Assessing climate change impacts on agriculture and identifying adaptation strategies in Western Maharashtra with special reference to Kolhapur, Sangli, and Pune districts

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***Abstract*—Climate change is no longer a concern of the future; it is here and now, and it is slowly changing everyday life for the farmers in Western Maharashtra. Nothing-from how they grow their crops to manage the water to keep their livelihood afloat-is going to remain the same in these semi-arid regions. "This study gets down to what's really happening on the ground." Rising temperatures, erratic monsoons, repeated droughts, and soil that is not as productive-all are taking their heavy toll on farmers, especially those who continue to grow highly water-consuming crops such as sugarcane. Climatic records were collected, the soil was tested, field observations were made, and farmers themselves were consulted. And what was found was not very encouraging. More heat stress, wells that have dried up, rains that have ceased to be reliable, and a feeling of economic uncertainty on a day-to-day basis were all talks amongst farmers. This is disturbing farming practices that have stood the test of time. This study also discussed Traditional Ecological Knowledge, previously the bedrock of sustainable agriculture here; it is facing extinction. However, "the farmers were not waiting for the situation to improve." They are trying to adapt-crop changes, drip irrigation, mulching, planting weather-tolerant varieties of seeds. Yet, adaption is not uniform. Information, technology, and more so the money are creating rifts in society. The inference is clear: farming to be resilient in Western Maharashtra has to be climate-smart-that is more than just a catchphrase. It needs better policy, genuine farmer support services, and community-led actual water management. "This goes beyond data and trends; it is about people, their land, and their future." And time is running out-it is urgent to find adaptation solutions that work for both the land and the people who know it best.**

***Keywords*— Climate Change, Agricultural Vulnerability, Western Maharashtra, Soil Degradation, Rainfall Variability, Adaptation Strategies, Traditional Ecological Knowledge-TEK, Farmer Perceptions, Climate Resilient Agriculture, and Drought Impacts.**

I. INTRODUCTION

Many Indians rely on agriculture as their primary income source. Agriculture is also essential for India's food security and continues to play a major part in India's economy. Since independence, the Indian government has attempted to develop agriculture by implementing development programmes and providing support and technology to increase agricultural productivity. The Green Revolution and the introduction of hybrid and high-yielding varieties of crops helped make India self-sufficient in food production. However, climate change is one of the serious threats to sustain agriculture for the 21st century and is threatening agricultural advances that have been achieved.

The agriculture sector in India has been severely affected by climate change due to an increase in temperatures, extreme events, and the unpredictability of rainfall. India is one of the most vulnerable countries in terms of climate change impact. Some studies estimate that there will be a reduction of 20-25 per cent in farm income due to climate change in regions that rely on rainfall alone for the majority of crops. Reports show that Maharashtra has experienced increasing maximum and minimum temperatures and that there has been a rise in extreme and dramatic climatic weather since the late 20th century.

The Region of Western Maharashtra, which includes Kolhapur, Sangli, Pune, Satara, Solapur and Nashik, is significant in Agricultural Production and includes several different types of crop production including sugarcane, fruits, vegetables, grains and pulses. However, the area has been negatively impacted by an increase in Climate-related threats to agricultural production include delayed Monsoon seasons, extended droughts, intense heat, depletion of groundwater resources, soil erosion and flooding at various periods, which significantly affect agriculture in the region. The experience of Solapur and Sangli's drought events, which resulted in loss of crops, as well as extreme Rainfall Events that have occurred in Kolhapur and Pune indicates that the Region is vulnerable to Climate Change impacts. Rising temperatures are compounding the existing water-shortage problem through accelerated Evapotranspiration and problems associated with urban Water Over-extraction and depletion and competition for water resources threatening the viability of Agriculture, particularly for small and marginal farmers. Agriculture has experienced a decline in Ecological Resilience resulting from Climatic Challenges added to the existing Structural Issues within the Industry such as reliance on Water-Intensive crops and monoculture farming. Historically, Farmers have adapted to unpredictable changing climatic conditions through various adaptive strategies, including crop diversification and the use of Community Resource Management Methods. However, the influence of several adverse Institutional, Technological and Policy Developments on Food Production have weakened adaptive strategies, resulting in increasing vulnerability in Agriculture as a result of worsening Climate Conditions. As a result, Climate Smart Agriculture Methods and Adaptation Techniques are becoming increasingly necessary to sustain Agricultural Livelihoods and Agricultural Production. Modern Techniques That will Increase Resiliency Relies Heavily on:

