance farmers' income by 3-5 times over 3-4 years (Table 2).

Policy interventions

Considering the vulnerability of the Indian agricultural ecosystem, farming methods must be modified to improve climate resilience. Increased public investment in creating and promoting crop types that are more resilient to climate adversaries should be the top priority of policy interventions. Increasing crop productivity and creating safety nets to reduce climate-related hazards are the goals of agricultural policies. Sustainable agriculture should be cen-

Table 2. IFS models in different agro-ecosystems

Eco-system and location	AER* (Number)	Net income from existing systems (₹ lakhs/ha/year)	Components of region-specific prototype IFS model	Net Returns (₹ Lakhs/ha/year)	Improvement in net return (Number of times)
Arid SK Nagar (Gujarat)	2	0.88	Crop+ dairy+ farm pond + boundary plantation	3.61	4.1
Semi-AridVaranasi (Uttar Pradesh), Siruguppa (Karnataka), Rajendranagar (Telangana), Thanjavur (Tamil Nadu), Pantnagar (Uttarakhand)	4, 6,7, 8, 9	0.74	Crop+ horticulture + dairy + poultry + Goat +fishery+ Boundary Plantation +farm pond	2.76	3.7
Sub humid Jabalpur (Madhya Pradesh), Raipur (Chhattisgarh), Ranchi (Jharkhand), Sabour (Bihar), Jammu (Jammu and Kashmir), Jorhat (Assam)	10, 11, 12, 13, 14, 15	0.67	Cropping systems, horticulture, cow, goat Poultry, duckery, Fishery, Mushroom, Apiary, Biogas, boundary plantation, Agro-forestry	2.47	3.7
Humid Umiam (Meghalaya) Bhubaneswar (Odisha), Goa (Goa), Port Blair (Andaman and Nicobar Islands)	17, 18, 19, 20	0.58	Cropping systems, Horticulture (Cashew, coconut with pineapple, arecanut + banana), cow, pig, Poultry, fishery, duckery, Boundary Plantation, land configuration-based systems	2.08	3.6

**For AER details please see (Panwar and Ravisankar, 2022)* tered on the effective management of water resources, with an emphasis on tactics like developing new storage systems and encouraging water harvesting, especially in areas that are experiencing water scarcity. In the Indian context, the focus of policy support for the water sector should be on increasing irrigational infrastructure and enhancing irrigation water use efficiency (Chakraborty, 2023). For enhancing livelihood security promotion of integrated farming systems could also prove vital in providing sustainable solutions to climate-related challenges to agri-food systems. Creating connections between the systems of food, land, and water by using sustainable farming methods, restoring degraded areas, and enhancing water management systems while leveraging technology-led innovations could be the key to achieving desired goals in transformative approaches. The Climate Change formed a strong research network to evaluate the impact of climate change on Indian agriculture. Indian Council of Agricultural Research (ICAR), through its program on National Initiative on Climate Resilient Agriculture (NICRA) leading the research towards developing better crop varieties and identifying technologies for agriculture, horticulture, livestock, poultry, and fisheries through KVKs and other research organizations. NICRA's technology demonstration initiatives have directly introduced climate-resilient techniques to farmers. NICRA's technology demonstration efforts have directly introduced farmers to climate-resilient practices. Furthermore, 650 districts around India now have district-level agricultural contingency plans that allow for real-time reactions to weather extremes. The National Mission for Sustainable Agriculture (NMSA), and initiatives such as Maharashtra's PoCRA (Project on Climate Resilient Agriculture) are also efforts in this direction. Additionally, programs and initiatives like National Mission on Natural Farming (NMNF), All India Coordinated Research Project on Integrated Farming Systems (AICRP on IFS), All India Coordinated Research Project for Dryland Agriculture (AICRPDA), All India Network Program on Organic Farming, and All India Coordinated Research Project on Agrometeorology (AICRPAM) are working to develop and demonstrate technologies that improve agrifood systems' resilience as well as farmers' income and standard of living. This strategy strives to create beneficial results across climate-sensitive sectors, including agriculture, forestry, fisheries, aquaculture, water resources, and environmental management, eventually increasing global food security.

Digital agriculture

The use of digital agriculture, sometimes known as "Smart Farming," is one way that digitalization is rapidly changing the agricultural industry and is seen as a tool for tackling climate-related adversaries (Walter *et al.,* 2017; Kamilaris *et al.,* 2017). This strategy supports farmers in making site-specific, real-time decisions by leveraging data-driven technology and accuracy (Rose and Chilvers, 2018; Weersink *et al.,* 2018). Agriculture is changing as a result of digital agriculture, especially in response to the problems caused by climate change. Farmers can foresee climatic changes, improve resource efficiency, and make data-informed decisions with the use of Artificial Intelligence (AI) techniques like machine learning and predictive analytics. The agri-food industry has progressively used digital tools and innovative technology to address new difficulties (Housson *et al.,* 2023). The use of digital tools in agriculture has significantly changed agriculture in recent years, increasing farming systems' sustainability and efficiency. In addition to resolving enduring problems for farmers, this digital revolution promotes a more robust and sustainable agricultural environment. The next agricultural revolution might be fuelled by digitalization, which will improve crop and livestock output while lessening its negative effects on the environment, eventually helping farmers, consumers, and society as a whole (MacPherson, 2022).

Conclusion and the way forward

Transforming food, land, and water systems requires a concerted focus on research, policy, and community engagement. Developing region-specific climate models can help predict the localized impacts, enabling precise interventions. It is also important to assess the effects of adaptive techniques like integrated resource management and conservation agriculture in longer terms. Scaling innovations involves identifying effective pathways for upscaling successful technologies, like precision farming and resilient crop varieties while addressing barriers in research-to-policy translation. Bridging this gap is essential to ensure policies are informed by scientific evidence and practical experiences. Cross-border knowledge sharing and technology transfer are made possible by international cooperation and agreements. Future research priorities should include examining the socio-economic impacts of mass-scale adaptation measures with a focus on small and marginal households.

Incentivizing private sector involvement in sustainable farming and natural resource management can drive innovation and investment. Strengthening international partnerships to exchange best practices will also enhance the collective response to climate challenges. Community involvement is still essential because it may promote resilience at the local level by encouraging local involvement in resource conservation and increasing knowledge of sustainable consumption habits. These tactics work together to improve the food, land, and water systems in a way that is inclusive and sustainable. To guarantee food security, ecological balance, and fair resource allocation, future efforts must concentrate on developing resilient, inclusive, and adaptable systems.

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