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Climate change perception and adaptation strategies among farmers: A socio-economic synthesis across agro-ecological zones

[1]Pooja Krishna J, [2]Anupama S, [3]Holy Mercy Divina Matla [4]Megha AM and [5]Anjana PM

[1]Assistant Professor, School of Agricultural Sciences, Joy University, Tirunelveli, Tamil Nadu, India

[2]Assistant Professor, Department of Agriculture Extension Education, College of Agriculture, Padannakad, Kerala Agricultural University, Kasaragod, Kerala, India

[3]Ph.D. Scholar, Department of Agriculture Extension Education, College of Agriculture, Vellayani Kerala Agricultural University, Thiruvananthapuram, Kerala, India

[4]M.Sc. (Agricultural Extension Education), Kerala Agricultural University, Kerala, India

[5]PG scholar, Department of Agricultural Economics, College of Agriculture, Vellayani, Kerala Agricultural University, Thiruvananthapuram, Kerala, India

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Corresponding Author: Anupama S

Abstract

Farmers' perceptions of climate change play a pivotal role in shaping adaptation strategies and determining the resilience of agricultural systems. Perceptions, grounded in observed shifts in rainfall, temperature, and extreme weather events, directly influence farmers' decision-making under conditions of uncertainty. Evidence indicates that accurate climate risk perception enhances the adoption of effective adaptive practices, while misperceptions may result in maladaptation, thereby increasing vulnerability and threatening food and livelihood security. Over the past decade (2015-2025), methodological approaches for assessing farmers' perceptions and adaptation strategies have evolved considerably, transitioning from basic surveys and descriptive statistics to advanced mixed-methods designs, econometric modelling, and integration of meteorological and psychological data. This review synthesizes insights across agro-ecological zones, highlighting typologies of adaptation strategies, socio-economic determinants of adoption, gendered dimensions of adaptation, and the structural barriers that hinder effective responses. Comparative analyses demonstrate that adaptation is shaped not only by farm-level attributes such as experience, land size, and crop type-but also by broader institutional and policy environments. The review further emphasizes the role of targeted interventions, inclusive policy frameworks, and institutional support in facilitating effective adaptation. Emerging trends, including digital agricultural extension, climate services, and participatory approaches, present new opportunities for strengthening farmer resilience. Research gaps remain, particularly in linking perception with long-term behavioural change, ensuring equity in adaptation, and evaluating the sustainability of adaptation measures. Addressing these gaps will be critical for developing inclusive, evidence-based strategies that align with sustainable agricultural development under changing climatic conditions.

Keywords: Climate change perception, adaptation strategies, agro-ecological zones, climate risk management, agricultural resilience

1. Introduction

The Oxford Dictionary defines perception as "an idea, a belief, or an image you have based on how you see or understand something." It describes how something is viewed, understood, or interpreted. Perception influences knowledge, which in turn shapes perceptions of objects, events, or phenomena. This interaction greatly affects how farmers understand and respond to climate-related risks and uncertainties, guiding their actions to reduce the negative impacts of climate change on agriculture.

Accurate perception is crucial for mitigating adverse impacts and implementing effective adaptation strategies. Farmers mainly perceive climate change through changes in rainfall, temperature patterns, variability, and the frequency of extreme weather events. According to Udmale *et al.* (2014) [177], most farmers perceive many environmental impacts, such as rising average atmospheric temperatures, and these perceptions are shaped and reinforced through daily experiences and multiple external sources. Farmers' perceptions are vital for mitigating the adverse effects of climate change on agriculture. Implementing targeted interventions involving the farming community and other stakeholders is essential to improve their readiness for its detrimental impacts (Raghuvanshi *et al.*, 2018) [149].

The analysis of farmers' perceptions regarding climate change, both long term and short term, is a prerequisite for evaluating their adaptation decisions. Three critical factors shall be considered for a successful and efficient adaptation:

timely recognition of the need, the incentive and the ability to adapt. According to Sanghi and Mendelsohn (2008) [156] and Bryan *et al.* (2009) [37], for the agricultural producers to identify the necessity for adaptation, they must first discern and internalize the actual changes in the climate affecting their livelihoods while adjusting the indigenous farming systems to maximise the outputs in each new environment. The viability of sustainable agricultural development under changing climatic conditions is significantly influenced by the farmers' cognitions and their implementation of adaptive strategies.

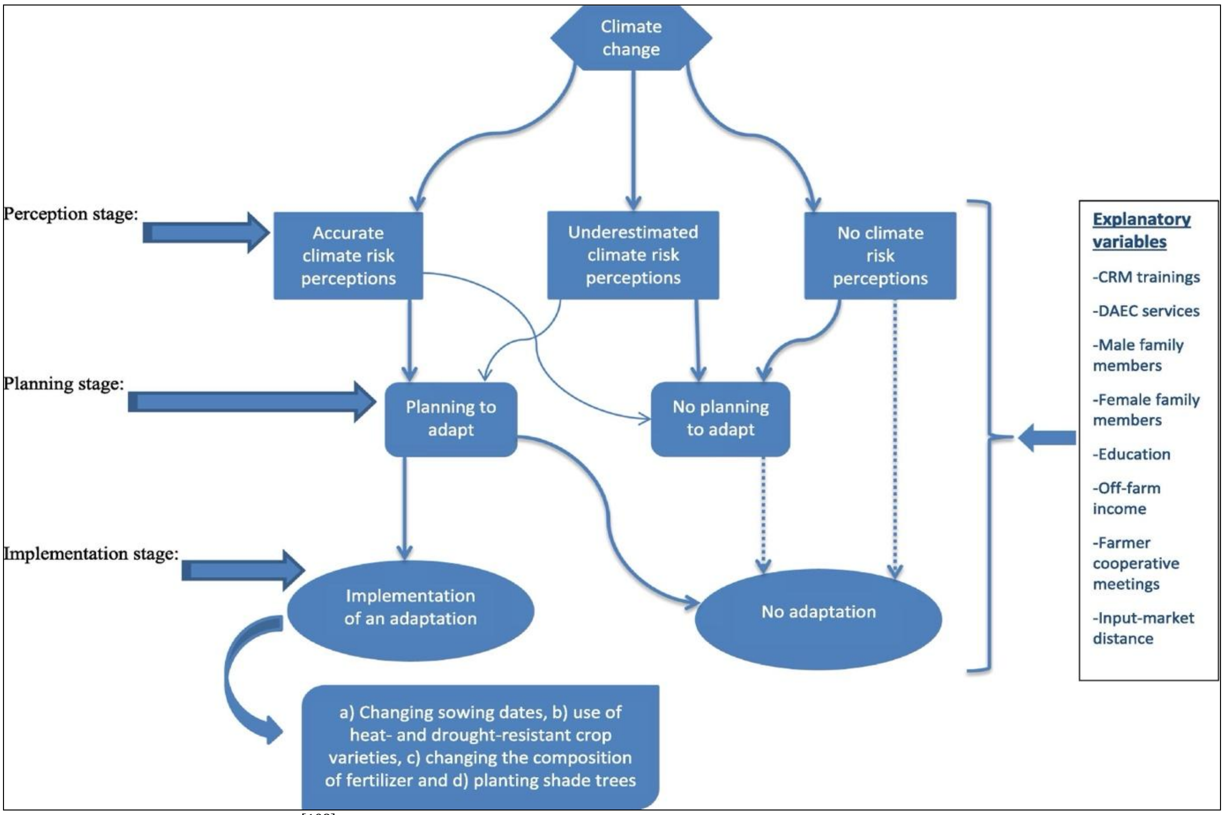
According to IPCC (2001) [85], adaptation at farm level is a potential strategy for building resilience to reduce climate vulnerability. It empowers rural households and communities by making them better equipped to prepare their farming systems for climate fluctuations, mitigate projected damages and bolster their ability to deal with extreme weather conditions. The adaptive response of farmers to climate change follows a structured, linear pathway, comprising three distinct stages that logically follow one another *viz.* perception (or accurate climate risk perception), intention (or adaptation planning) and implementation of an adaptation. A farmer's intention to adapt is ultimately determined by their perception, a stage which is mediated by a confluence of endogenous and exogenous factors (Abid *et al.*, 2019) [2].

