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Review of climate-resilient agriculture for ensuring food security: Sustainability opportunities and challenges of India

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ABSTRACT

Climate Resilient Agriculture (CRA) effectively responds to climate change while contributing to sustainable productivity adapted to local hydro-meteorological conditions. CRA provides resilience to climate variability by enhancing agricultural viability through water exchange between surface and groundwater systems. In water-stressed countries such as India, where demand for water from agriculture, industry, and domestic use is increasing, CRA offers ways to address current and future food security challenges. This review examines the role of the CRA in agricultural sustainability and community participation in India. It assesses critical CRA projects and policies in India and explores how CRA can improve water policy by integrating farmers' perspectives in groundwater-based agriculture. The study also shows that collaboration between government agencies, NGOs, and local groups is important to sustaining CRA initiatives. Discussions indicated that empirical studies, clear sustainability indicators, and integration of advanced technology such as artificial intelligence and geo-spatial tools are needed to improve India's adaptation strategies to climate change. This study highlighted how CRA aligns with key SDGs by addressing poverty, hunger, climate action, and community wellbeing. GRACE data indicated that northwestern India emerged as a critical water scarcity hotspot, displaying negative trends of around −7.413 cm per year. Furthermore, the analysis clearly showed that the Western Dry Region, Western Himalayan, and Gangetic Plain agro-ecological zone (AEZ) experienced the sharpest declines in equivalent water thickness (EWT) compared to other AEZ regions in India. The review also highlighted the value of knowledge-sharing platforms and tailored CRA strategies that increase agricultural productivity and enable farmers to make informed decisions in the face of climate uncertainty.

1. Introduction

Human activities, such as industrialization and deforestation, have caused significant, long-term alterations in temperature and weather patterns, leading to the phenomenon known as human-induced or modern climate change (Karl and Trenberth, 2003; Wilson and VanBuren, 2022). These activities increase carbon dioxide levels, intensifying the greenhouse effect and threatening global climate stability (Rhodes et al., 2021; Toledo-Gallegos et al., 2022; Ward, 2022; Zong et al., 2022). As a result, global temperatures have risen by 1 °C since the 1950s, with projections indicating further increase of 1.5 °C by 2030–2052, posing severe risks to global food security and agricultural productivity, mainly in low- and middle-income nations (Acevedo et al., 2020; Islam et al., 2022; IPCC 6th Assessment ReportWG1, 2021; United Nations, 2015; NOAA, 2024; Zong et al., 2022; Zizinga et al., 2022).

In India, where agriculture is the backbone of the rural economy, climate-related stresses (e.g., erratic precipitation, pest infestations, and extreme weather events) significantly impact agricultural stability (Dagar et al., 2012; Dar et al., 2020a; Singh et al., 2021). The nation's diverse climate, while supporting a wide range of crops, also heightens the threat to essential staples like wheat and rice. Projections of a 2.8 °C temperature increase by 2050 highlight the urgent need for robust climate-resilient agriculture (CRA) strategies across various agro-climatic zones in India (Srivastav et al., 2021; Birthal et al., 2021;

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Rao et al., 2019a; Singh et al., 2021; Shanabhoga et al., 2020).

By integrating traditional knowledge and modern techniques, CRA can provide a promising pathway to improve productivity, resilience, and carbon sequestration (Birthal et al., 2021; Singha et al., 2024; Angom and Viswanathan, 2023; Goswami et al., 2023; Shiiba, 2022). Global case studies demonstrate the CRA's efficacy in improving food security and water management (Sekaran et al., 2021). For example, Kim et al. (2019) applied generalized linear models (GLMs) in South Korea to study the impact of land cover on flooding, emphasizing the role of farmer-maintained irrigation systems informed by traditional ecological knowledge. Similarly, Ha et al. (2020) employed dynamic modeling to assess climate-resilient livelihoods for smallholder farmers in Vietnam, while Shahzad et al. (2021) explored the development of stress-responsive plant transcription factors for cultivating climate-resilient crops globally. Studies by Schiavon et al. (2021) and Antwi-Agyei et al. (2021) further showed sustainable farming practices over Europe and Africa, respectively, highlighting CRA's global applicability. Galappaththi et al. (2020) investigated stress-responsive transcription factors in cultivating crops capable of withstanding biotic and abiotic stress. Likewise, Mpanga et al. (2021) analyzed sustainable food production among small-scale farmers in north-central Arizona, noting an increase in farm numbers but a decline in average farm size due to population growth and challenging climate conditions from 1997 to 2017. Furthermore, Zong et al. (2022) formulated a comprehensive assessment methodology for CRA, using an indicator system that examines agricultural production, farmer income, climate adaptability, and green development to foster sustainable farming practices and food security.

These studies demonstrate CRA's global applicability and potential lessons for India. Despite CRA's evident benefits, its widespread adoption in India faces significant obstacles, particularly among smallholders comprising 80% of the agricultural workforce (Government of India, 2014; Sanga et al., 2021). These farmers are particularly vulnerable to climate-related stresses, including erratic monsoon rains, pest infestations, and diseases, which can lead to significant economic losses and agricultural instability (Singh et al., 2019; Mohapatra et al., 2022; Singha et al., 2023a; Kumar and Gupta, 2021; Balaji et al., 2015; Kashyap et al., 2017). The increasing levels of CO_2 and methane in the atmosphere are exacerbating these stresses, making it even more challenging for smallholders to adapt to changing weather patterns (Das et al., 2019; Sapkota et al., 2019). Empowering these farmers is very important not only to bolster national food security (given their contribution of 70% of vegetables, 52% of cereals, 55% of fruits, and 69% of milk production (Birthal et al., 2011)), but also to achieve climate targets like the '4 per thousand' initiative. Such empowerment remains essential as India's population is projected to reach 1.7 billion by 2050 (United Nations, 2015; Government of India, 2014; Lal, 2016; Swaminathan and Bhavani, 2013).

Despite past advances such as the Green Revolution (Chakravarti, 1973; Eliazer Nelson et al., 2019), India now faces significant agricultural risks from rising heat stress and fluctuations in soil organic carbon, which can impact food grain production during the rabi season (Tesfaye et al., 2017; Sehgal et al., 2021; Nath et al., 2018). Establishing CRA initiatives is thus critical for ensuring a stable food supply, nutritional security, and sustainable agricultural systems (Rao et al., 2019a). The pressing need for robust policy frameworks and governance support to facilitate CRA adoption also highlights the importance of navigating these complex challenges effectively (Kharrazi et al., 2020; Bawa and Seidler, 2023). Integrating indigenous farming practices, which have proven effective in building resilience, can also enhance sustainability efforts and bolster food security (Aich et al., 2022). The increasing body of literature on climate change signifies a growing acknowledgment of resilience, adaptation, and sustainability as pivotal themes in agriculture, reiterating the necessity of climate-resilient practices for food security and sustainability in India (Bremer et al., 2019; Baraj et al., 2024) (see Table 1).

While these studies show promising results, variations in CRA's effectiveness through different environmental contexts raise vital questions.

- How can smallholder farmers access and utilize climate data to inform water management decisions?
- What opportunities exist to improve farming systems within agro-ecological zones?
- What community incentives might facilitate CRA adoption and sustainability?

Although these questions have been partially addressed in the ICAR policy paper (Rao et al., 2019) and previous comprehensive reviews (Benitez-Alfonso et al., 2023; Baraj et al., 2024; Goswami et al., 2023; Datta et al., 2022; Bawa and Seidler, 2023; Simpson et al., 2020), further research is needed to understand how CRA can be adapted to the specific challenges of water-scarce regions in India. This study investigates the potential of CRA systems in managing and planning sustainable agriculture under changing climate conditions in these regions. It also provides strategic insights for local governments to guide investments in climate risk assessment and support stakeholder knowledge to improve adaptation planning. Aligning CRA strategies with the Sustainable Development Goals (SDGs), this study demonstrates their capacity to address climate challenges while improving livelihoods.

2. Methodology

We employed the PRISMA framework (Moher et al., 2010) for formulating questions and selecting relevant papers included in our meta-analysis (see Fig. 1). This review process was conducted from research studies published from May 1990 to October 2024 using two primary databases: Scopus and Web of ScienceDirect. We also used a series of keywords and their combinations, including "climate-resilient agriculture," "climate change," "climate-smart agriculture," "sustainability," "agricultural adaptability," "environmental indicators," and "food security," to guide our search. Out of the 520 documents screened, 279 papers were identified as relevant based on various CRA indicators and were primarily used in this study for further investigation.

Fig. 2a illustrates the annual increase in the number of publications over the past decade within CRA research, which aligns with the findings of Baraj et al., (2024). To visualize recurring word frequencies across thematic areas, a word cloud was generated using keywords from the titles and objectives of 208 peer-reviewed papers published between 2014 and 2024 (see Fig. 2b). In this visualization, the size and instances of words represent their occurrence rates. Similar terms, such as "environment" and "environmental," were aggregated. The word cloud analysis highlights key trends, highlights key trends, showcasing prominent themes such as "climate," "resilience," "agriculture," "sustainable," "environment," "water," and "remote sensing."

3. The need for CRA in India

According to global population estimates, India was the second most populous nation after China, with a population of 1.38 billion in 2020 (The Economic Times, 2023). Despite occupying only 2.4% of the world's land area, the average landholding size in India is merely 1.08 ha per state. Small farmers, who own between one and 2 ha, make up about half of the farming community across Indian states. These small-scale farmers face significant challenges, including inadequate transportation, insufficient market infrastructure, and limited input access. Agriculture supports 58% of the population and 70% of rural households (82% of farmers are small and marginal), producing 291.95 million metric tons of food in 2019–20 despite climate uncertainties (Borkar, 2019; FAO, 2023a).