II. REVIEW OF LITERATURE

Research Articles

Empirical research on agricultural vulnerability to climate change in Maharashtra continues to expand, with much of it now adopting integrated, multidimensional frameworks. Athare et al. (2024) are notable in this regard—they use the IPCC (2007) vulnerability framework to chart agricultural vulnerability across Maharashtra. They combine climate data from 1968 to 2017 with socio-economic and agricultural statistics. Their findings reveal pronounced regional disparities: Marathwada and Vidarbha emerge as the most vulnerable, largely due to high climate exposure and limited adaptive capacity. Western Maharashtra, particularly Pune, is less vulnerable—thanks to better infrastructure and stronger adaptive systems. However, even within Western Maharashtra, Sangli district stands out as high-risk. This highlights how broad regional categories can miss specific district-level challenges, strengthening the argument for more detailed, district-based assessments.

Swami and Parthasarathy (2024) take a long-term perspective, examining changes in agricultural vulnerability in Maharashtra over fifty years, from 1966 to 2015. Their indicator-based approach looks at shifts in exposure, such as monsoon variability and temperature, sensitivity, including barren land and fragmented holdings, and adaptive capacity, like human capital, assets, and land productivity. They demonstrate that vulnerability is not fixed—it changes with shifts in infrastructure, land use, and the quality of institutional support. Where districts build adaptive capacity, vulnerability decreases, even if climate pressures persist. The central message: policy and institutional actions are crucial for reducing vulnerability.

Water stress remains central to how climate change affects agriculture in Western Maharashtra. Thorat, N. R., through a detailed study, examines long-term trends in crop water requirements using the FAO-56 Penman–Monteith method across nine locations over 42 years. Focusing on rabi crops—wheat, tomato, maize, and potato—the study uncovers significant variations in water needs, both geographically and over time. Jalgaon and Solapur, for example, require more water. Trend analysis using Mann–Kendall tests and Sen’s slope estimators indicates changing irrigation demands. The implication: irrigation planning must be responsive to climate and tailored to local conditions.

Socio-economic vulnerability is also a major focus. Adhav et al. develop a Socio-economic Vulnerability Index (SeVI) for Maharashtra, using indicators of exposure, sensitivity, and adaptive capacity across 34 districts. Their results reveal stark inter-district differences. Sangli is among the most exposed, while Pune leads in adaptive capacity. Nandurbar is the most vulnerable overall; Pune, the least. The study underscores that vulnerability is shaped not just by climate, but by access to resources, infrastructure, and social support.

Environmental degradation further intensifies agricultural vulnerability. Vikash Singh et al. employ remote sensing and GIS tools, together with Spatial Principal Component Analysis (SPCA), to assess eco-environmental vulnerability in 2000 and 2011. Their findings are concerning: soil erosion and land degradation rose by over 50 percent on average, with vulnerability increasing particularly in dryland and semi-arid areas. These results illustrate how climate stress and human activity together have made ecosystems more fragile, emphasizing the urgent need for integrated land and water management strategies.

Books and Conceptual Literature

To truly grasp how climate change heightens the vulnerability of agriculture, it's essential to explore both conceptual analyses and policy-based literature. In his 2024 book Development and Deprivation Dimensions of Indian Economy, Dr. Sharanappa Saidapur emphasizes that economic growth doesn't fix all issues. Persistent regional inequalities and climate-driven deprivation remain, especially within farming communities. Saidapur applies the Sustainable Development Goals framework to illustrate how uneven progress and social exclusion intensify these challenges. Delving into the specifics of Indian agriculture, Govil and Tripathi's Agricultural Economy of India (2016) examines production systems, government policies, irrigation, subsidies, and rural development. They go beyond simple description—pointing out that small and marginal farmers repeatedly encounter deep-seated obstacles that policy alone hasn't resolved. While they argue for evidence-based policymaking, they also highlight the need for changes that tackle these underlying problems. Broader textbooks like Agricultural Economics by Subba Reddy and colleagues link together production, markets, resource management, and sustainability, placing climate change within the larger context of globalization, food security, and environmental decline. Some works focus specifically on sustainability. Farm Systems and Sustainable Agriculture, edited by Kalhapure, Dhonde, and Shete, advocates for integrated farming systems, agroforestry, and organic methods. The editors also underscore the critical importance of institutions and markets in supporting sustainable transitions—a point particularly relevant for semi-arid regions like Western Maharashtra, where climate adaptation is vital. For a more direct perspective on climate, R. R. Kelkar's Climate Change: A Holistic View connects climate impacts with equity, justice, and poverty, with a focus on developing countries. D. Lenka's Climate, Weather and Crop in India takes an in-depth look at how climate factors affect cropping systems nationwide, arguing that adjusting cropping patterns to fit local agro-climatic conditions is fundamental. Finally, adaptation is a major focus in works such as G. S. L. H. V. Prasad Rao's Climate Change Adaptation Strategies in Agriculture and Allied Sectors. Rao highlights the rising risk of extreme weather, urging crop diversification, the breeding of new varieties, and significant system reforms to adapt. Alongside this, Sustainable Crop Protection Strategies by Sardana, Bambawale, and Prasad advocates for integrated pest management, the application of indigenous knowledge, and precision agriculture—all strategies aimed at boosting agricultural resilience in a changing climate.