However, misperceptions of climate risks among the farmers may lead to maladaptive practices, thereby increasing their vulnerability, consequently posing a significant threat to both food and livelihood security (Mahmood *et al.*, 2021) [108]. In this context, the initial stage is subdivided into two categories: "accurate climate risk perception" denoting the coherence between farmers' risk perception and historical climatic trends (i.e. temperature and rainfall) and "underestimated climate risk perceptions" which are marked by a discrepancy between these two. In order to reduce the climate vulnerability, accurate risk perceptions are perquisite for effective adaptation. In contrast, the underestimated risk perception results in maladaptation, characterised by poor planning or no adaptation at all.

The diagram depicts a linear unidirectional model of adaptation, wherein each stage functions as a precursor to the subsequent one. The strength of the association between consecutive stages is visually represented by the thickness of the arrows: bold arrows indicate a strong connection, whereas thin arrows denote a weaker link. Furthermore, dotted arrows delineate a pathway towards non-adaptation to climate-induced risks. The potential factors influencing this adaptation process are enumerated on the right-hand side of the figure.

2. Methodological approaches in assessing farmers' perception of climate change and adaptation strategies

Evaluating farmers' perceptions of climate change and their adaptation strategies necessitates multifaceted approaches that incorporate both qualitative and quantitative methodologies (Abid *et al.*, 2015) [1]. The collection of data generally involves surveys (utilising both structured and open-ended questions), interviews, and focus group discussions, followed by statistical analyses such as descriptive statistics, inferential statistics, and econometric models.



Source: Mahmood *et al.*, 2021 [108] (CRM- Climate Risk Management; DAEC- Digital Agricultural Extension and Communication)

2.1 A chronological analysis of methodological approaches for the period from 2015 to 2025

A clear evolution can be observed in the methodological approaches used to assess farmers' perceptions of climate change and their adaptation strategies from 2015 to 2025. Studies increasingly combine quantitative and qualitative methods, with a growing emphasis on statistical modelling and the integration of meteorological data.

Over the decade from 2015 to 2025, the assessment of farmers' perceptions of climate change and their adaptation strategies has experienced a significant methodological evolution. The shift in research from foundational techniques such as basic surveys and descriptive analysis to more advanced mixed-methods designs and statistical modelling is evident in the later studies. This progress, characterised by the increasing integration of both meteorological data and psychological constructs, has considerably improved the accuracy and policy relevance of findings in the field.

3.1.2.1.3 Change in cropping pattern and calendar of planting: Climate change disrupts agricultural systems through shifting rainfall patterns, forcing farmers to modify planting strategies. In Central Africa, staggered planting helps mitigate drought risks - some crops are sown before rains (dry planting), others after first showers (Urama & Ozor, 2011) [179]. This approach, documented in Tanzania (Liwenga, 2003; Adger *et al.*, 2005) [105, 5], maximizes water use while controlling weeds. Such calendar modifications represent crucial adaptations, enabling farmers to align cultivation with favourable weather windows and avoid extreme climate events during critical growth stages.

3.1.2.1.4 Mixed cropping: Mixed cropping combines complementary crops like cereals (maize, sorghum), legumes (beans), and oilseeds (groundnuts) in one field. This system offers multiple climate adaptation benefits: diversified maturity periods enhance drought tolerance, while legume-cereal combinations improve soil nitrogen and reduce pests (Liwenga, 2003) [105]. Compared to monocultures, intercropping provides more stable yields, better resource use efficiency, and higher nutritional value (Urama & Ozor, 2011) [179]. Together, these strategies help farmers buffer against rainfall variability and extreme weather events while maintaining productivity.

3.1.2.1.5 Improved irrigation efficiency: Effective climate adaptation in drought-prone regions hinges on water availability. Improved irrigation efficiency offers significant benefits even under moderate climate change scenarios (Selvaraju *et al.*, 2006) [158]. While irrigation counters warming impacts through more frequent application (Nkomo *et al.*, 2006) [133], its effectiveness varies, South African studies show mixed results (Ndhleve *et al.*, 2017) [124], and Swiss maize irrigation yields economic returns too small to justify costs despite boosting production (Finger *et al.*, 2011) [60].

3.1.2.1.6 Adopting soil conservation measures that conserve soil moisture: Asian farmers implement multiple climate-smart practices including: (1) optimized cropping schedules, (2) residue management (burying/burning), and (3) livestock-soil integration (Lema & Majule, 2009) [101]. Traditional techniques like pruning and organic fertilization combat desertification, while conservation agriculture (zero-tillage, mulching - Nyong *et al.*, 2007) [136] enhances carbon sequestration (Kapoor, 2020) [90]. Together, these integrated approaches deliver triple benefits: increased productivity, climate adaptation, and mitigation - forming a comprehensive strategy against climate impacts.

3.1.2.1.7 Planting of trees (afforestation) and agroforestry: Tree planting through agroforestry systems helps farmers adapt to climate change while delivering multiple benefits (Adesina *et al.*, 2011) [3]. Unlike natural regeneration, intentional seedling transplantation ensures faster, more reliable reforestation of degraded lands. African and Asian smallholders increasingly adopt these systems, which: 1) improve soil organic matter (Nyong *et al.*, 2007) [136], 2) enhance productivity under drier conditions, and 3) reduce deforestation pressure. Beyond carbon sequestration, agroforestry buffers against climate variability while providing economic and environmental co-benefits.

3.1.2.1.8 Agricultural biodiversity and crop germplasm exploration: Conserving diverse plant genetic material - including wild relatives and traditional varieties provides vital raw materials for breeding climate-tolerant crops. CRIDA's breakthrough with transgenic sorghum (Maheswari *et al.*, 2006) demonstrates how genetic engineering can enhance drought/salt tolerance, with modified seeds showing significantly improved germination under stress (Mertz *et al.*, 2010) [114]. Evaluating existing genetic diversity may reveal overlooked traits valuable for climate adaptation, making germplasm conservation a cost-effective strategy for developing resilient crop varieties to withstand temperature extremes, water scarcity, and other climate challenges.

3.1.2.2. Livestock adaptation strategies

5.1.2.2.1 Production adjustments: Changes in livestock practices could include: (i) integrated crop-livestock systems with improved pasture management, (2) adjusted seasonal operations, (3) ecosystem conservation measures, (4) modified grazing patterns, and (5) diversified production systems combining stall-feeding with rotational grazing (Venkateswarlu and Shanker, 2009; Mairura *et al.*, 2021) [181, 109]. These adaptive measures help maintain livestock productivity despite increasing climate variability and extreme weather events.