Despite achieving economic diversification and food self-sufficiency, India's agricultural GDP share has diminished, while over ~190 million

Table 1
Summary of some CRA studies in India.

Reference	Geographic Area	Data Used	Methods/Process	Application	Adaptation	Policy
Balaji et al. (2015)	Peddavagu river basin, Telangana, Andhra Pradesh, and Karnataka, lower Krishna basin, India	Annual rainfall data (mm), Drought data	Information sharing and communication methods, MobiMOOC (massive open online course) application.	v	v	×
Kashyap et al. (2017)	Trichoderma spp., India	*Trichoderma* spp, Trichoderma species	Study of eco-friendly agricultural methods using Trichoderma species	×	v	×
Rymbai and Sheikh (2018)	Eastern Himalaya region (Sikkim), India	Household survey data.	Tobit model, Multinomial logit model, and Probability models	×	v	×
Sapkota et al. (2019)	India.	Household survey data.	Green House Gas(GHG) emissions model, Confidence Intervals (CI)	×	v	×
Srinivasa Rao et al. (2019)	India.	Country experiences, Climate plans, Village institutions, and State action plans	Weighted sum model (WSM) and Analytic hierarchy process (AHP)	×	×	v
Das et al. (2019)	Odisha, India	Agricultural conditions by district, groundwater irrigation, socio-economic data, household data	Agricultural Scenario Index (ASI), Composite Irrigation Index (CII), Irrigation Coverage Index (ICI), Ground Water Development Index (GWDI), and Socio-Economic Index (SEI), Climatic Variability Index (CVI)	v	v	×
Singh et al. (2019)	Gangetic Plains Region, India	Annual rainfall (mm) data, Temperature data, Population data, Food grains yield.	Empirical strategy model, Regression coefficients, Projected changes.	×	v	×
Dar et al. (2020a)	Bihar, Chhattisgarh, Jharkhand, Odisha and West Bengal, India	Quality Seed Production (QSP), Survey data.	Empirical analysis	×	v	×
Choudhary and Sirohi (2020)	Trans- and Upper Gangetic Plains	District level panel data, Reliable agricultural data	Fixed and Random Effect models, Gross Cropped Area(GCA), and Climate change impact projections.	v	v	×
Kumar and Gupta (2021)	Bihar in Eastern India	Survey data, Climate change data.	Sample selection, Questionnaire design, Statistical analysis, Regression Model	v	v	v
Sehgal et al. (2021)	Districts of India	Data on public health and the susceptibility of agriculture to climate change.	Vulnerability Index(VI), Child Health Index (CHI)	v	v	×
Birthal et al. (2021)	31One districts of India	Rainfall and temperature data (Kharif and Rabi seasons) and temperature and crop yield data.	Descriptive statistics, Analytical framework, Generalized Method of Moments (GMM), Fractional Multinomial Logit Model (FMLOGIT).	v	v	×
(Dhanya et al., 2021)	Kancheepuram, Thiruvallur, Chengalpet district of Tamil Nadu, Semi-arid expanse of South India.	Meteorological data, Rice and Groundnut crop data, Population data, Annual mean Temperature data, Annual Rain data, Multivariate ENSO Index (MEI) and Total South West Monsoon Rainfall data, Survey data.	Focal Group Discussions (FGDs), Rapid Rural Appraisals (RRAs), and In-Depth Interviews(IDS). check	v	v	v
Singh et al. (2021)	India.	Forest coverage (+) data, Stage of the ground water extraction (−)data, Waste land (−) data, Food grain yield (+), Livestock density (+), etc.	Environmental Index, Technological Index, Institutional and Infrastructural Index, Socio-economic Index, Climate-Resilient Agriculture Index(ACZ), Rainfall deviation index (−), and Agriculture emission index (−).	v	v	v
Surendran et al. (2021)	India.	Rice cultivated area (Mha), production (MT), the area under irrigation (%) and yield (kg/ha), Productivity, Growing seasonal, Irrigation water quantity data.	Future climate models, Earth System Model (NorESM1-M), water saving technologies (WST).	v	v	×
Srivastav (2021)	India	Climate change data, Soil health data,	CropSyst, Cool Farm Tool (CFT). SWAT (soil and water assessment tool), GHG Emission.	×	×	v
Angom et al. (2021)	29th district in Gujarat state (India).	Annual rainfall, temperature, Demographics, industrial estates, and torrential rain data.	climate Smart Agriculture (CSA).	×	×	v
Sanga et al. (2021)	The Northern state of Bihar is in India.	Environmental and Social data, Household survey data.	Agent-based model (ABM), Model validation model with sensitivity and scenario analysis.	×	v	v
Mohapatra et al. (2022)	India	Agricultural data, Weather data.	Translog functional, Exponential function, Technical Efficiency(TE), Scale Effect(SE), Technical Change (TC)	×	×	v
Tanti et al. (2022)	Eastern Indian(West Bengal, Tamil Nadu, Andhra Pradesh, and Odisha)	Household survey data.	Multistage purposive stratified sampling methods, Econometrics model, probit model.	×	×	v

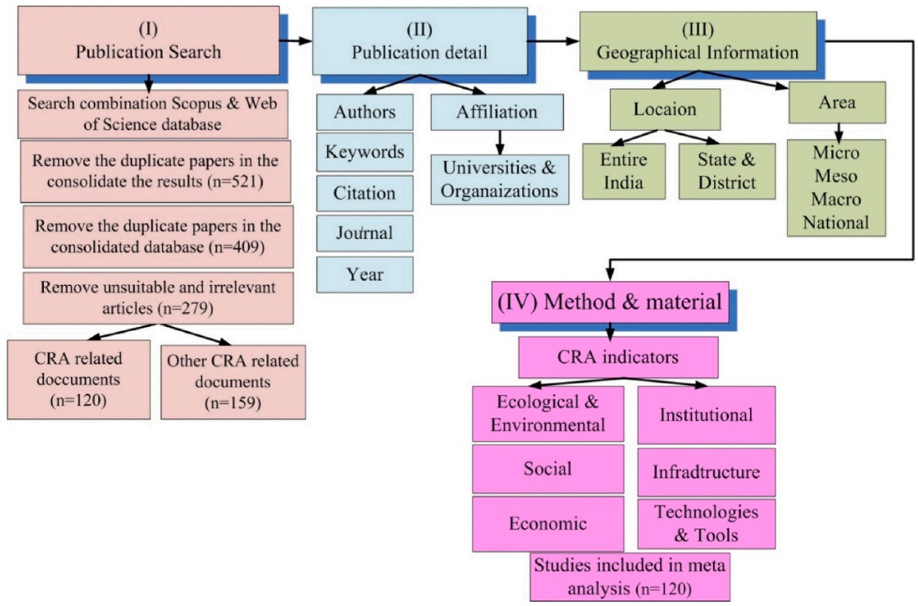

Fig. 1. PRISMA framework for the review and meta-analysis in this study.

are undernourished, and nearly 30% live in poverty (FAO, 2023a, 2023b). The rapidly growing population, projected to exceed 1.5 billion by 2030 and 1.64 billion by 2050, intensifies pressure on the food supply, exacerbating poverty, uneven regional growth, urbanization problems, and unsustainable farming practices (Gulati et al., 2023; United Nations, 2019). This burgeoning population and increasing urbanization will 2030 heighten the demand for nutritious food from rural areas already strained by climate change impacts, such as rising temperatures, droughts, groundwater depletion, and severe weather affecting river basins (IPCC, 2018). To meet these challenges and economic development, food production needs to double by 2050. Marginal and small farmers are crucial in ensuring the country's food security and achieving the SDGs (Pawlak and Kołodziejczak, 2020). Supporting these farmers can significantly advance SDG 2 (Zero Hunger), SDG 13 (Climate Action), and SDG 15 (Life on Land). Nevertheless, climate-induced extreme weather and a forecasted 1–2.5 °C temperature rise by 2030 threaten agricultural output, nutrient cycles, and fertilizer efficacy (Rao et al., 2019a) (see SF.1).

4. CRA initiatives and projects in India

This section describes some invaluable, successful CRA projects in India, detailed in the following.

4.1. National Innovations in CRA (NICRA) (2010–2011)

Initiated by the Indian Council of Agricultural Research (ICAR) in 2011, NICRA was a comprehensive, interdisciplinary network project aimed at improving the resilience of Indian agriculture to climate change and variability (URL: http://www.nicra-icar.in/). The project mainly focused on improving agricultural adaptability, showcasing customized technology packages and solutions to tackle climate-related challenges in farmers' fields, and enhancing the skills of scientists and stakeholders.

4.2. Enhancing adaptive capacity and increasing resilience of small and marginal farmers in Purulia and Bankura district of West Bengal (2015–2019)

This project, led by the Development Research Communication and Services Centre (DRCSC), aimed to create climate-resilient and adaptive livelihood systems for small and marginal farmers in West Bengal's Lateritic Zone (URL: http://www.drcsc.org/ and https://www.nabard.org/). This project mainly focused on agriculture and related sectors, achieved through diversification, technology integration, and effective natural resource management. The initiative aims to build the adaptive capacity of vulnerable farming households in the semi-arid areas of Purulia and Bankura districts by implementing strategies to mitigate the adverse impacts of climate change on their food and livelihood security. It is targeted to benefit a significant number households, including many individuals from vulnerable farming communities and those reliant on natural resources.