Literature Gap

A significant amount of research covers climate patterns, vulnerability, and adaptation in Maharashtra, but much of it remains general or focuses on a single aspect at a time. What's lacking is a comprehensive, district-level analysis that ties together climate exposure, agriculture's response, and the adaptation measures people take—all in one study. Western Maharashtra, particularly districts like Kolhapur, Sangli, and Pune, receive little attention regarding differences within the region itself. This study aims to address that gap. It compares these districts directly, examining how climate change unfolds locally and how adaptation strategies develop on the ground.

Rationale of the Study

This research explores how climate change is transforming agriculture in Maharashtra's Western Ghats, with a close look at soil properties and cropping systems. The team will purposely collect soil samples—not just at random—to get a clear sense of factors like pH, organic carbon, nutrient levels, and the soil's water-holding capacity, all of which are critical to crop health and yields in the region.

The Western Ghats are more than just another landscape; they're a biodiversity hotspot with a unique ecology, now feeling the mounting impacts of climate change. Understanding how changing weather patterns—such as rising temperatures and shifting rainfall—affect the very basis of farming is vital for the region's resilience. As climate variability becomes increasingly unpredictable, this study takes a targeted approach. It examines how soil health, pest outbreaks, crop yields, and the broader concept of sustainability react to new trends in temperature and rainfall. Agriculture responds quickly to climate change here, so the research will dig into adaptation and mitigation strategies tailored to the Ghats' specific agro-ecological conditions. The information from soil analysis will clearly show how climate change influences soil fertility. Building on these findings, the team plans to develop interventions that are not generic but fit the local farming context—practical, climate-smart solutions that farmers can actually use. Why is this important?

First, for food and nutritional security. As the world population increases, the pressure on agriculture intensifies. Climate change already threatens to reduce crop yields, and this is especially urgent in a region like the Western Ghats. By focusing on how these changes impact local soils, the study addresses the critical need to safeguard food supplies in an increasingly uncertain climate.

Second, it's about adaptation and mitigation. The research is not just about identifying problems; it's about building workable solutions. The results will provide farmers in the Ghats with a set of climate-smart agricultural practices that enhance both resilience and productivity. In a region where agriculture relies so closely on the environment, this is not just helpful—it's essential.

Third, the research stands out for its interdisciplinary approach. It combines soil science, practical farming knowledge, and climate modeling. This is not just theoretical work; it's about creating solutions that are scientifically robust, economically viable, and effective for those working the land.

Fourth, policy is a key factor. The insights gained will go beyond the farm. With real data, policymakers in Maharashtra and across India can use the findings to inform climate and agricultural policy, manage resources, and secure the region's agricultural future.

Finally, while the main focus is on the Western Ghats, the impact reaches much farther. The region acts as a global case study. What researchers discover here about soil, climate, and adaptation can inspire similar efforts in other climate-vulnerable regions worldwide.

Ultimately, this research aims to connect scientific understanding with the daily realities of farming. It's about building a future where agriculture in Maharashtra—and beyond—can withstand the challenges of climate change. By deepening knowledge of soil health in a warming world, the study empowers farmers, strengthens food security, and provides guidance for policies that help agriculture endure the worst impacts of climate change.

III. OBJECTIVES OF THE STUDY

The study aims to examine the impacts of climate change on agriculture in Western Maharashtra and to identify pathways for enhancing resilience. The specific objectives are:

1. To assess the current and perceived impacts of climate change on agriculture in Western Maharashtra, focusing on temperature variation, rainfall irregularities, and extreme weather events.
2. To identify agricultural and socio-economic vulnerabilities across crops, regions, and farming communities.
3. To analyse existing and potential adaptation strategies, including changes in farm practices, water management, and technology adoption.
4. To examine the role of Traditional Ecological Knowledge (TEK) in influencing resilience outcomes.
5. To evaluate the effectiveness and inclusivity of government schemes aimed at climate adaptation.
6. To assess knowledge-transfer mechanisms, particularly agricultural extension services, in promoting climate-resilient practices.