3.1.2.2.2 Breeding strategies: Many local breeds are already adapted to harsh living conditions. Adaptation strategies address not only the tolerance of livestock to heat, but also their ability to survive, grow and reproduce in conditions of poor nutrition, parasites and diseases. Such measures could include: (i) identifying and strengthening local breeds that have adapted to local climatic stress and feed sources and (ii) improving local genetics through cross-breeding with heat and disease tolerant breeds (Weinhofer and Hoffmann, 2010) [182].

3.1.2.2.3 Livestock management systems: Affordable climate adaptation solutions for resource-limited farmers include: (1) natural shade structures and water access points to combat heat stress; (2) maintaining smaller herds of higher-yielding livestock to reduce emissions (Batima *et al.*, 2013) [30]; (3) transitioning to larger, more climate-resilient animal breeds; and (4) implementing simple water management systems like rooftop rainwater harvesting, small dams, and efficient drip irrigation (Hoffmann, 2010) [82]. These cost-effective approaches help vulnerable farmers adapt without expensive technologies, focusing instead on optimizing existing resources and traditional knowledge to build climate resilience while maintaining productivity.

3.1.2.2.4 Capacity building for livestock keepers: There is a need to improve the capacity of livestock producers and herders to understand and deal with climate change increasing their awareness of global changes ((Venkateswarlu and Shanker, 2009) [181]. In addition, training in agro-ecological technologies and practices for the production and conservation of fodder improves the supply of animal feed and reduces malnutrition and mortality in herds.

3.1.2.3 Other adaptation strategies

3.1.2.3.1 Labour migration: Migration serves as a critical livelihood strategy, particularly for small farmers and landless labourers facing climate shocks (Brown *et al.*, 2007) [36]. Remittances help households cope with drought and food price volatility (Adesina *et al.*, 2011) [3]. Climate change is altering migration patterns, with increased rural-urban movement due to droughts and floods (IPCC, 2022) [84]. Research in Mexico shows a 10 per cent crop yield decline leads to 2% higher emigration (Feng *et al.*, 2014) [59], projecting 1.4-6.7 million climate migrants by 2080 from agricultural impacts alone.

3.1.2.3.2 Income diversification: Farmers increasingly turn to off-farm activities to compensate for climate-affected yields, as shown in Burkina Faso where dry-season gardening and non-farm work boosted household resilience (Mertz *et al.*, 2010) [114]. Nielsen & Reenberg (2010) [132] found communities shifting to climate-independent livelihoods, with national surveys revealing rising wealth across groups from 1998-2007. This demonstrates how income diversification, particularly in marginal areas, provides critical adaptation pathways, enabling long-term climate adjustment beyond traditional farming.

3.1.2.3.3 Purchase of insurance: Climate insurance reduces economic vulnerability by spreading risk across policyholders, enabling farmers to reinvest savings into productive and adaptive practices rather than emergency reserves (Brink and Wamsler, 2019) [34]. While effective for financial recovery, insurance has limitations: it doesn't mitigate physical hazards or emotional trauma, and may create moral hazard by reducing preventive measures. For instance, subsidized flood insurance can perpetuate risky floodplain settlement patterns (Liu *et al.*, 2018) [104].

3.1.2.3.4 Integrated Nutrient Management (INM) and Site-Specific Nutrient Management (SSNM): Innovative rice farming technologies demonstrate multiple benefits: 30-40% improved nitrogen efficiency, higher yields, and reduced greenhouse emissions. Practical solutions like neem-coated urea offer affordable emission reduction for South Asian smallholders. Integrated farming systems combining crops, livestock, and aquaculture enhance resilience through diversification (Brooks *et al.*, 2010; Snyder *et al.*, 2014) [35, 162]. These approaches collectively address productivity, adaptation and mitigation needs.

3.1.3 Information consolidation

Effective climate adaptation requires accessible platforms that integrate scientific data, local knowledge, and practical tools to support decision-making. Important elements include developing centralized portals for climate projections and risk assessments, improving early warning systems, and creating sector-specific advisory services tailored to farmers' needs (Raihan, 2023; Petersen, 2022; Kundo *et al.*, 2021) [150, 145, 96]. While such information systems help communities understand climate risks and potential solutions like heat-resistant crops or modified planting schedules must be paired with capacity-building programs to drive real change. Research shows that successful adaptation depends on combining data dissemination with hands-on training, policy support, and financial resources (IPCC, 2022; FAO, 2021) [84, 62]. However, overcoming barriers like limited digital access and varying literacy levels remains critical to ensuring these tools reach vulnerable populations.

3.1.4 Communication and Awareness

To the extent possible and as quickly as possible, it is important to initiate and encourage communication about risk and the provision of risk-related information to citizens and other concerned parties, while adequately considering and efficiently using existing structures and frameworks (Venkateswarlu and Shanker, 2009; Feng *et al.*, 2014) [181, 59]. This information is the basis for all adaptation measures, including decisions about implementing adaptation measures. For example: Risk-related information provision, communication about risk, and awareness-raising activities (combined with mitigation efforts) targeting citizens and businesses; Sharing of information among relevant government departments; Establishing supportive institutional arrangements; and creating collaborative arrangements among governments, research institutes, and NGOs (Lui *et al.*, 2018; Nielsen and Reenberg, 2010; Brown *et al.*, 2007) [104, 132, 36].

3.1.5 Political action: While governments traditionally lead adaptation efforts, democratic systems enable citizens to influence policy through voting, lobbying officials, and collective actions like petitions (Selvaraju *et al.*, 2006) [158]. For durable solutions, policymakers must combine climate projections with participatory decision-making, considering: (1) immediate implementation of high-priority measures, (2) phased approaches that incorporate emerging climate data, and (3) managed-risk strategies that allow for incremental improvements (Ndhleve *et al.*, 2017) [124]. Successful execution of strategies demands regional collaboration among stakeholders to align standards, share climate data, and build consensus on uncertainty management. Local governments should establish partnerships with neighbouring jurisdictions facing similar climate risks to coordinate planning, pool resources, and develop unified adaptation frameworks. This collaborative model ensures infrastructure investments account for projected conditions while maintaining public support through transparent, science-based decision processes alongside technical assessments.

3. Socio-economic determinants influencing adaptation decisions: Several works demonstrates that agricultural adaptation is shaped by multiple contextual factors including farm characteristics, ecological conditions, and socioeconomic circumstances (Eriksen *et al.,* 2011) [55]. Studies typically examine four key themes: (1) climate change perceptions (Apata, 2011; Deressa *et al.,* 2011) [17, 49], (2) impact assessments (Ngondjeb, 2013) [129], (3) adaptation strategies (Esham and Garforth, 2013) [56], and (4) implementation barriers (Bryan *et al.,* 2009) [37]. Common determinants include demographic factors (age, gender), economic resources (income, credit), and institutional access (extension services) (Gbetibouo *et al.,* 2010) [68]. Context-specific factors also emerge, such as cultural norms in Burkina Faso (Nielsen & Reenberg, 2010) [13] and belief 2systems (Arbuckle *et al.,* 2015) [19].

Considering the nature of these factors, as well as their similarities and differences, the important factors in our reviewed studies are categorized into the following five groups: demographic and socio-economic factors; resources, services and technologies; institutional and political factors; social and cultural factors; cognitive and psychological factors which are detailed as follows:

4.1. Demographic and socio-economic factors

4.1.1 Age: Farmers' age presents competing influences on adaptation choices. While older farmers' experience enhances climate awareness and promotes conservation practices (Deressa *et al.,* 2009; Hassan and Nhemachena, 2008) [50, 80], their risk aversion may limit innovative measures. Research shows age positively correlates with tree planting and irrigation adoption, as veteran farmers better recognize environmental changes. However, shorter planning horizons make older farmers 40% less likely to pursue livelihood diversification (Arega *et al.,* 2023) [20], particularly non-farm activities (Gebrehiwot and Veen, 2013) [69]. This paradox draws attention to how experience facilitates ecological adaptations while potentially hindering economic diversification strategies.