4.3. Scaling-up CRA towards climate-smart villages (CSVs) in Haryana (2016–2019)

This project was designed to empower rural communities in Haryana to adapt to climate change by promoting CRA practices across selected villages (URL: https://www.nabard.org/). This project positively impacted numerous families in several villages across multiple districts, including Yamunanagar, Ambala, Kurukshetra, Karnal, Jind, Kaithal, Panipat, Sonipat, Sirsa, and Fatehabad. The project also operated with a substantial budget and was spearheaded by the Department of Agriculture, Government of Haryana.

4.4. Resilient agricultural households through adaptation to climate change in Mahbubnagar district, Telangana (2016–2020)

This project was defined to enhance the livelihoods of farming communities in specific villages by implementing science-based and suitable CRA practices (URL: https://www.nabard.org/). The project aimed to promote sustainable farming techniques in the area through soil and water conservation, efficient irrigation methods, establishing climate-resilient cropping systems, and developing forecasting models. Additionally, it sought to share knowledge and experiences with the broader community. The projected impact was to benefit over significant number of farming households in Mahbubnagar district, with 30–50% of the beneficiaries being women. It was also expected that small and marginal farmers would benefit the most from this initiative.

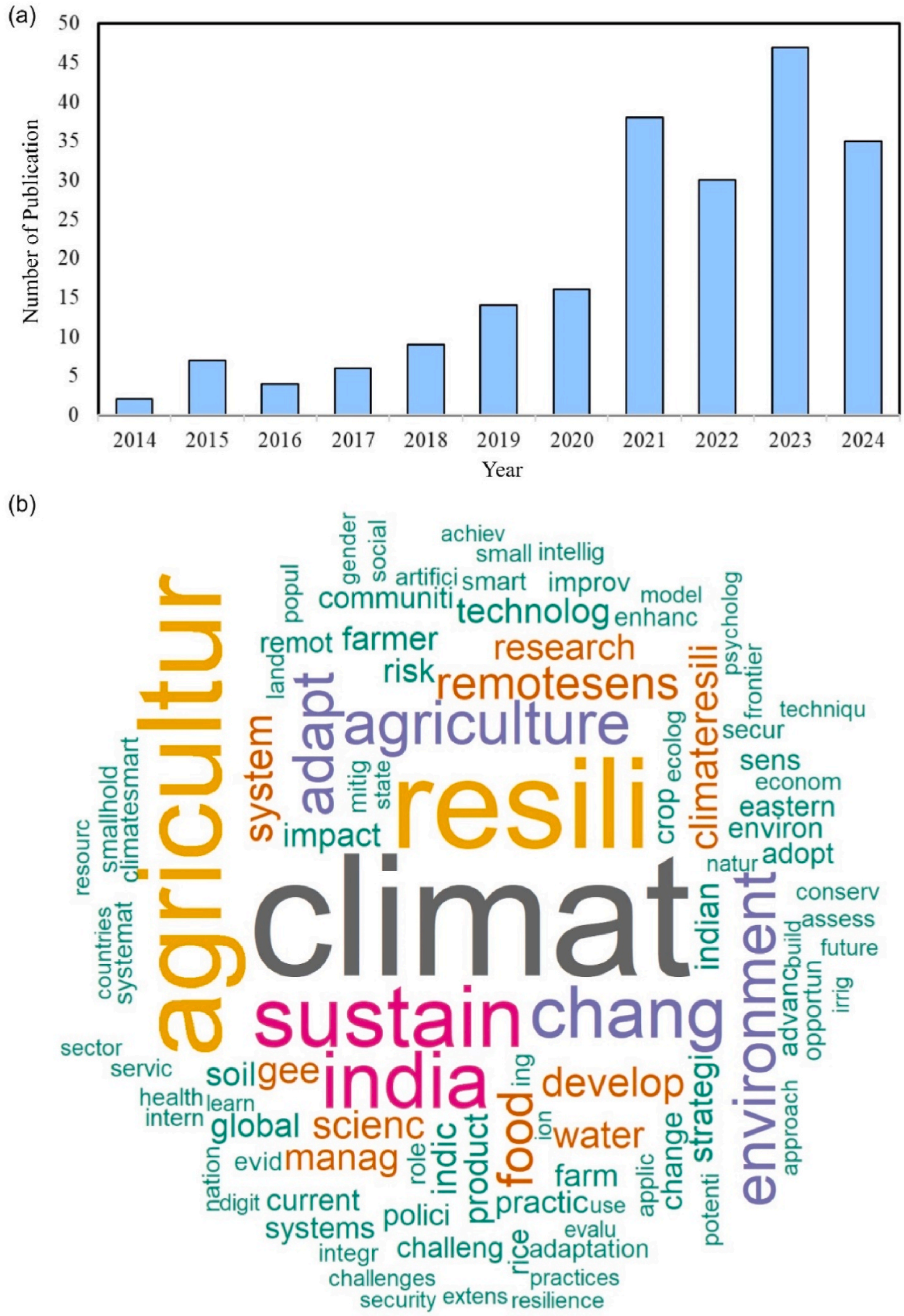

Fig. 2. (a) The distribution of selected publications on CRA over the last ten years, and (b) a word cloud schema generated from the titles and objectives of 208 peer-reviewed papers on CRA.

4.5. Climate resilient sustainable agriculture in rain-fed farming areas of Jammu and Kashmir (2016–2020)

The agriculture production department of the government of Jammu and Kashmir implemented this project to enhance the resilience of farmers in the region against climate change (URL: https://www.nabard.org/). The project's main aims included reducing farmers' vulnerability in water-stressed areas, promoting appropriate agricultural methods and rainwater harvesting, and enhancing farmers' adaptive capacity, especially for small and marginal farms.

4.6. Scaling climate-smart agriculture through main streaming climate-smart villages in Bihar (2017–2020)

The project aimed to promote conservation agriculture practices such as zero tillage, direct seeded rice, cropping system optimization/diversification, residue management, decision support (nutrition expert) and sensor-based site-specific nutrient management, precision water management (laser leveling), stress-resistant cultivars, capacity building, and knowledge dissemination to the broader population (URL: https://www.nabard.org/). It was conducted across multiple villages over four corridors: Samastipur-Darbhanga, Katihar-Purnea, Bihar Sharif-Patna, and Bhagalpur-Munger in Bihar. The project served villages in the Banswara district and was implemented by the department of agriculture, government of Bihar, with a NAFCC grant of Rs. 23.06 crore.

4.7. Project on CRA- Maharashtra (POCRA) (2018–2024)

The POCRA is a collaborative initiative between the Maharashtra government and the World Bank. It focuses on developing a climate-resilient strategy for the state's agricultural sector (URL: https://projects.worldbank.org/). The project has aimed to improve the climate resilience and profitability of smallholder farming systems in various districts of Maharashtra while addressing the potential effects of climate change and its unpredictability. The government has approved the project's second phase, which is set to begin in June 2024 and extend to five more districts: Nagpur, Bhandara, Gondia, Chandrapur, and Gadchiroli. For more information on available CRA projects in India, see ST.1.

5. Sustainability indicators for CRA

According to multiple sources (Rao et al., 2019b ; Singh et al., 2021; Zong et al., 2022; García and Rubio, 2022; Satapathy et al., 2011), comprehensive indicators for CRA are categorized into six primary groups: ecological and environmental, social, economic, institutional, infrastructural, and technological (see Fig. 3). In India, ecological and economic impacts within CRA are mainly influenced by factors such as rainfall deviation, greenhouse gas emissions, and farm market dynamics (Rao et al., 2019a).

Regions like the Indo-Gangetic Plains exhibit high adoption rates of farm mechanization, highlighted by socioeconomic resilience indicators in Delhi, Punjab, Haryana, Goa, and Kerala (Aryal et al., 2020). In terms of infrastructural and institutional resilience, Andhra Pradesh, Chandigarh, Maharashtra, Gujarat, Kerala, and Puducherry demonstrate significant adaptability.

Over peninsular India's agroecological zones, institutional efforts have led to the adoption of low-carbon strategies, including biofuels, solar energy, and optimized water management (Kritee et al., 2019). In Rajasthan, NGOs enhance soil health with water-conserving plants and assist farmers in transitioning from irrigated to rain-fed agriculture as streamflow diminishes (Ludwig et al., 2018; Chatterjee et al., 2005).

In eastern India, integrating wheat and rice crops into unified systems has proven essential for maximizing productivity, supporting food security, and bolstering climate resilience (Acevedo et al., 2020). In the northeastern region, particularly in Sikkim and Nagaland, key CRA

Fig. 3. Sustainability indicators for CRA (adaptation from Zong et al., 2022; Douxchamps et al., 2017; Rao et al., 2019b; Acevedo et al., 2020; Hellin et al., 2023; Huyer et al., 2021).

evaluation indicators include vulnerability, adaptation, and resilience. Initiatives like the "Organic Sikkim" mission enhance climate resilience through biodiversity management, traditional medicinal plant promotion, and infrastructure development (Bhatnagar, 2021).

6. Overcoming constraints through CRA

India's 160 million hectares of agricultural land cover includes five diverse bioclimatic regions, each characterized by varying annual rainfall levels, ranging from arid and semi-arid to sub-humid, humid, and coastal zones (Nath et al., 2018). These climatic variations, coupled with diverse soil types like Inceptisols and Mollisols, present significant challenges for smallholders both on and off the farm (Kuchimanchi et al., 2021).