IV. RESEARCH METHODOLOGY

Objective 1: Assessing Climate Change Impacts

Climate-impact indicators relating to heat stress, rainfall irregularity, water scarcity, and crop loss were extracted from the survey dataset. Categorical responses were standardized and transformed into ordered or numeric variables, while percentage-range responses were converted into midpoint values to allow quantitative analysis. Descriptive statistics and graphical visualizations were used to examine severity and distribution of impacts. Correlation analysis identified interlinkages among climate stressors, and a composite Climate Impact Index was constructed to capture cumulative climatic pressure on agricultural systems.

Objective 2: Identifying Socio-Economic Vulnerabilities
Agricultural vulnerability was assessed using a composite framework combining climate challenges and crop sensitivity. Climate-related constraints were aggregated into a challenge score, while crops were classified into sensitivity tiers based on water dependence and climatic exposure. A Vulnerability Index was developed and categorized into Low, Medium, and High vulnerability levels. Cross-tabulations and inferential tests (Chi-square and Fisher's Exact tests) were applied to examine associations between vulnerability and socio-economic variables such as landholding size, income, and farming practices.

Objective 3: Adaptation Strategies and Farm Practices
Variables related to adaptation measures, technology use, irrigation methods, seed choice, and fertilizer practices were standardized. Binary adoption indicators were constructed for major adaptation options. Descriptive analysis and cross-tabulations mapped adaptation patterns across farm characteristics, while Chi-square tests identified statistically significant relationships, enabling identification of behavioural and structural drivers of adaptation.

Objective 4: Traditional Ecological Knowledge (TEK)
TEK was analysed using both historical and current practice indicators. A TEK Intensity Index (Low–Medium–High) was constructed based on the number of traditional practices currently in use. Comparative analysis assessed continuity, decline, and revival of TEK practices. Inferential tests examined associations between TEK intensity and outcomes such as crop loss, soil fertility decline, and climate stress.

Objective 5: Policy Effectiveness and Inclusivity
Government schemes were evaluated using a policy-funnel framework comprising awareness, access, and perceived benefit. Scheme responses were standardized, and benefit levels were recoded into a unified scale. Drop-off rates across funnel stages were analysed to identify implementation gaps. Inclusivity was assessed across landholding categories using Chi-square tests.

Objective 6: Capacity Building and Knowledge Transfer
Knowledge transfer was analysed through indicators related to awareness of Krishi Vigyan Kendras (KVKs), advisory access, and adoption of modern practices. Comparative analysis between KVK-aware and non-aware farmers employed cross-tabulations and Chi-square tests to evaluate extension effectiveness.

Research Design
This study adopts a mixed-methods approach, integrating data from household surveys with available climate and soil datasets. The analysis is guided by the IPCC's vulnerability framework, which defines climate risk as a function of exposure, sensitivity, and adaptive capacity. To reflect these components, I utilize several quantitative indicators sourced from climate, agricultural, and socio-economic data.

For each research objective, I establish a clear analytical pathway. This ensures methodological consistency and reliability of results. By combining descriptive statistics, composite indices, and inferential analyses, I am able to identify patterns and rigorously test my hypotheses.

Data Sources and tools
Climate data were sourced from the India Meteorological Department (IMD). Soil information combined primary field sampling with secondary records from the Soil Department, Pune. Socio-economic data were collected through a structured household survey. Data cleaning was conducted using Microsoft Excel, while statistical analysis and visualization were performed using R/RStudio and PAST software.