4.1.2 Gender: Research reveals contrasting gender-based adaptation approaches. Male farmers typically demonstrate greater risk tolerance, adopting new technologies (Asfaw and Admassie, 2004) [21], while female farmers often prefer traditional methods (Tenge *et al.,* 2004) [168]. However, Nhemachena and Hassan (2007) [130] found women more adaptive in regions where they dominate farming. Studies show women excel in conservation practices, yet face barriers implementing agronomic adaptations like crop diversification. These mixed findings underline how contextual factors shape gender roles in climate responses, with male household heads generally having better access to adaptation resources despite women's deeper engagement in daily agricultural operations.

4.1.3 Education

Household head's education level considerably determines climate adaptation, with each additional schooling year improving information processing and implementation of conservation practices (Deressa *et al.,* 2011) [49]. However, gender disparities persist: female-headed households demonstrate 32% lower adaptation rates despite greater climate vulnerability (Asrat and Simane, 2018) [22]. These households face triple constraints: (1) disproportionate domestic burdens, (2) limited resource access, and (3) economic disadvantages (Balew *et al.,* 2014) [29]. While educated farmers more readily adopt soil conservation and planting adjustments (Trinh *et al.,* 2018) [175], structural barriers prevent female heads from translating knowledge into action, underscoring need for gender-sensitive adaptation policies.

4.1.4 Labour force

Household labour availability substantially impacts farmers' capacity to implement climate adaptation strategies, with each additional worker increasing adaptation likelihood by 78.4% (Ndamani and Watanabe, 2016; Asrat and Simane, 2018) [122, 22]. Labour enables critical adjustments like crop diversification and soil improvement, particularly in low-mechanization contexts. However, Trinh *et al.* (2018) [175] found no significant labour-adaptation correlation, revealing contextual variations. Labour shortages create dual constraints: limiting agricultural adjustments and reducing income for adaptation investments (Al-amin *et al.,* 2020) [13]. Financially-stressed households often prioritize immediate needs over long-term resilience measures, demonstrating how labour and income factors interact to shape adaptive capacity.

4.1.5 Farm size

Research reveals contradictory findings about farm size's influence on adaptation strategies. While larger farms facilitate irrigation adoption (Gbetibouo, 2010) [68] and allow more land for soil conservation structures, smaller landholders often show greater conservation investment (Moser and Ekstrom, 2010) [117]. Interestingly, land area negatively correlates with livelihood diversification into non-farm activities. The prevailing hypothesis suggests farm size positively influences irrigation adoption, as larger operations can better absorb infrastructure costs and water requirements (Arega *et al.,* 2023; Ndamani and Watanabe, 2016; Tenge *et al.,* 2004) [20, 122, 168]. However, the relationship varies significantly across different adaptation measures and regional contexts.

4.1.6 Family/Household size

Family size significantly influences farmers' adoption of climate adaptation strategies, though with complex effects. Larger households possess greater labour capacity, facilitating implementation of labour-intensive measures like soil conservation and irrigation during peak seasons (Croppenstedt *et al.,* 2003; Deressa *et al.,* 2009) [45, 50]. This reduces reliance on costly hired labour. However, empirical evidence remains mixed - while some families leverage extra manpower for agricultural adaptation, others may divert labour to non-farm income generation to meet household consumption needs. The prevailing hypothesis suggests household size positively correlates with adoption of labour-demanding adaptation practices, as domestic labour availability often outweighs potential trade-offs in agricultural-focused households.

4.1.7 Farm income: Household income strongly affects farmers' capacity to implement climate adaptation strategies. Greater financial resources enable adoption of costlier, potentially more effective measures (Franzel, 1999) [63]. Research shows both farm and non-farm income affect adaptation choices differently: higher agricultural earnings support soil conservation and crop diversification, while non-farm income facilitates tree planting and irrigation (Deressa *et al.*, 2009) [50]. Overall, wealthier households demonstrate greater adaptive capacity, as income determines willingness and ability to invest in climate-resilient practices (Knowler and Bradshaw, 2007) [94].

4.1.8 Non-farm income: Studies reveal conflicting evidence about non-farm income's influence on agricultural adaptation. While some findings show each 10% increase in non-farm income reduces adaptation likelihood by 8.7 per cent due to reduced agricultural focus, other research contradicts this. Deressa *et al.* (2009) [50] and Asrat & Simane (2018) [22] found non-farm earnings actually enable adaptation by funding measures like new cultivars or irrigation. Although off-farm activities (e.g., construction, transport) provide crucial income, particularly during lean seasons, they may divert attention from farming. Many farmers perceive non-farm work as less risky and more immediately profitable than implementing climate adaptation strategies, potentially discouraging long-term agricultural investments.

4.2 Resources, services and technologies

4.2.1 Access to extension services: Extension services significantly increase adoption of adaptive measures like crop diversification and agroforestry (Deressa *et al.*, 2009) [50]. When combined with credit access and land security, these services create synergistic effects, enhancing farmers' adaptive capacity (Bryan *et al.*, 2009) [37]. Studies across Africa confirm that extension access, financial resources, and farm assets collectively determine adaptation success (Balew *et al.*, 2014; Gbetibouo *et al.*, 2010) [29, 68]. Extension officers provide critical climate-smart agricultural knowledge, enabling farmers to evaluate and select optimal practices (Gebrehiwot and Veen, 2013) [69]. This support system promotes informed decision-making regarding irrigation, planting schedules, and soil conservation techniques, ultimately building climate resilience in farming communities.

4.2.2 Access to information: Climate information availability significantly influences farmers' adaptive capacity. Constraints include limited access to both climate data (Kwaghe and Mohammed, 2013) [97] and adaptation knowledge (Muller and Shackleton, 2013) [119]. Studies demonstrate that weather information access boosts adoption of diversification strategies (Deressa *et al.*, 2009) [50] and enhances overall adaptation likelihood (Ndambiri *et al.*, 2012) [123]. Multiple agricultural systems confirm climate information as a critical determinant of adaptation choices (Alemayehu and Bewket, 2017; Gedefaw *et al.*, 2019) [14, 70], with temperature and rainfall data proving particularly impactful for implementing effective responses.

4.2.3 Access to technology: Better access to technology is critical for farmers' adaptation (Hassan & Nhemachena, 2008) [80]. The scarcity of technologies was identified as one of the major barriers to farmers' adaptation (Bello *et al.*, 2013; Salau *et al.*, 2012) [32, 155]. Farmers in were significantly constrained by a lac3k of improved agricultural technologies in adaptation to climate change (Ozor and Cynthia, 2010) [138].

4.2.4 Access to credit: Research demonstrates that financial capacity significantly enhances farmers' ability to implement climate adaptation strategies. Deressa *et al.* (2011) [49] and Gbetibouo (2010) [68] found that resource-endowed farmers more effectively utilize available information to adopt irrigation systems, improved agricultural inputs, drought-resistant crops, and livelihood diversification. Access to credit particularly helps overcome financial barriers, enabling farmers to modify practices in anticipation of climate changes. These findings advised credit availability positively influences adoption of: (1) irrigation technologies, (2) climate-adaptive measures, (3) drought-tolerant varieties, and (4) livelihood diversification through off-farm activities.