To address on-farm constraints, CRA employs various practices to improve soil health, such as conservation tillage, balanced nutrient application, crop residue management, crop rotation, weed management, and organic farming (Rahman et al., 2021; Rodríguez et al., 2022). These methods boost soil fertility, combat degradation, and promote long-term productivity (Nath et al., 2018). Water management techniques, including rainwater harvesting, drip irrigation, mulching, and drought-resistant crops, are employed to alleviate water scarcity (Pal et al., 2015). Crop diversification by introducing diverse crops and agroforestry systems further enhances resilience to climatic shocks like droughts and floods, mitigating crop failure risk (Zomer et al., 2016). CRA can also reduce reliance on costly synthetic inputs by promoting organic options, biofertilizers, and biopesticides, lowering costs for smallholders (Wolf et al., 2023). Social and economic challenges are addressed by empowering women and marginalized groups through access to land rights, credit, training, and community-based resource management that fosters collaboration and reduces costs (Dev, 2012). Access to financial services such as microloans and crop insurance mitigates financial risks and supports investment in climate-adaptive technologies (Amarnath et al., 2023; Tripathi and Bisen, 2019). Forming cooperatives also increases bargaining power and resource access, while CRA-linked extension services provide crucial knowledge for sustainable farming practices (Huyer et al., 2021).

Beyond farm borders, CRA assists in overcoming off-farm constraints by facilitating market access through income diversification. This is achieved by integrating farming systems that combine livestock and agroforestry, creating new market opportunities and product sales avenues (Sánchez et al., 2022). Policy and financial support also align with government programs offering crop insurance and subsidies for climate-adaptive technologies, aiding smallholders in effective risk management. Adjusting cost-benefit dynamics through pricing strategies and enhancing marketing margins through certification and labeling further increases returns (Van Asseldonk et al., 2023). Moreover, CRA can provide access to knowledge and technology by providing training and extension services that equip smallholders with climate-smart practices and risk mitigation technologies, such as mobile applications, UAVs, IoT, and precision agriculture tools for weather forecasting and farm management (Nanjappan, 2018; Simelton et al., 2021). Social equity is also emphasized through policies targeting marginalized groups, including women and landless laborers, to ensure access to land rights, financial resources, and participation in decision-making processes (Huyer et al., 2021).

Based on the delineated solutions, CRA is expected to enhance the resilience of India's smallholder farmers, enabling them to adapt to climate change, improve their livelihoods, and promote sustainable practices.

7. Elements and conditions of resilience

In this section, we explain the site-specific factors and critical elements of CRA that enhance the resilience of agricultural systems, providing detailed insights into how each component contributes to sustainable and adaptive farming practices.

7.1. Site-specific conditions of CRA

Singh et al. (2021) identified the West Coast Plains, Ghats, and Gangetic Plains as regions exhibiting the highest resilience to climatic threats. In contrast, the Middle Gangetic Plains, Eastern Hills, Plateau, and Western Dry regions were noted as less resilient. The Gangetic Plains experience significant fluctuations in annual precipitation and greenhouse gas emissions from crops. Due to deforestation and diminished water storage, environmental resilience was found to be lowest in Punjab, Haryana, and Rajasthan. Conversely, states in the southern region, including Maharashtra, Tamil Nadu, Karnataka, and Odisha, demonstrated relatively better adaptation to climate-related challenges. In contrast, areas such as Uttar Pradesh, Jharkhand, and Bihar exhibited the lowest resilience to climatic shocks (Tolani et al., 2024).

Climate-smart agriculture is particularly relevant in India due to the agriculture sector's vulnerability and its role in the national economy (Kumar et al., 2018; Aryal et al., 2020). Farmers in Odisha have responded to natural calamities such as heatwaves, floods, cyclones, and droughts by adjusting planting dates and concentrating efforts on the rabi season rather than the Kharif season (Samaddar et al., 2024). Similarly, farmers in coastal regions of India employ the "land holiday" strategy, leaving their farms uncultivated to safeguard land resources from the impacts of droughts (Bahinipati and Venkatachalam, 2015). This strategy, aimed at protecting farms from severe weather events, involves altering planting dates in response to weather variations, often as a self-adaptive measure to changes brought about by the monsoon season. This method is similarly employed in Punjab to accelerate crop maturity and reduce groundwater usage (Ojha et al., 2014).

Adaptations in the Himalayan regions include contour and terrace farming along with snow water retention techniques for CRA adaptation, while converting Jhum fields to commercial agricultural fields has proven more reliable in the northeastern region (Singh et al., 2017). In the eastern Himalayas, the Apatani people use a paddy-cum-fish agroecosystem, while in the Western Himalayan region, the Lahaula practice a high degree of agro-biodiversity through snow-water collection and mixed cropping-livestock farming (Aich et al., 2022).

In southern and central India, low-cost adaptation strategies such as altering sorghum planting dates and varieties can reduce crop sensitivity and enhance productivity (Srivastava et al., 2010). Additionally, foxtail millet cultivation has provided a resilient livelihood during significant rainfall variability and severe drought in the semi-arid Deccan Plateau (Bala, 2004).

7.2. Key elements that enhance resilience in India

Indian farmers are diversifying crops like cereals, pulses, and vegetables to reduce risks from climate change and market instability. Agroforestry, livestock, and fisheries add their income security. Water management through rainwater harvesting and drip irrigation is crucial, supported by programs like PMKSY (The Pradhan Mantri Krishi Sinchayee Yojana) (URL: https://pmksy.gov.in/).

Organic farming, crop rotation, and the Soil Health Card Scheme improve soil health. Initiatives like NMSA (the National Mission on Sustainable Agriculture) endorse CRA varieties to ensure stable production (URL: https://nmsa.dac.gov.in/). Farmers are adopting agroecological methods such as natural farming and integrated pest management, enhancing biodiversity and reducing chemical use. Technologies like satellite weather forecasts and apps like Kisan Suvidha help farmers make informed decisions. Government schemes like NFSM (The National Food Security Mission) (URL: https://www.nfsm.gov.in/) and PMFBY (The Pradhan Mantri Fasal Bima Yojana) (URL: https://pmfby.gov.in/) provide support, crop insurance, and credit access. SHGs and cooperatives encourage collective action and resource sharing.

Traditional practices, including mixed cropping, minimum tillage, and water conservation, help farmers address climate challenges. Preserving indigenous knowledge and India's rich agrobiodiversity strengthens long-term agricultural resilience (Jiao et al., 2024). These elements and India's growing focus on climate adaptation, sustainable farming practices, and technological progress are vital for enhancing agricultural resilience in a country where millions rely on farming for their livelihoods. In addition, the following strategies can mainly shape the best CRA achievement.

Environment sustainability: Subsistence cultivators frequently adopt environmentally friendly methods such as organic farming, short-duration crop varieties, flood and drought-resistant crops, and insect-resistant varieties, often incorporating renewable energy and hydroponics-based agriculture (van Etten et al., 2019; Naab et al., 2019).

Predicative ability: Utilizing the best available information and technology for managing climate change impacts, focusing on hydro-meteorological data, enhances the system's capacity to anticipate and respond to environmental changes (Paparrizos et al., 2023).

Flexibility: Access to credit and financing is crucial for rural families, as it facilitates economic growth by boosting agricultural yields, reducing input costs, and increasing resilience to climate change (Singh et al., 2018). Therefore, crop management strategies, water conservation techniques, and technological setups should be adjusted to facilitate adaptable operations.

Easily measurable: Understanding CRA adaptation methods, including financial gains, carbon emission reductions, and environmental and health benefits, is essential for evaluating the effectiveness of sustainable agronomic practices (Zobeidi et al., 2024).

Redundancy: The cultivation of low-carbon crops such as rice, groundnuts, finger millet, and foxtail millet helps assess the mitigation potential and ensures stability in production despite climate variability (Tiwari et al., 2014).

Community development: Engaging entities like SHGs, NGOs, and educational institutions in capacity building supports the integrated development of CRA at the micro-level (Sivakami and Shamala, 2021).

Social equalization: Addressing issues of caste and gender discrimination within CRA promotes inclusivity and equitable access to resources (Pyakurel, 2021).

Adaptation: Studies should pay attention to the different aspects that influence the farmers' adaptation and vulnerability rather than only concentrating on how they perceive CRA. This encompasses individuals' perceptions of the stressors they face, their efforts to reduce vulnerability, and their ability to adapt to climate change. Formulating effective policy responses grounded in farmers' adaptations and their views on climate change is essential. The researchers will be able to pinpoint the weaknesses in the current policies and increase their efficacy using a participative method (Datta et al., 2022).

Social networks: Participating in social networks is one of the most crucial things that farmers should consider when adopting climate-resilient techniques. They can easily convert seeds through these networks and recover the adoption of new types suitable for their climate. The advancement of seed development plans was aided by the input of different social networks, including seed banks, farmer clusters, seed organizations, and intra-community or neighborhood systems (Acevedo et al., 2020).

8. Integration of artificial intelligence and digital tools in CRA

Artificial intelligence (AI) in agriculture includes various technological advancements, such as advisory services, data analytics, Internet of Things (IoT) applications, and the use of cameras and sensors (Sahoo et al., 2024a; Singha et al., 2023b; Khan et al., 2022). AI-driven decision support systems utilize climate analytics, soil condition insights, and crop performance data to improve decision-making processes (Jung et al., 2021).

By leveraging this information, these systems help reduce the risks linked to climate fluctuations and advance the agricultural industry toward sustainability (Othmeni, 2023). Investigates emerging digital innovations' capabilities, emphasizing AI's crucial influence in developing agrifood systems that are resilient to climate change while being more efficient, sustainable, and flexible (Sahoo et al., 2024b; FAO, 2023a,b). By convening specialists across the extensive realms of agriculture and technology, the gathering aims to foster discussions on fostering sustainable farming practices and climate initiatives, guided by the responsible utilization of data and cutting-edge technologies amidst evolving social and ethical considerations. Barkakoti et al. (2024) explored how AI technologies can improve resilience in Indian agriculture, focusing on how these innovations can reduce vulnerabilities and enhance productivity. Through the adoption of technological advancements, Indian agriculturists have the opportunity to strengthen their adaptability, lessen uncertainties, and guarantee food sustainability amidst changing agricultural scenarios. Some CRA indicators monitored by AI technology can be seen in Fig. 4 (Javaid et al., 2023).