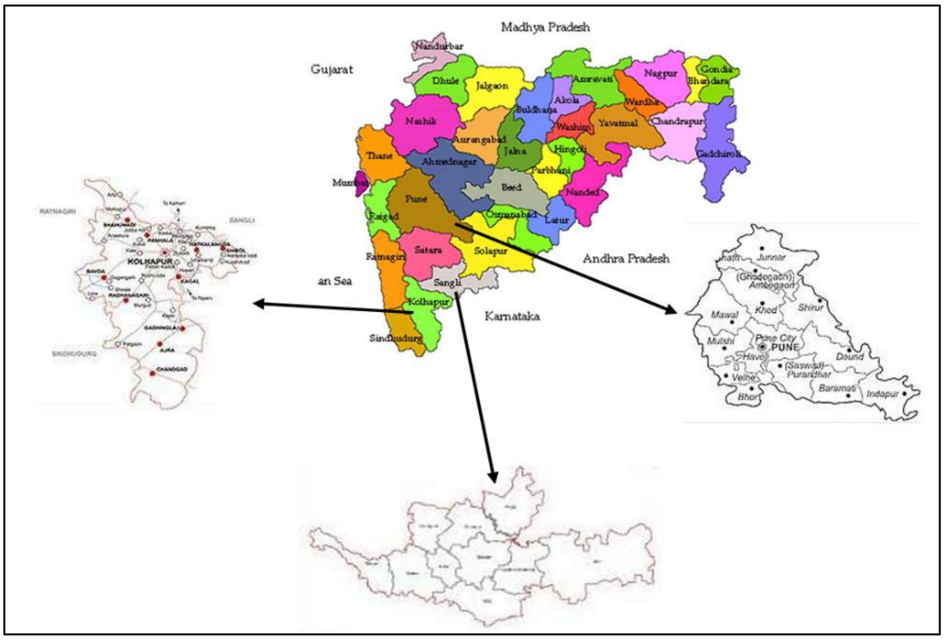

Figure 1: Study area description

V. STUDY AREA

The study covers Western Maharashtra, focusing on Kolhapur, Sangli, and Pune districts. These districts represent diverse agro-climatic conditions ranging from flood-prone high-rainfall zones to semi-arid regions, enabling comparative analysis of climate impacts and adaptation responses.

Limitations of the Study

The analysis is constrained by limited historical soil data and restricted field access in certain locations. Despite these limitations, the dataset provides robust insights into climate vulnerability and adaptation dynamics in Western Maharashtra.

VI. RESULTS

Climate Change Impacts on Agriculture

Climate change has become a structural constraint on agricultural production in Western Maharashtra. Farmers report widespread exposure to heatwaves, irregular rainfall, and water stress, indicating that short-term climatic variability and extreme events—rather than gradual shifts alone—are driving disruption. Heatwave impacts are largely of medium severity, reflecting persistent thermal stress across cropping systems. Rainfall-related problems are dominated by excess and irregular rainfall, with water scarcity acting as a reinforcing stressor where rainfall timing is unpredictable.

The composite Climate Impact Severity Index averages about 38%, confirming continuous climatic pressure rather than episodic shocks. Correlation analysis reveals strong interlinkages among irregular rainfall, excess rainfall, sudden weather changes, and production losses, while long-term rainfall decline shows weak association. This highlights climate variability as the dominant driver of agricultural risk