4.2.5 Market access: Proximity to markets significantly influences farmers' adoption of climate adaptation strategies, serving as a proxy for input/output market accessibility. Studies demonstrate that greater market distance reduces adaptation practice adoption (Maddison and Rehdanz, 2020) [107]. Nearby input markets facilitate access to essential resources like improved seeds and irrigation equipment, while output markets incentivize cash crop production that enhances adaptive capacity. Research in Africa (Maddison and Rehdanz, 2020) [107], the Philippines (Pandey, 2019) [141], and Nepal (Piya *et al.*, 2013) [148] consistently shows market proximity positively affects technology adoption. Remote households typically rely more on traditional coping mechanisms than modern adaptation strategies like crop diversification or water storage infrastructure.

4.2.6 Livestock ownership: Research presents conflicting evidence regarding how livestock ownership affects farmers' climate adaptation decisions. Teshome *et al.* (2016) [172] demonstrated a negative correlation, suggesting that livestock ownership may discourage the adoption of adaptive measures. Conversely, greater specialization in livestock production appears to reduce economic incentives for implementing adaptation strategies. Farmers with smaller herds often turn to off-farm and non-farm livelihood diversification as an adaptive response to meet their needs. These findings collectively suggest an inverse relationship between livestock ownership and the adoption of climate adaptation strategies.

4.2.7 Access to weather information: Farmers require targeted climate information at each production stage, including weather forecasts, pest alerts, and market data, to effectively adapt to climate change. Studies show information access boosts adoption of adaptive strategies: Nhemachena and Hassan (2018) found it promotes irrigation, drought-resistant crops, and livelihood diversification. Similarly, Deressa *et al.* (2011) [49] demonstrated improved adaptation through crop variety selection when farmers had better climate information access.

4.3 Institutional and political factors

Land tenure systems and institutional frameworks significantly shape farmers' adaptive capacity (Yegbemey *et al.,* 2013) [186]. Research reveals stark contrasts in effectiveness among institutions: NGOs and international organizations consistently support adaptation initiatives (Comoé and Siegrist, 2015) [44], while state institutions often fail to gain farmers' trust (Baudoin, 2013) [31]. Key institutional barriers include limited community-level political influence (Jones and Boyd, 2011) [88], restrictive natural resource policies, and inadequate government guidance (Wilk *et al.,* 2013) [184]. Policy misalignment further constrains adaptation, as unfavourable regulations frequently hinder implementation of adaptive measures (Bello *et al.,* 2013) [32]. These findings underline how institutional credibility and policy coherence critically determine the success of climate adaptation strategies in agricultural communities.

4.4 Social and Cultural Factors

4.4.1 Membership in a social group: Participation in farmer groups and cooperatives enhances access to critical resources like agricultural information, credit, and training opportunities. Tafa *et al.* (2015) [165] demonstrated that group membership significantly increases adoption of climate adaptation strategies, including conservation agriculture and drought-resistant crops. These social networks facilitate knowledge sharing and collective action, making them effective platforms for disseminating adaptive technologies. The study confirms that social capital through organized groups positively influences farmers' capacity to respond to climate variability.

4.4.2 Involvement in community organization: Farmers actively participating in community organizations are 8.32 times more likely to adapt to climate change effectively. These groups foster social engagement and mutual support, enhancing livelihoods. Regular involvement provides access to valuable information, skills, and resources, encouraging practical adaptation. By observing others' adaptation strategies within these organizations, farmers gain confidence in these practices, increasing adoption likelihood (Khanal *et al.* 2019) [92]. However, this contrasts with findings by Trinh *et al.* (2018) [175] and Piya *et al.* (2013) [148], who suggest that membership in local organizations has little impact on farmers' climate change adaptation.

4.5 Cognitive and psychological factors

Psychological and cognitive factors significantly influence farmers' adoption of climate adaptation strategies, though research in this area remains limited. The socio-cognitive model (Grothmann and Patt, 2005; Grothmann and Reusswig, 2006) [75, 76] provides a framework for understanding individual adaptation processes. Studies reveal that farmers' climate change beliefs strongly shape their adaptive responses (Kuehne, 2014) [95]. Those recognizing climate risks show greater willingness to implement adaptive measures, while skeptics often resist mitigation efforts (Arbuckle *et al.*, 2013) [18]. Important psychological determinants include: risk perception, perceived adaptation efficacy, cognitive biases (e.g., denial or fatalism), social pressures, and concerns about rising costs (Dang *et al.*, 2014; Truelove *et al.*, 2015) [46, 176]. Human cognition emerges as a critical factor in adaptation decisions (Esham & Garforth, 2013) [56], demonstrating that mental frameworks fundamentally influence farmers' engagement with climate challenges. These findings showcased the need to address psychological barriers alongside technical solutions in adaptation programs.

5. Constraints and barriers to climate change adaptation

5.1 Adaptations Constraints

The concept of barriers and limits, first outlined in the IPCC's Fourth Assessment Report (Adger *et al.*, 2007) [4], is now central to understanding constraints on climate adaptation. Current research examines where and how these barriers arise, recognizing their varied nature across disciplines (Dow *et al.*, 2013; Palutikof *et al.*, 2014) [51, 140]. The IPCC groups them into key categories such as knowledge gaps, technological limits, environmental and biological thresholds, financial and human resource constraints, sociocultural factors, and governance issues (Klein *et al.*, 2014) [93]. Eisenack *et al.* (2014) [53] view barriers as obstacles to specific actions, often shaped by competing priorities. This framework explains why adaptation may fall short, underscoring its complex and multidimensional challenges.

5.2 Characteristics of constraints of adaptation strategies

5.2.1 Knowledge, Awareness, and Technology Constraints: Persistent knowledge gaps remain a critical obstacle to climate adaptation globally (Tribbia & Moser, 2008; Pasquini *et al.*, 2013) [174, 143]. While awareness programs shape risk perception (Hamilton, 2011) [78], institutional-local perception gaps, and political influences (McCright & Dunlap, 2011) [113]. Effective knowledge application requires contextual dissemination methods (Tribbia & Moser, 2008) [174]. Technological adoption faces four key barriers: availability, affordability, social compatibility, and demonstrated effectiveness (Adger *et al.*, 2007; Van Aalst *et al.*, 2008) [4, 180]. Agricultural technologies show uneven adoption patterns (Parry *et al.*, 2009) [142] due to cost, maintenance complexity, and local suitability constraints. Successful adaptation requires integrated solutions combining: (1) tailored knowledge transfer, (2) appropriate technological packages, and (3) socioeconomic alignment with farmers' realities.

5.2.2 Physical constraints: The adaptive capacity of agriculture is strongly influenced by environmental factors, with the extent of climate change being especially critical. Adapting to a 4°C rise by 2100 will be far more difficult than smaller increases (Fung *et al.*, 2011; Nicholls *et al.*, 2011) [65, 131]. Physical barriers such as limited altitudinal range, coastal or river boundaries (Clark *et al.*, 2011) [43], and soil conditions (Lafleur *et al.,* 2010) [98] restrict species and forest migration. Land use changes also hinder responses, as seen in the Andes (Feeley & Silman, 2010) [58]. Farmers face major constraints from water scarcity, with many regions nearing sustainable limits (Pfister *et al.,* 2011) [146], affecting food and water security (Hanjra & Qureshi, 2010) [79]. Degraded soil and water quality further reduce adaptation potential (Lobell *et al.,* 2011) [106]. Nonetheless, these challenges can be mitigated through targeted resource management strategies.