8.1. Case study I (climate change impact for CRA analysis)

This case study investigates the hydrometeorological factors impacting climate change over 62 years (1958–2020) in the Khoyrasole block of West Bengal, India, utilizing data from TerraClimate and GRACE (2002–2021) (see Fig. 5). The analysis focuses on annual precipitation, maximum temperature (Tmax), minimum temperature (Tmin), and climate water deficit (DEF) to assess long-term climatic trends in the region. The findings indicate a declining trend in water storage, highlighting the sensitivity of Equivalent Water Thickness (EWT) in the area (see SF.2). The region covers approximately 197.64 square kilometers and is predominantly used for agriculture (ESA, 2021).

Nag and Das (2020) emphasized the shift towards monocultural rainfed farming due to inadequate irrigation infrastructure and unpredictable rainfall. Farmers in the region echo this challenge (see Fig. 6).

- Murshidabad Farmer (LH 1): "The lack of water facilities makes it difficult to grow rice, and heavy rains sometimes destroy crops. The lowland areas are prone to waterlogging. Producing pulses is not profitable as the market price is too low for us to sell them profitably."

DEF exhibits an east-to-west gradient, with positive trends widespread across the region. Villages such as Parsundi, Arjjunsuli, Geruhapahari, Babuijore, Kese, Lokepur, and Haripur encounter minimal precipitation, affecting agricultural productivity because of ground stress and reduced water infiltration. This issue is reflected in the experiences of local farmers.

- Birbhum Farmer (LH 2): "Farmers do not cultivate as much due to dry land and a lack of water, which lowers the paddy yield. There are no seeds on the market, and carrying them is quite expensive."

High evapotranspiration, low soil moisture, and diminished groundwater storage further exacerbate these challenges, driven by elevated Tmax and Tmin values and negative DEF. In Paschim Medinipur, such climatic conditions have visibly altered land use, as noted by.

- Paschim Medinipur Farmer (LH 3): "Growing multiple crop varieties on the same land could increase yields, but the fields often get flooded due to low elevation and excessive rains. Due to agricultural challenges, some lands have been converted into brick kilns and fisheries."

Recommendations to cope with these challenges include adopting

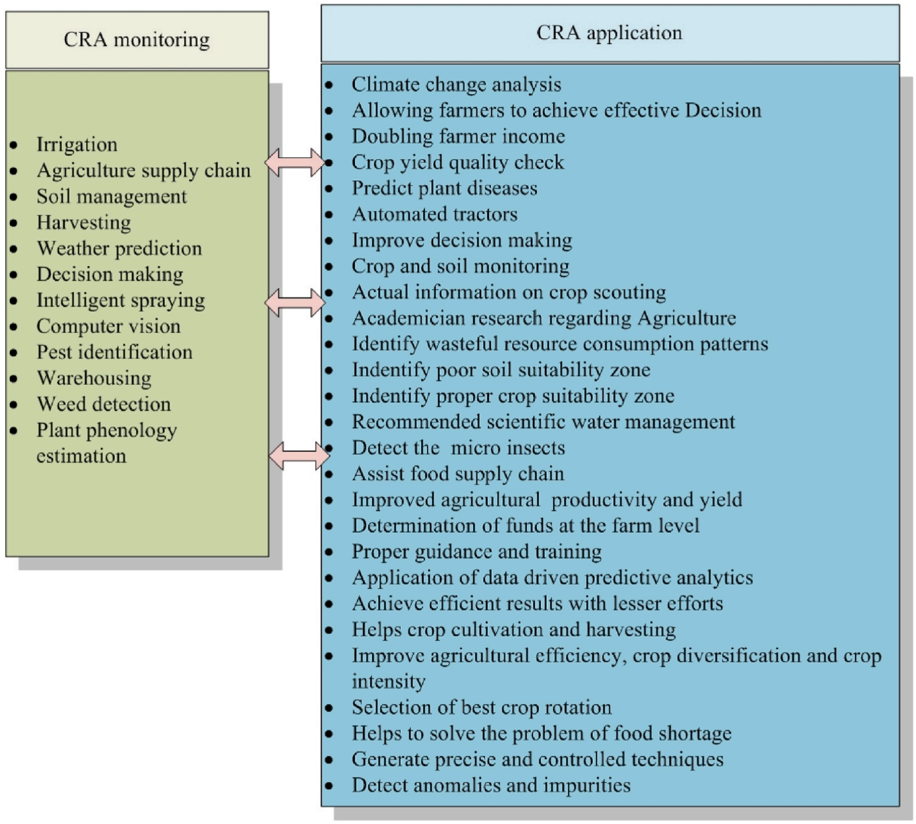

Fig. 4. CRA application with the AI technology (Javaid et al., 2023).

climate-smart and CRA practices such as crop diversification, crop rotation, and mixed farming. Further strategies involve adjusting planting schedules, implementing micro-irrigation and rainwater harvesting, and incorporating climate-smart livestock rearing alongside drought-tolerant and short-duration crop varieties to enhance agricultural systems for smallholder farmers.

8.2. *Case study II (application of AI techniques for the CRA analysis)*

The second case study investigates the application of AI in analyzing hydrometeorological factors related to CRA over 62 years (1960–2022) using TerraClimate data. The study focused on the Onda block within the Dwarakeser River basin in West Bengal, India, aiming to assess long-term trends in groundwater level (GWL) changes via machine learning (ML) models.

Several key parameters were analyzed, including precipitation (Pr), temperature extremes (Tmax and Tmin), actual and potential evapotranspiration (AET and PET), climate water deficit (DEF), vapor pressure deficit (VPD), and runoff (RO).

Precipitation trends revealed an increase in the southern part of the block at a rate of 0.132 mm/year, while the northern part experienced the lowest trend at 0.158 mm/year (see Fig. 7a). The variability in temperatures showed significant fluctuations, with Tmax and Tmin changes more pronounced in the western regions, ranging from 0.062 to 0.058 °C/year, compared to variations between 0.128 and 0.121 °C/year in eastern areas (see Fig. 7b & c). DEF and AET trends displayed a range from −0.75 to −0.58 mm/year and 0.848 to 0.631 mm/year, respectively (Fig. 7d & e). PET spatial distribution indicated an upward trend from 0.18 mm/year in the northeast to 0.002 mm/year in the south, as shown in Fig. 7f. The study area also showed negative DEF trends in the upper region, transitioning to positive trends in the lower part, ranging from −0.0116 to +0.0085 mm/year (see Fig. 7g). The highest runoff trends were identified in the lower section at 0.0807 mm/year, contrasting with lower trends of approximately 0.0536 mm/year in central and upper regions (see Fig. 7h).

The study utilized ML techniques, specifically Random Forest (RF) and Extreme Gradient Boosting (XGB) models, to predict GWL. Using 70 in situ GWL data points collected between 2010 and 2022, the RF model results showed lower GWL levels in the upper and lower regions, around 6.20 m below ground level (mbgl), while higher levels were observed in central areas near the river, around 3.68 mbgl (see Fig. 7i). Similarly, the XGB model identified the lowest GWL trend, about 6.74 mbgl, in the upper region, with higher levels of approximately 2.87 mbgl in the eastern and western areas (see Fig. 7j). This analysis highlighted the agricultural challenges faced by villages in the upper region, such as Kokilpur and Haripur, which experience low precipitation, reduced AET, and elevated VPD, increasing ground stress and reducing water infiltration. High rates of evapotranspiration, coupled with low soil moisture and diminished groundwater storage driven by elevated Tmax and Tmin values and negative DEF trends, exacerbate these issues.

Considering these factors, several management strategies have been proposed to enhance pulse yields in challenging rice fallow environments to promote climate-smart and CRA practices in the region. These strategies include selecting appropriate pulse varieties, implementing water management through managed aquifer recharge (MAR), using various drought-tolerant crops, implementing zero tillage practices, adopting relay cropping, maintaining crop residues, using mulching techniques, applying seed priming methods, employing life-saving irrigation, and providing nutrient foliar sprays.

9. CRA and development practices

The assessment of seed practices, training sessions, agro-based products, and information dissemination have highlighted distinct adoption patterns among farmers, with female farmers more likely to implement these techniques than males. Training and outreach