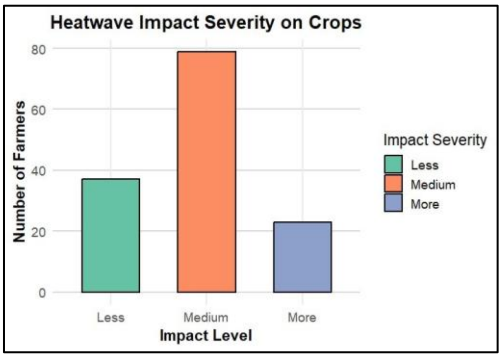

Figure 2: Heatwave Impact Severity on Crops

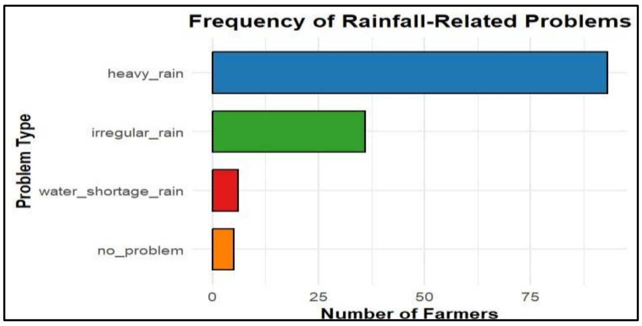

Figure 3: Frequency of Rainfall-Related Problems

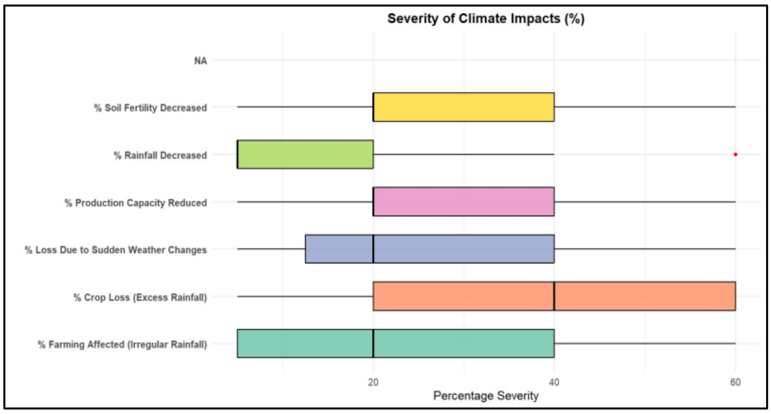

Figure 4: Average Severity of Climate Impact Variables

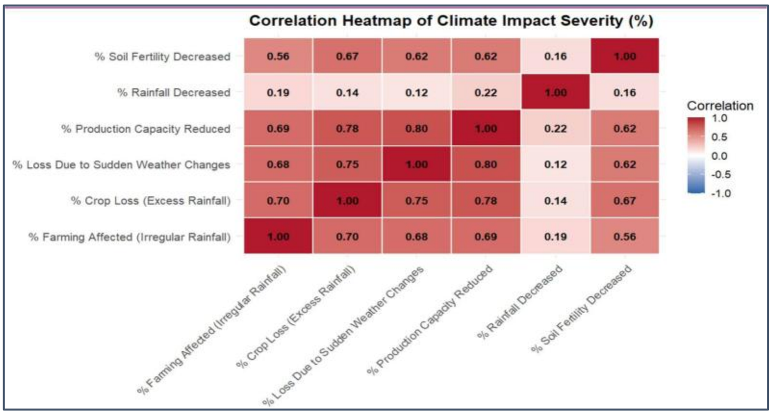

Figure 5: Distribution of Climate Impact Index

Crop Sensitivity and Socio-Economic Vulnerability

Vulnerability patterns show that climate impacts are unevenly distributed across crops and farmer groups. Sugarcane is the most climate-sensitive crop, followed by wheat, gram, and selected vegetables, reflecting high water dependence and sensitivity to rainfall variability. These patterns indicate that vulnerability is driven more by cropping choices than by climatic exposure alone. Socio-economic analysis reveals that small and semi-medium farmers face significantly higher vulnerability ($p < 0.05$) due to limited landholdings and restricted adaptive capacity. Land size and crop portfolios emerge as stronger predictors of vulnerability than income, underscoring the structural nature of agrarian risk.