5.2.3 Biological constraints: Research reveals significant biological limitations affecting farmers' adaptive capacity to climate change. Organisms' ability to tolerate climate stress through physiological, behavioural, or genetic adaptations influences agricultural resilience (Somero, 2010; Aitken *et al.*, 2011) [163, 9]. However, environmental degradation, including soil depletion and desertification, reduces ecosystem services critical for farming livelihoods (Lal *et al.*, 2011). Non-climatic pressures, such as habitat loss and pollution, further weaken ecological resilience, as seen in coral reefs, forests, and wetlands (Svenning & Sandel, 2013) [164]. Climate change may also disrupt pest and disease control, though predictive uncertainty remains high (Dukes *et al.*, 2009) [52]. These biological constraints, compounded by declining natural capital (Nelson *et al.*, 2010) [126], limit farmers' ability to sustain productivity under climate stress, necessitating adaptive strategies that restore ecological health alongside agricultural practices.

5.2.4 Economic constraints: Economic conditions strongly influence farmers' ability to adapt to climate change, with both long-term development and short-term fluctuations acting as constraints (Adger *et al.,* 2007) [4]. Economies reliant on climate-sensitive sectors face greater risks, while diversification generally supports resilience. However, activities like shrimp farming or mangrove conversion can worsen vulnerability by degrading natural defences. Urbanization in hazard-prone areas also heightens exposure to extreme weather and related losses (Baldassare *et al.,* 2010) [28]. Rapid economic growth may further strain ecosystems, limiting their adaptive capacity (Titus *et al.,* 2009) [173]. In contrast, sustainable, low-impact development can enhance resilience and reduce vulnerability, stressing the importance of climate-smart economic policies in agricultural regions.

5.2.5 Financial constraints: Financial barriers significantly limit farmers' ability to implement climate adaptation strategies. Access to various forms of capital - including credit, insurance, and household savings - often determines adaptive capacity (Paavola, 2008; Moser & Ekstrom, 2010) [139, 117]. African smallholders face particular challenges, where financial limitations heighten vulnerability to climate variability (Deressa *et al.,* 2011) [49]. Similar constraints affect Bangladeshi fishers (Islam *et al.*, 2014) [86] and South African municipalities (Pasquini *et al.*, 2013) [143]. Even in developed nations like Australia, local governments report cost barriers to climate adaptation (Gardner *et al.*, 2011) [66]. While insurance could facilitate risk management, rising costs and reduced accessibility often diminish its effectiveness (Islam *et al.*, 2014) [86]. These financial hurdles, spanning micro-level farmer needs to macro-level institutional budgets and critically constrain the adoption of adaptive measures across diverse agricultural contexts.

5.2.6 Human Resource constraints: Human resources are vital but often overlooked in farmers' climate change adaptation. They are discussed mainly in two ways: as part of adaptive capacity, such as public health (Ebi & Semenza, 2008), rural resilience (Nelson *et al.,* 2011), and leadership in institutional adaptation (Termeer *et al.,* 2012) [170]; and as limitations, requiring participatory approaches (Van Aalst *et al.,* 2008) [180] and capacity building. Education initiatives (Murphy *et al.,* 2007) [120] help, but shortages of expertise, leadership, and labour remain key barriers. Strengthening human capital through training and institutional support is therefore critical (Adger *et al.,* 2007) [4].

5.2.7 Social and Cultural Constraints: Social and cultural factors, including values, norms, and worldviews, shape farmers' climate adaptation by influencing risk perceptions, restricting choices, and creating unequal vulnerabilities (Moser & Ekstrom, 2010) [117]. The loss of traditional knowledge among Arctic Inuit communities reduces adaptive capacity, while lifestyle-driven migration to high-risk areas weakens risk awareness (Gordon *et al.,* 2013) [74]. In Nepal and India, gender norms limit women's adaptation through male-dominated land ownership (Jones & Boyd, 2011) [88] and restricted access to hazard information (Ahmed & Fajber, 2009) [7]. Emotional ties to land can also hinder adaptive actions (Fresque *et al.,* 2012) [64]. These barriers highlight the need for context-sensitive strategies.

5.2.8 Governance and institutional Constraints

The IPCC highlighted governance and institutional barriers as an important constraint in climate adaptation, particularly for farmers. Effective adaptation requires resource mobilization, policy implementation, and decision-making by institutions, but success depends on contextual alignment with local actors (Garschagen, 2013). Institutional capacity, often tied to adaptation prioritization, plays a crucial role (Westerhoff *et al.,* 2010) [183]. Similarly, adaptation efforts depend on broader institutional commitment to environmental management (Lesnikowski *et al.*, 2013) [103]. However, existing policies and institutional structures often misalign with adaptation goals (Huntjens *et al.*, 2012) [83]. Divergent perceptions across governance scales further complicate farmer adaptation, necessitating new bridging institutions to integrate multi-level planning. Thus, governance reforms are critical to overcoming institutional barriers in agricultural adaptation.

6. Comparative Insights across Agro-Ecological Zones of India: As a developing economy highly dependent on agriculture and other climate-sensitive sectors, India is particularly vulnerable to the impacts of global climate change. However, this vulnerability is not uniform across the country; it varies substantially across agro-ecological zones due to differences in climatic exposure, socio-economic sensitivity, and adaptive capacity. These regional disparities demand localized approaches to climate adaptation rather than one-size-fits-all solutions. Strengthening climate resilience in agriculture necessitates region-specific interventions grounded in a robust understanding of local ecological systems.

A landmark study by Singh *et al.* (2021) [159] assessed the resilience of Indian agriculture using a multi-scalar and multi-indicator framework. The authors developed a Climate-Resilient Agriculture Index composed of 26 indicators grouped under four major dimensions-environmental, technological, socio-economic, and institutional/infrastructural. Their analysis revealed clear inter- and intra-zonal differences in resilience levels. Among the agro-climatic zones, the West Coast Plains & Ghats and the Trans-Gangetic Plains exhibited relatively high resilience to climate risks, while the Eastern Himalayan Region, Middle Gangetic Plains, Eastern Plateau & Hills, and Western Dry Region recorded lower resilience. The study emphasized the need to identify region-specific drivers and constraints of resilience at finer scales, and called for strategic interventions that include resource conservation, infrastructure development, diversification, institutional strengthening, and the mainstreaming of climate adaptation into developmental policies.

6.1 Climate Change and Agricultural Vulnerability across Agro-Ecological Zones of Kerala

Kerala, with its diverse topography and microclimatic conditions, experiences wide variations in climate vulnerability across districts. Giridhar *et al.* (2022) [72] developed an Agricultural Climate Vulnerability Index (ACVI) for Kerala using 17 indicators aligned with the IPCC framework, encompassing the components of exposure, sensitivity, and adaptive capacity. The study revealed that Palakkad and Malappuram were among the most vulnerable districts, primarily due to high exposure and limited adaptive infrastructure. In contrast, Ernakulam and Alappuzha exhibited lower vulnerability, supported by robust socio-economic indicators and infrastructural readiness. The findings underscore the importance of tailored adaptation strategies based on the agro-ecological context of each zone. Instead of relying on generalized approaches, the study recommends localized responses such as climate-resilient cropping systems, infrastructural improvements, and grassroots institutional support to foster resilience in agriculture.