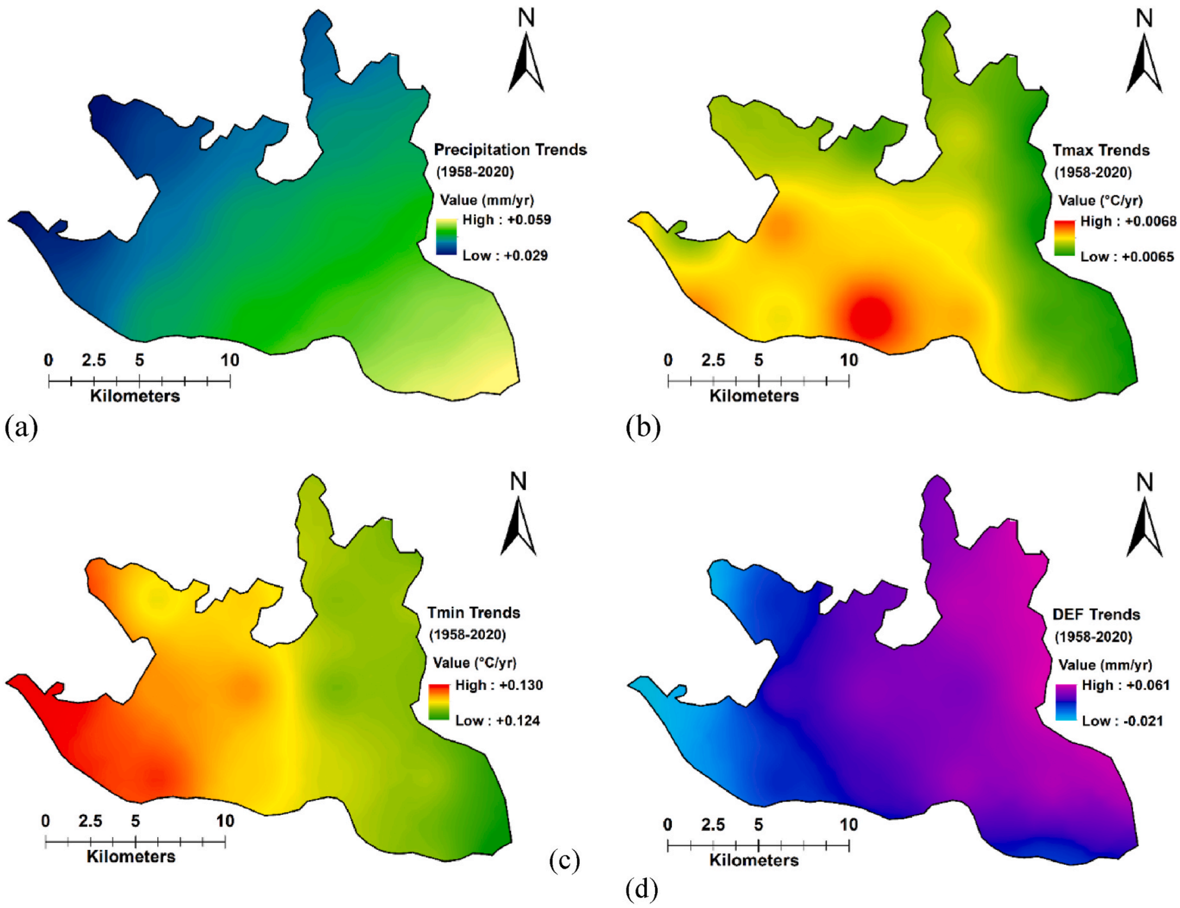

Fig. 5. Spatial distribution maps of (a) Precipitation, (b) Tmax, (c) Tmin, and (d) DEF trends for Khoyrasole block, Birbhum, West Bengal, India.

Fig. 6. Field survey photographs for CRA information from Murshidabad and Birbhum districts, West Bengal, India (Sahoo et al., 2024b).

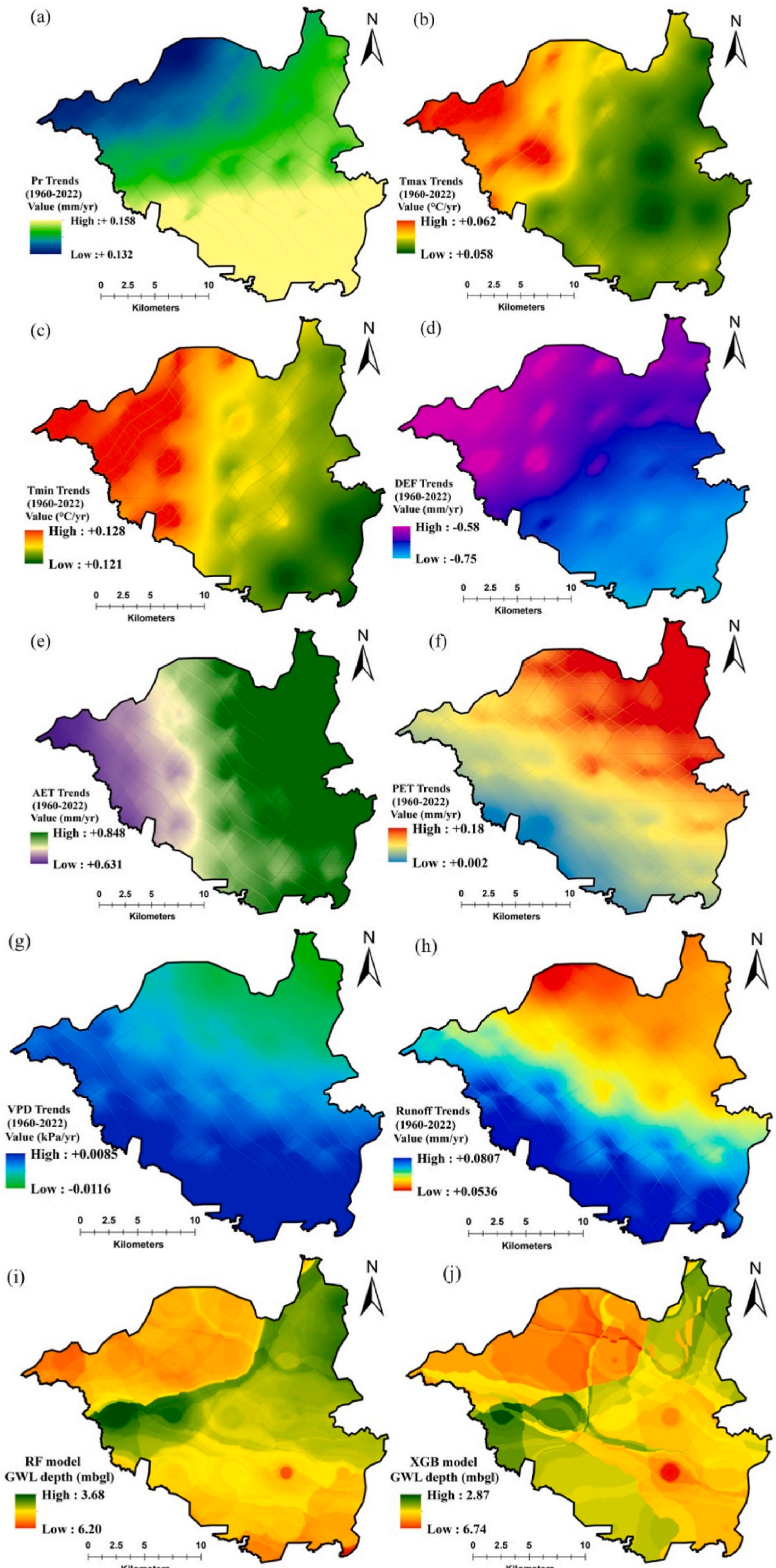

Fig. 7. Application of AI techniques for the CRA study: hydrometeorological parameters (a)–(h): (a) Pr, (b) Tmax, (c) Tmin, (d) DEF, (e) AET, (f) PET, (g) VPD and (h) RO trend (slope of the linear regression) map and ML model: (i)–(j): (i) RF and (j) XGB for the Onda block, Bankura district, West Bengal, India.

programs significantly enhanced their comprehension of climate-resilient, high-yielding varieties (HYVs) and drought, disease, pest tolerance, or short-term crop varieties (Dar et al., 2020a). Pandey et al. (2021) advocate for developing CRA methods tailored to policymakers' demands and emphasize the necessity of diverse and effective social engagement.

In regions like the Aravalli district, organic farming has been adopted to tackle pest adaptability, leveraging conventional pest management strategies (Angom et al., 2021). In Gujarat, organic farming has doubled farmers' incomes without increased input costs (Kashyap et al., 2017). Strategic crop rotation boosts productivity, controls nutrient levels, and reduces crop failure risks (Mazhar et al., 2020). Technologies like mulching, waterland transformation, and zero tillage have improved soil health and productivity, particularly in semi-arid regions (PLP, 2018; Goswami et al., 2022).

It is also worth noting that CRA practices often develop independently and without significant external funding, highlighting their potential to improve landholders' livelihood strategies (Ahmad et al., 2022). The Indian government has also integrated CRA into its development policies and initiatives, including livestock management strategies under climate change, micro-irrigation system planning, and renewable energy projects (Government of India (GOI), 2017; Patel et al., 2018). A flexible approach embracing Earth observation (EO) based data-driven practices and nature-based solutions is essential for achieving CRA targets in the future. Addressing the practical requirements for bridging the gap between observed and potential performance in agro-environmental policies is imperative.

Indian agriculture has adapted to climate change through various methods, including soil organic carbon integration, in-situ moisture management, water-saving technologies, crop diversification strategies, improved livestock feeding, and recycling practices to reduce burning (Government of India (GOI), 2017; Patel et al., 2018). Social capital's role in community development can also encourage financial institutions to meet the credit needs of low-to moderate-income communities. While India lacks a direct equivalent, grassroots initiatives can promote community involvement (Prince, 2024). These efforts engage residents in identifying their needs and priorities, leading to more relevant and effective programs.

Community participation is also essential for advancing CRA efforts in India, as it harnesses local expertise, fosters collaboration, and empowers farmers (Santosh et al., 2020). Through community involvement, CRA initiatives can enhance financial literacy, create jobs, and address health issues (Mahesha, 2023). Partnerships with businesses and educational institutions can strengthen these efforts. Additionally, community-led health programs can address local health issues by engaging residents in health awareness campaigns, sanitation projects, and nutrition education (Kadariya et al., 2023).

Leveraging farmers' knowledge and collaborative efforts among stakeholders increases CRA effectiveness, strengthens social networks, and ensures that practices are tailored to specific contexts (Dhawi and Aleidan, 2024; Ma et al., 2023). This collaboration among farmers, NGOs, local governments, and other stakeholders facilitates resource sharing and the exchange of best practices, thereby increasing the effectiveness of CRA initiatives.