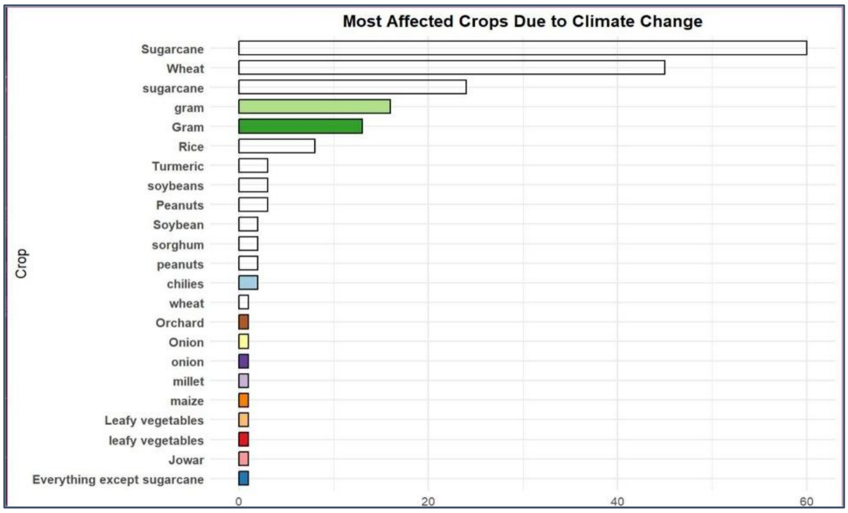

Figure 6: Most Affected Crops Due to Climate Change

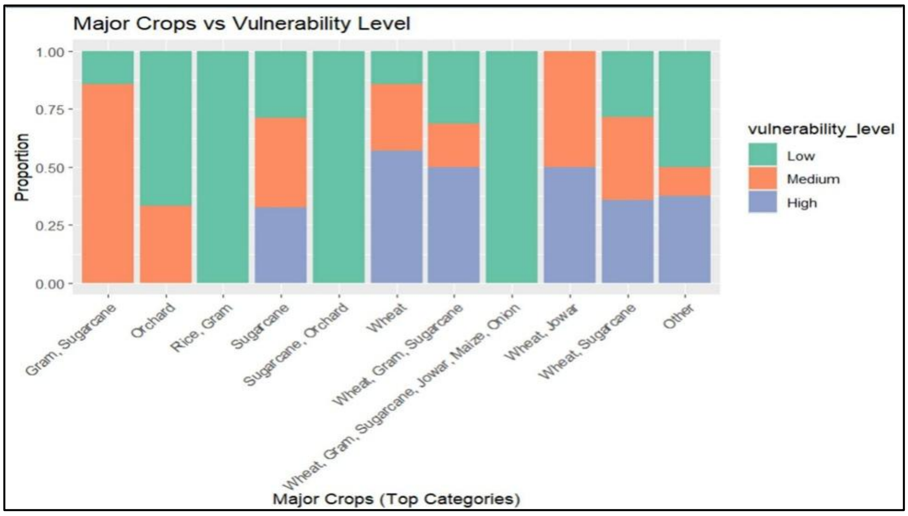

Figure 7: Crop Type × Vulnerability Level

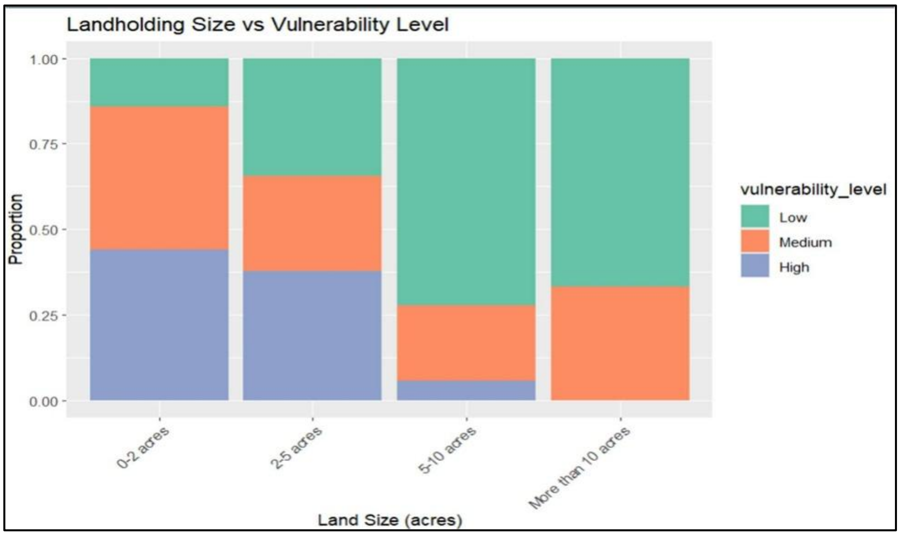

Figure 8: Landholding Size × Vulnerability

Adaptation Behaviour and Farm Practices

Farmers demonstrate partial but uneven adaptation responses to climate stress. Technology use and crop diversification are the most common strategies, followed by improvements in irrigation practices. However, nearly one-fifth of farmers report no adaptation, indicating persistent barriers to behavioural change. Adoption patterns are significantly associated with landholding size ($p < 0.05$), confirming that adaptive capacity is resource-dependent.

Farming systems strongly influence information access and input decisions. Monocropping farmers rely on a broader mix of advisory sources, while multicropping and mixed systems depend predominantly on personal experience, reflecting limited institutional engagement. Fertilizer choices further reveal contrasting cultivation philosophies: chemical fertilizer use is closely tied to short-term production goals, whereas organic manure users prioritise soil health and long-term sustainability. These statistically significant associations demonstrate that adaptation is not uniform but shaped by structural and behavioural factors.