A district-level study conducted by Kerala Agricultural University (2023) highlighted the heightened climate risk in Wayanad, which lies at the interface of humid and semi-humid zones in Kerala's highland agro-ecological region. Due to its altitudinal gradient and location within the Western Ghats, Wayanad is particularly sensitive to climate extremes such as droughts, unseasonal rainfall, and flash floods. The study found that the district's geographic and climatic peculiarities amplify its exposure to erratic weather patterns. Importantly, it emphasized that Kerala's agro-ecological zones cannot be treated as a monolith; each region's unique topography and microclimate require customized adaptation strategies. This reinforces the broader argument that successful climate action in agriculture must be grounded in ecological specificity and localized planning.

Kerala's agro-ecological zones are increasingly fragile under extreme weather. The floods of 2018 and 2020, causing major crop losses and landslides, were linked to unusually intense monsoons amplified by intraseasonal phenomena such as Mixed Rossby-Gravity waves and the Madden-Julian Oscillation (Roxy *et al.*, 2021) [154]. The 2024 Wayanad landslides further highlighted the combined effects of climate variability, deforestation, and unregulated hillside development. With nearly 50% of the state classified as landslide-prone, densely populated and agriculture-dependent midland and highland regions face mounting risks. These events emphasize the urgency of integrating climate risk into land-use planning, watershed management, and agricultural programs in terrain-sensitive areas.

7. Gender and Social Equity in Climate Adaptation

Climate change does not affect all individuals equally; its impacts are mediated by existing social hierarchies and access to resources. Women, economically disadvantaged communities, and socially marginalized groups are often the most affected due to multiple forms of inequality. Gender intersects with class, caste, age, and geographic remoteness, influencing people's exposure to climate hazards and their adaptive capacity.

7.1 Understanding Gendered Vulnerability

Vulnerability to climate change is shaped not just by physical exposure, but also by unequal social structures. Women, particularly in rural and ecologically fragile areas like semi-arid zones, deltas, and mountainous basins, often have limited access to land ownership, credit, education, and institutional support. These disadvantages are compounded by unpaid domestic responsibilities and mobility restrictions, reducing their ability to adapt to climate stress. According to CARIAA (2018) [41], women, despite being perceived primarily as vulnerable, often demonstrate significant agency. In response to climate challenges and male out-migration, women are increasingly assuming new roles in farming, decision-making, and livelihood diversification. However, without supportive policies and institutional mechanisms, these shifts result in increased time burdens and limited empowerment.

7.2 Intersectionality in Adaptation Responses

An intersectional approach is essential to understanding how various identities compound climate vulnerability. Balan and Sreechandana (2025) [26] argue that a gender lens alone is insufficient; adaptation strategies must also consider caste, socio-economic status, education, and age. For example, a woman from a Scheduled Caste community in a drought-prone area may face overlapping disadvantages that a wealthier or upper-caste woman may not. Carr and Thompson (2016) [42], in their study from Bihar and Uttarakhand, highlight that climate adaptation is highly context-dependent. Power relations within households and communities influence who participates in planning and who benefits from adaptation interventions. Thus, adaptation must be locally grounded and socially responsive, enabling meaningful participation from diverse social groups.

7.3 Evidence from Kerala

In Kerala, recent climate events have shown how socio-economic disadvantages intersect with climate exposure.

George *et al.* (2022) [71] studied women in Wayanad during flood events and found that lack of access to financial institutions, weather information, and secure income made them particularly vulnerable. Enhancing financial inclusion and strengthening community-level information systems could significantly improve their adaptive capacity.

Pavanan *et al.* (2024) [144] assessed the experiences of female-headed households in Thrissur during the 2018 floods. These households reported higher economic losses due to limited financial literacy, dependence on informal employment, and weak institutional links. The study emphasizes the role of education, livelihood diversification, and support from Panchayati Raj Institutions in reducing vulnerability among women-led families.

7.4 Towards Inclusive and Equitable Adaptation

The reviewed literature emphasizes that adaptation policies must move beyond technical solutions and prioritize social justice. This means enabling marginalized communities including women, indigenous groups, and the poor to actively participate in decision-making processes. Policies should strengthen local institutions, enhance access to credit and information, and build networks that support collective resilience. Progressive steps like the inclusion of gender chapters in state climate plans (e.g., Odisha SAPCC) are encouraging, but more consistent, intersectional integration is needed. Kerala's institutions like *Kudumbashree* provide promising models for women-led adaptation and should be scaled and integrated into broader climate strategies.

8. Policy Interventions and Institutional Support Mechanisms: Addressing climate risks which not only threaten the country's ecological balance, but also severely impact agriculture, water resources, health, and livelihoods requires more than just technological innovations. A multi-layered response involving robust policy interventions, efficient governance, and coordinated institutional support is essential. Kerala, known for its ecological fragility, has been at the forefront of state-level climate action, offering localized models of governance that align with national climate goals.

8.1 National Climate Policy Framework

India took a significant step in formalizing its climate policy with the introduction of the National Action Plan on Climate Change (NAPCC) in 2008, initiated by the Ministry of Environment, Forest and Climate Change (MoEFCC). The NAPCC outlines eight national missions that target both mitigation and adaptation efforts. These include the National Mission on Sustainable Agriculture (NMSA), National Water Mission, National Solar Mission, and National Mission for a Green India, among others. Each mission addresses a specific vulnerability, aiming to build long-term resilience across critical sectors (MoEFCC, 2008) [115].

India's commitments under international agreements are reflected in its Nationally Determined Contributions (NDCs) submitted to the United Nations Framework Convention on Climate Change (UNFCCC). The updated NDCs, released in 2022, set ambitious targets such as reducing emissions intensity by 45% by 2030 compared to 2005 levels, increasing forest cover, and generating 50% of electricity from non-fossil sources. These targets are part of India's broader vision to align climate action with inclusive development and green growth (MoEFCC, 2022) [116].

8.2 Institutional Architecture for Climate Governance

India's climate governance operates across multiple layers. At the national level, the MoEFCC serves as the primary policy-making body, while implementation responsibilities are distributed across sectoral ministries. Scientific institutions like the Indian Meteorological Department (IMD) provide crucial data and forecasts. Financial institutions such as the National Bank for Agriculture and Rural Development (NABARD) oversee funding mechanisms, including the National Adaptation Fund for Climate Change (NAFCC), which supports state-led initiatives.

State-level institutions complement national efforts through Climate Change Cells, typically housed within environment departments. These cells are responsible for drafting and updating State Action Plans on Climate Change (SAPCCs). Collaborations with research institutions such as the Indian Council of Agricultural Research (ICAR), Indian Institute of Tropical Meteorology (IITM), and agricultural universities strengthen the technical basis for policy planning. However, institutional overlaps, weak inter-departmental coordination, and inadequate capacity at the local level remain persistent challenges.

8.3 Kerala's Climate Governance Strategies

Kerala has developed an adaptive climate governance model that integrates its socio-ecological specificity with national frameworks. The state's first SAPCC was published in 2014, followed by a revised version (SAPCC 2.0) in 2020. The updated plan emphasizes 13 key sectors, including agriculture, biodiversity, water, coastal management, and public health. SAPCC 2.0 aligns with the Sustainable Development Goals (SDGs) and emphasizes a climate-resilient development pathway (GoK, 2020) [73].

A distinctive aspect of Kerala's approach is the integration of climate planning with decentralized governance. Through the People's Planning Campaign, Local Self-Governments (LSGs) are empowered to incorporate climate resilience into their annual development plans. Institutions such as the Kerala State Disaster Management Authority (KSDMA), Directorate of Environment and Climate Change, and the Rebuild Kerala Initiative (RKI) play key roles in planning and implementation.