Community-driven initiatives in CRA can also promote collaborative resource management, such as community-based rainwater harvesting and irrigation schemes, to improve resource efficiency and climate resilience (Kim et al., 2016). Community-driven initiatives promote resource management and engagement in research, advocating for policies that reflect local agricultural needs. They facilitate knowledge-sharing and improve CRA strategies through community involvement (Tay et al., 2024). Furthermore, incorporating CRA practices into India's broader economic and development goals requires harmonizing agricultural strategies with national economic agendas, poverty alleviation programs, and sustainability targets. The Indian government can incorporate CRA into initiatives like the National Action Plan on Climate Change (NAPCC) (Pandve, 2009) and PMKSY (URL: https://pmksy.gov.in/), which focus on vital elements of economic advancement like water efficiency and soil conservation. Endorsing crop diversification, agroforestry, minimum tillage, and mixed farming boosts climate adaptability and offers new income opportunities for small farmers, enhancing rural livelihoods.

Supportive measures, such as enhancing climate risk insurance through the PMFBY and offering affordable credit through programs such as Kisan Credit Card (KCC), can also enable farmers to adopt CRA practices without financial strain. Therefore, integrating these initiatives into financial inclusion plans can reduce farmers' vulnerability to extreme weather. Encouraging water-efficient technologies, like drip irrigation and systems such as MAR, aligns with India's sustainable water use goals and the Jal Jeevan Mission (https://jaljeevanmission.gov.in/), can also boost agricultural output while conserving resources (Bandyopadhyay et al., 2021; Sarkar and Bharat, 2021).

Digitalization and adopting digital technologies, like using remote sensing (RS) sensors and data, cloud platforms like Google Earth Engine (GEE) (https://earthengine.google.com/), and precision farming techniques can further expand CRA (Sirmacek and Vinuesa, 2022). Programs such as Digital India (https://www.investindia.gov.in/team-india-blogs/digital-india-revolutionising-tech-landscape) can drive tech sector growth while improving farm resource management. Training farmers in climate-smart practices can support broader educational and rural development goals, enhancing resilience and advancing skill development (Arulmanikandan et al., 2024). Collaboration among government, private sector, and civil society is also essential for attracting investment in climate-smart agricultural technologies and infrastructure, supporting India's aims of increased agricultural productivity and rural job creation.

10. Challenges in implementing CRA

Implementing CRA in India requires addressing several interconnected challenges across socioeconomic, cultural, institutional, technological, and policy domains.

Socioeconomic and Cultural Barriers: Smallholders often face poverty and limited access to essential resources like credit, high-quality seeds, and agricultural inputs, hindering the adoption of CRA techniques (Kapari et al., 2023). Additionally, traditional practices and cultural norms, including those tied to gender, may discourage the shift to CRA. Farmers' preference for familiar methods, coupled with limited awareness and educational deficits, exacerbates these challenges and reinforces the gender divide in agriculture, contributing to the disconnect between researchers and end-users (Huyer et al., 2021; Okoronkwo et al., 2024).

Awareness and Information Gaps: Although numerous initiatives and policies have been established to tackle climate change adaptation, small and marginal farmers remain unaware of the available information and benefits (Cummings, 2019; Marques and Teixeira, 2023). This gap persists even with the presence of automated weather stations and skilled field staff monitoring farm activities in real time.

- *Infrastructure and Mechanization:* While machinery subsidies have been provided, inadequate infrastructure (e.g., roads, electricity, storage facilities) poses challenges to mechanized agriculture, with unpredictable monsoons further complicating adaptation efforts (Eeswaran et al., 2021).
- *Financial Awareness and Market Access:* Many farmers lack understanding of financial tools like loans and insurance, which affects their resilience building and profitability (Calle et al., 2020). Restricted market access for CRA products, such as organic crops, also limits potential economic benefits.
- *Technological and Data Challenges:* Limited access to modern agricultural technologies and insufficient R&D investment restrict the development of locally relevant solutions (Ukhurebor et al., 2021).

Challenges in merging traditional methods with modern technologies complicate CRA practices, and the digital divide further restricts farmers' access to necessary information and technology. (Samadder et al., 2023).

- *Institutional and Policy Barriers:* Fragmented agricultural extension services and inconsistent climate adaptation policies can deter investment in CRA initiatives (Mishra et al., 2024). Moreover, inadequate cooperation among NGOs, government agencies, and local communities reduces the effectiveness of CRA promotion efforts (Debangshi, 2021; Gopalakrishnan and Sylvia, 2023).
- *Emissions and Incentives:* The lack of incentives limits agricultural emission mitigation strategies, which are more complex to monitor than fossil fuel emissions (Bizikova, 2012). Inadequate property rights and financial structures further hinder practical mitigation efforts (Malhi et al., 2021). Using available funding is one of the most effective methods to enhance the synergy between adaptation and mitigation in the agricultural sector, but it also needs to consider the priorities.

Precision Farming Barriers: Small-scale Indian farmers face obstacles in adopting precision farming due to knowledge, technology, and financial challenges. Transitioning to intelligent farming necessitates adopting advanced technology and institutional funding (Dadhich et al., 2017)

- *Data and Environmental Conditions:* Coarse spatial resolution data limits monitoring of climate change solutions like nature-based methods and green infrastructures. Although public agriculture policy is advancing towards a Green Economy, regulatory frameworks remain imperfect (Schiavon et al., 2021). Unstable weather conditions like extreme temperature fluctuations, which cause droughts/floods, pose significant challenges to planning and implementing CRA systems.

While these challenges, obtained from literature and our perspectives, persist, technological advancements offer hope for future solutions. Some issues are already being resolved, and continued progress is expected to address these barriers effectively. The ICAR policy paper (Rao et al., 2019b) stands out as one of the most insightful references on this topic, offering a comprehensive understanding of the role of CRA in India and providing researchers with valuable ideas about the challenges farmers currently face. Nevertheless, we believe that the macro and micro policies highlighted in this document need to be effectively and thoroughly communicated to farmers by knowledgeable experts. Employing diverse and efficient teaching methods is crucial to empower farmers to adapt more effectively to climate change. Furthermore, while poverty continues to affect a portion of the population, India is home to a dynamic and youthful demographic with a strong enthusiasm for learning and a notable footprint in global technology. In this context, leveraging the voluntary educational efforts of Indian youth for innovative climate resilience training presents a promising opportunity. Although this approach alone may not serve as a comprehensive solution, it undoubtedly holds significant potential and warrants further exploration and development.

11. Recommendations and future directions

This study aligns closely with several SDGs within social, environmental, and governance frameworks (see Fig. 8). In the social context, CRA supports SDGs such as no poverty (SDG∼1), zero hunger (SDG∼2), gender equality (SDG∼5), and reduced inequalities (SDG∼10) by focusing on community development, education, and welfare programs. Environmentally, CRA aligns with SDGs 6 (clean water and sanitation), 12 (responsible consumption and production), 13 (climate action), and 15 (life on land) through efforts like renewable energy implementation and water resource management. Additionally, cooperatives contribute to community growth by facilitating partnerships with government, businesses, and educational institutions, positioning them to fulfill SDGs 8 (decent work and economic growth) and 17 (partnerships for the goals).

Regional planning is essential for addressing geographic disparities in environmental resilience. Comprehensive supervision strategies and detailed contingency plans are necessary to manage resources effectively in areas experiencing reckless groundwater withdrawal (Sikka et al., 2022). Implementing web-based, near-real-time monitoring of hotspots for pests, diseases, soil spectroscopy systems, and vulnerable

Fig. 8. SDGs indicators that can be answered by CRA strategy.

ecoregions effectively supports CRA (Jena et al., 2023; Singha et al., 2023a).

To enhance climate adaptation, local traditional knowledge should guide the planning of agricultural adaptation strategies, ensuring unbiased access to irrigation techniques and field-based cropping patterns (Bahinipati and Patnaik, 2022). These factors can enhance profits, water efficiency, and value creation. Frequent training sessions delivered to farmers and the availability of incentives aid in a quicker degree of recovery. Diversifying agriculture and livelihoods is essential to managing climate uncertainties and promoting resilience through crop-livestock diversity and agro-meteorological practices (Birthal and Hazrana, 2019). This diversification reduces vulnerability to low yields and food insecurity by improving adaptive measures and extension services.

Implementing weather and crop insurance, especially in regions with limited capital access, can effectively manage risks (Madaki et al., 2023). Extending credit in these areas expands the capacity for pre- and post-climate response. Policy interventions must address grassroots institutional gaps to foster knowledge sharing.

Advancing poverty reduction requires policy measures that enhance adaptability by supporting multi-stakeholder enterprises and shifting the research agenda toward innovative agricultural techniques. CRA adoption can be boosted through agronomic and precision methods, including mixed cropping, livestock management, and cultivating short-duration crops. Practices like intercropping, farmyard manure use, crop hybridization, germplasm conservation, biofuels, and solar-powered irrigation should also be considered (Escarcha et al., 2018).

A comprehensive geodatabase powered by IoT and AI is essential for assessing CRA techniques (Javaid et al., 2023). This system should include guides for tool maintenance, setup, and flux sheet generation. Local NGOs and public-private partnerships (PPP) have mapped land and soil using digital soil data, RS/GIS technology, and GPS devices (Bwambale et al., 2022). These efforts have been integrated with household demographic data to create computerized geographic records that link land ownership information.

12. Region specifics practices of CRA in India

India's agricultural landscape is distinct, given its wide range of agroecological zones (AEZ) by National Commission on agriculture India (1971) (see SF.3). It provides more localized, region-specific recommendations, which would strengthen the CRA strategy by making it more practical and actionable for different areas, enhancing its overall effectiveness.

In forming these strategies, the adoption approach for CRA specific to each AEZ was validated through an analysis of water storage anomalies. These anomalies, measured in centimeters of Equivalent Water Thickness (EWT), were derived from data provided by the GRACE and GRACE-FO missions. Data processing was conducted at NASA's Jet

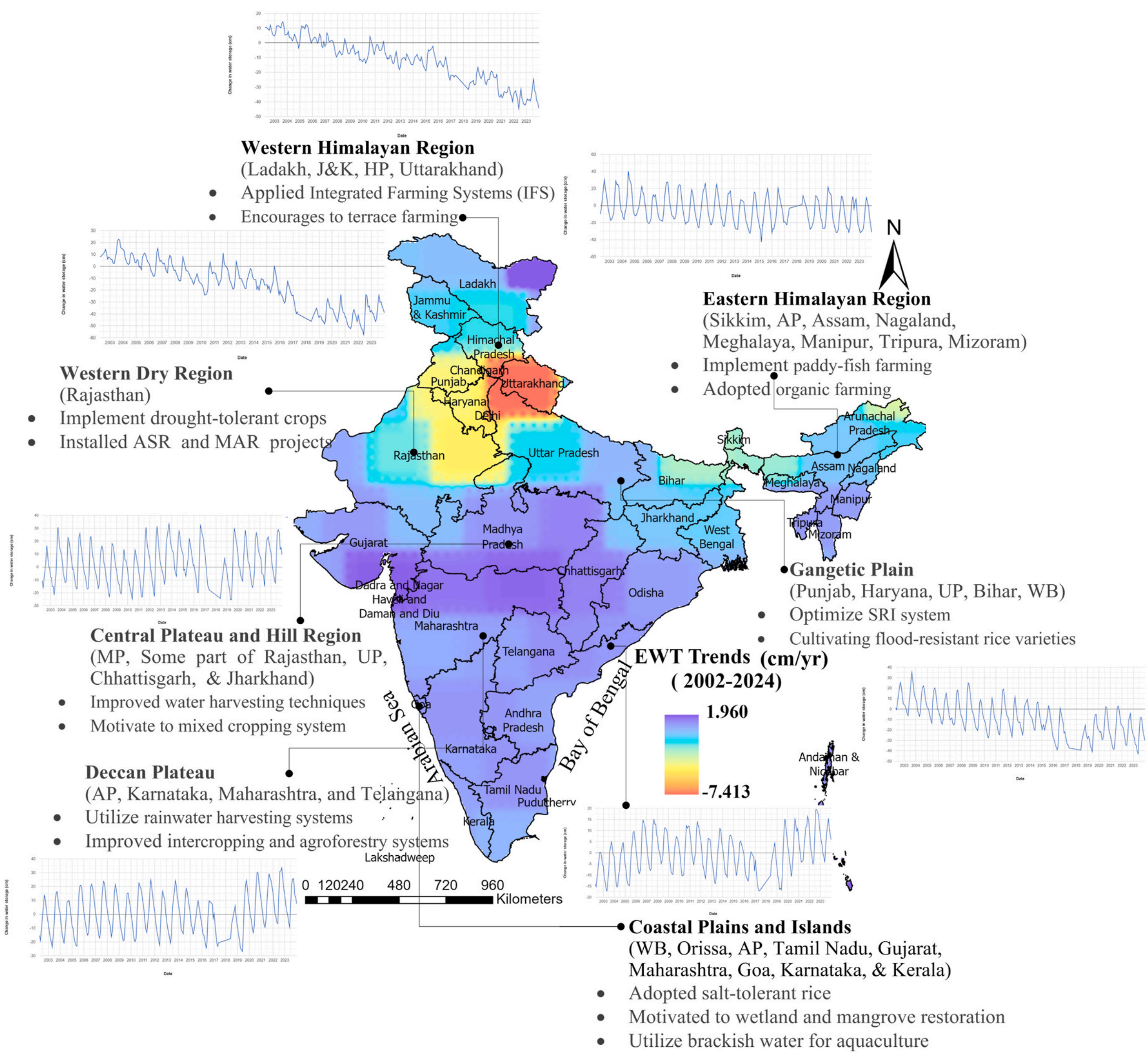

Fig. 9. The trend analysis (2002–2024) of equivalent water thickness (EWT) over India by the GRACE Mascon mission.

Propulsion Laboratory using the Mascon approach (RL06.1Mv03) (URL: https://grace.jpl.nasa.gov/data/get-data/jplglobalmascons/). The long-term trend of EWT from 2002 to 2024 across India was estimated using the Google Earth Engine cloud platform, applying the slope of the linear regression (SLR) method. This analysis revealed that the Western Dry Region, Western Himalayan, and Gangetic Plain AEZs experienced the steepest declines in EWT compared to other regions, underscoring the urgent need for CRA adoption in these areas to ensure future food security stability. Notably, the northwestern area emerged as the most vulnerable hotspot for water scarcity, exhibiting negative trends of around −7.413 cm per year (see Fig. 9).

In India, different regions adopt different sustainable agricultural practices to increase climate resilience (Alagh, 1990; Singh et al., 2021). In the Western Himalayan region, conservation agriculture and terrace farming are often used to maintain soil moisture and prevent erosion, with integrated farming systems providing food security through stable yields (Bisht et al., 2016; Arulmanikandan et al., 2024; Shanmugam et al., 2024). In the eastern Himalayan region, there is a shift from jhum cultivation to sustainable alternatives such as paddy-fish farming and organic practices such as the use of compost and green manure to promote soil health and resource efficiency (Rai, 2005; Das and Das, 2020; Samaddar et al., 2024). In the Gangetic Plains, farmers are using advanced cultivation techniques and flood/drought-resistant rice varieties to optimize water use and increase yields in the rice-wheat with intercropping system (Alagh, 1990; Hobbs and Gupta, 2003; Dar et al., 2020b). In the Central Plateau and Hill region, water management through harvesting techniques and efficient irrigation supports resilience, while mixed cropping and crop rotation improve soil health (Rastogi et al., 2024). The Western Dry region focuses on drought-resistant crops such as sorghum and millet, complemented by aquifer recharge projects such as drip irrigation and mulching (Singh, 2010; Bandyopadhyay et al., 2021). In the coastal plains and islands, salt-tolerant varieties such as rice and wheat are used, along with integrated farming systems that include crop rotation and intercropping to manage soil salinity (Mahata et al., 2010; Tarolli et al., 2024). In the Deccan Plateau, rainwater harvesting and drought-tolerant crops such as cowpea and pigeonpea are being used, with intercropping and agroforestry practices such as the use of nitrogen-fixing legumes and fruit trees improving resilience and income diversification (Nwaogu and Cherubin, 2024).

13. Conclusions

This study analyzed CRA as a strategy for ensuring food security in India, highlighting the country's sustainability opportunities and challenges. Effectively addressing the impacts of climate change on agricultural economies requires thorough research into CRA practices over various climate-resilient regions. This review showed that CRA research has gained notable recognition over the past decade, with a consistent rise in publications focused on sustainable agriculture. However, in India, there is a pressing need for greater adoption. As discussed, farmers and policymakers in India must be more familiar with the negative impact of climate change on agriculture and CRS rules. Developing scientific metrics to quantify sustainability and resilience will enable them to make informed decisions. Despite numerous studies, a comprehensive measurement set that accurately reflects the impact of climate change on agriculture remains elusive, and CRA strategies need to be considered in different terms. Integrating geospatial and AI techniques could accelerate the development of climate-resilient crops, although these methods produce complex datasets that challenge current analytical capabilities. Given India's diverse topography and agricultural systems, examining resilience indicators seems vital for addressing this complexity. This review emphasized the importance of CRA in designing climate risk management strategies tailored to agriculture in India. Our investigation also showed that CRA can advances key SDGs through social justice, environmental sustainability, and strategic partnerships, creating a pathway to a more equitable and resilient future. The GRACE findings identified northwestern India as a major hotspot for water scarcity, with negative trends of around −7.413 cm per year. Additionally, the analysis revealed that the Western Dry Region, Western Himalayan, and Gangetic Plain AEZ experienced the most significant declines in EWT compared to other AEZ. Establishing a knowledge repository for information sharing among researchers and planners is recommended to support programs aligned with India's climate change action plan. Adopting CRA practices also underscores the need for empirical studies to identify contextually relevant strategies. Traditional farm-level adaptation measures must be validated for broader application. Moreover, challenges such as insufficient funding, inadequate monitoring, and a predominantly top-down institutional approach require further study.

Farmers' decisions to adopt CRA practices are influenced by their risk assessment, knowledge and access to technology, economic status, and family needs. Initiatives should, therefore, strengthen farmers' decision-making capacities and systematically develop, validate, and disseminate adaptive knowledge. Support is needed for technology, institutions, financing, and creating a knowledge base and transfer framework tailored to different AEZ and local conditions in a changing climate. Understanding and incorporating farmers' perceptions into policy is essential for sustainable and effective climate action. Ensuring access to resources, stakeholder engagement, and robust monitoring are essential to promote food security and improve livelihoods.

CRediT authorship contribution statement

Satiprasad Sahoo: Writing – original draft, Resources, Project administration, Investigation, Formal analysis, Conceptualization. **Chiranjit Singha:** Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Data curation, Conceptualization. **Ajit Govind:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Investigation, Formal analysis. **Armin Moghimi:** reviewing, revising, and writing the paper and providing the geospatial maps.

Consent to participate

Informed consent was obtained from all interviewees. No names or any other identifying information was used in publications resulting from this research.

Ethics approval

Not relevant for this article. There were no mandatory procedures in this field in India at the time of the project. No personal data was collected in our research.

Consent for publication

All authors agreed with the final content of this manuscript.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.indic.2024.100544.

Data availability

Data will be made available on request.

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