The RKI, launched post the 2018 floods, represents a paradigm shift toward long-term adaptation. Supported by the World Bank, it emphasizes resilient infrastructure, ecosystem restoration, and watershed management with a focus on nature-based solutions and community participation (World Bank, 2021) [185].

8.4 Key Challenges and Gaps

Despite robust frameworks, implementation gaps remain a critical concern. Coordination among departments is often fragmented, leading to inefficiencies. Financial constraints and procedural delays hamper the timely execution of projects, particularly at the grassroots level. Another important limitation is the insufficient focus on gender and social equity. While women, tribal communities, and economically weaker groups are frequently cited as vulnerable, they are rarely engaged as decision-makers in planning processes. Research by Singh *et al.* (2021) [160] underscores that climate policy in India often lacks meaningful gender integration, resulting in exclusion from adaptation benefits. Additionally, the availability of localized climate data and technical expertise is inadequate at the Panchayat level. While Kerala's local institutions are relatively proactive, their capacity for climate forecasting, vulnerability mapping, and impact assessment is still limited.

9. Emerging Trends and Innovative Approaches in Adaptation: Kerala's agricultural system stretches across saline coastal belts, fragile backwaters, humid midlands, and steep highlands. Each zone faces distinct climate risks. Coastal regions contend with sea-level rise, saline intrusion, and cyclones. Low-lying regions such as Kuttanad suffer from prolonged flooding and waterlogging. Midland zones face crop stress due to rainfall variability, while highlands are increasingly prone to landslides, soil erosion, and extreme heat episodes. These variations necessitate targeted interventions rather than a one-size-fits-all approach.

The Climate-Resilient and Energy-Efficient Agriculture (CREEA) programme has pioneered interventions like climate mapping tools, innovation hubs such as K-CRAIL, and community-based seed systems. These initiatives provide localized solutions by matching crop varieties and practices to zone-specific challenges.

9.1. Agro-Ecological Zone-Specific Adaptation Approaches: Coastal regions: Key risks include salinity intrusion, tidal flooding, cyclones, soil sodicity. Adaptation strategies are salt-tolerant crops & bio-saline farming, use tolerant rice and millets; apply organic amendments (compost, press-mud, green manures) to improve cation exchange capacity and buffer salinity; encourage halophyte fodders on bunds; alternate or co-culture brackish-water fish/shrimp with paddy on seasonal calendars; use sluice gates and field bunds to regulate salinity pulses and *Pokkali* rice-prawn rotation. Benefits are income diversification, saline soil rehabilitation, blue-green value chains.

Low-lying wetlands (e.g., *Kuttanad*): Deep waterlogging, prolonged submergence, machinery access constraints are the issues associated. The approaches can be use of staggered nurseries, synchronized community planting, and raised seedbeds to dodge early floods; floating agriculture ("*baira*"-inspired); polders and community pump scheduling: Maintain embankments; operate diesel/solar pumps under a shared calendar to lower costs Benefits of following these measures include maintaining rice landscapes and creating monsoon-season vegetable niches.

Midlands: To address erratic rainfall, heat spells, and pest surges in Kerala's midlands, farmers can adopt crop diversification by intercropping pulses, sesame, tubers, and vegetables with rice or coconut, and rotating crops to disrupt pest cycles and spread risk. Conservation agriculture practices such as minimum tillage, in-situ residue retention, cover crops like cowpea or sunhemp, and mulching help conserve soil moisture, reduce evaporation, and suppress weeds. Agroforestry systems combining coconut with cocoa, banana, vegetables, or pepper on live standards, along with boundary timber, further enhance resilience (Pillai *et al.*, 2024) [147]. These strategies collectively stabilize yields, improve soil organic carbon, and support pollinator habitats, though careful residue management is needed to prevent termite issues and strong market linkages are essential for diversified produce.

Highlands: In Kerala's highlands, farmers face slope erosion, dry spells, and rising night-time temperatures. Adaptation measures include soil and water conservation practices such as contour bunds, graded terraces, vegetative barriers (vetiver or leucaena), percolation pits, and trench-cum-bund systems. Spice resilience can be strengthened through shade regulation in pepper and cardamom, the use of live mulches, biochar, windbreaks, and climate-tolerant varieties. Micro-irrigation using drip or sprinkler systems, coupled with solar pumps and fertigation scheduled by tensiometers or soil-moisture sensors, enhances efficiency. These strategies reduce sediment loss, improve water productivity, and boost crop quality, though care must be taken to ensure safe terrace drainage and to monitor fertigation to avoid nutrient leaching.

9.2. Innovative Climate Resilience Practices

Kerala's adaptation framework increasingly draws on both indigenous and modern practices:

- **Traditional models:** The Pokkali system integrates rice and shrimp farming, mitigating salinity stress and sustaining livelihoods. *Kaipad* farming and homestead multi-cropping systems provide additional models of ecological resilience (Ramachandran *et al.*, 2023) [151].
- **Scientific innovations:** Improved rice varieties like KAU-Rice 179 and 180 tolerate salinity and flooding. Hybrid spice and horticultural varieties are being developed for heat and drought tolerance.
- **Digital agriculture:** Mobile-based weather advisories, decision-support tools, and AI-enabled crop health monitoring systems allow farmers to make informed choices. IoT-based soil moisture sensors, drone-assisted nutrient spraying, and GIS-enabled water management tools are increasingly applied.
- **Smart water management:** Solar-powered micro-irrigation systems, precision irrigation using drip and sprinkler networks, and AI-based water-use efficiency models optimize scarce water resources.
- **Blockchain and traceability:** Blockchain platforms are being piloted to ensure transparency in supply chains, enabling farmers to receive fair prices and reducing climate-related market shocks.
- **Climate-smart livestock management:** Improved breeds, fodder banks, methane-reducing feed additives, and biogas-based energy systems enhance livestock resilience while reducing emissions.
- **Renewable energy integration:** Solar dryers, biomass-powered cold storage, and decentralized renewable grids are strengthening farmer resilience against climate-linked energy disruptions.

10. Research Gaps and Future Perspectives

While Kerala has made progress, several gaps remain:

- **Integration of indigenous knowledge:** Traditional models like *Pokkali* and *Kaipad* farming need greater scientific validation and mainstreaming.
- **Zone-specific climate studies:** More long-term research on high-value crops such as spices, plantation crops, and fruit trees is essential.
- **Technology adoption barriers:** Despite promising tools, limited access to credit, infrastructure, and training prevents smallholders from adopting advanced technologies.
- **Policy and institutional gaps:** Successful pilot projects remain fragmented without adequate policy support or scaling mechanisms.
- **Socio-economic research:** Studies on gendered impacts of climate change, youth engagement in farming, and migration patterns remain insufficient.

Future directions should include

- Strengthening public-private partnerships to scale up precision agriculture and digital tools.
- Developing farmer-centric platforms for real-time climate and market information.
- Expanding community seed banks and bioresource centres for localized adaptation.
- Enhancing climate finance access for smallholders through insurance, subsidies, and carbon credit schemes.
- Promoting climate literacy through farmer field schools and digital training platforms.

Adapting agriculture to climate change in Kerala requires a multidimensional approach that integrates indigenous knowledge, scientific innovation, and advanced digital tools. From Pokkali farming to AI-enabled irrigation, these practices demonstrate pathways to resilience across diverse zones. Strengthening institutions, scaling localized successes, and embedding adaptive measures into policies are essential. The agricultural future of Kerala hinges on harmonizing ecological diversity, technological innovation, and community engagement to build a sustainable and climate-resilient farming system.

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