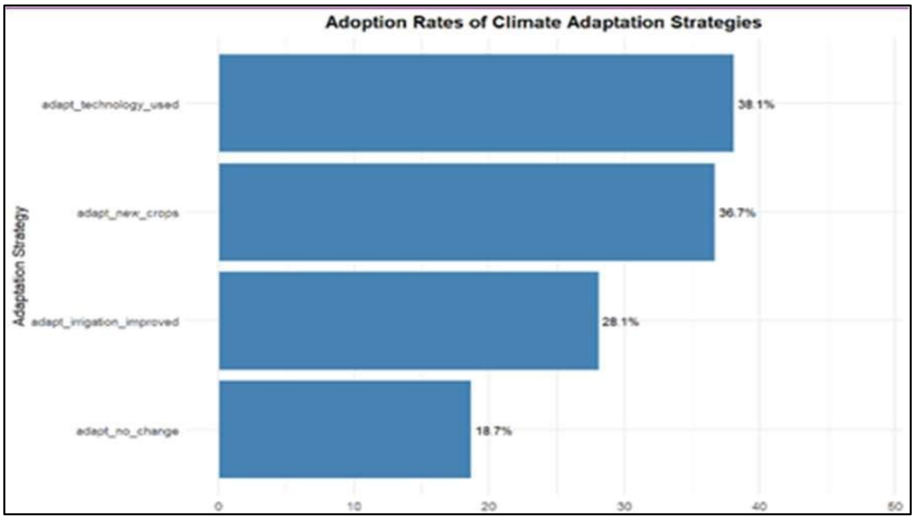

Figure 9: Adoption of Climate Adaptation Strategies

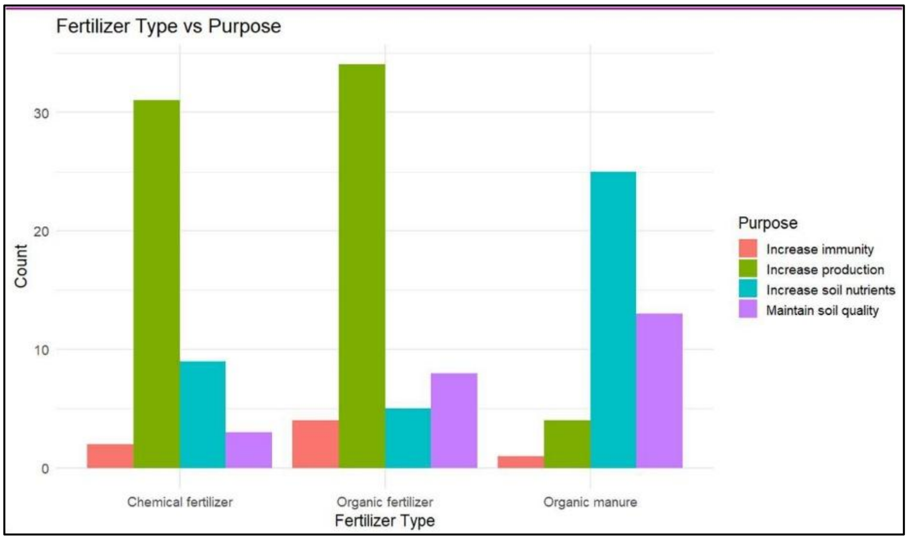

Figure 10: Farming Method × Fertilizer Guidance Source

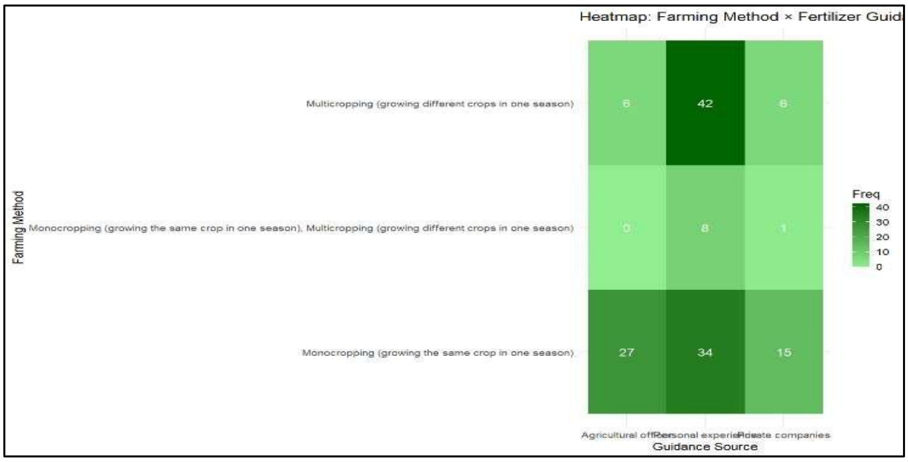

Figure 11: Fertilizer Type × Fertilizer Purpose

Traditional Ecological Knowledge (TEK)

Traditional Ecological Knowledge has undergone significant transformation. Historical analysis shows that practices such as neem-based pest control, traditional irrigation, and seed preservation have declined sharply, while intercropping shows modest revival. Current TEK usage is largely selective rather than holistic, with only a small proportion of farmers classified as high-intensity TEK users.

Statistical analysis reveals no significant association between TEK intensity and most climate impact outcomes, suggesting that current levels of TEK practice are insufficient to generate measurable resilience benefits at scale. However, farmers who continue TEK practices report better soil health outcomes ($p < 0.05$), indicating retained ecological value. The findings suggest that TEK has not become ineffective, but fragmented and inadequately integrated into contemporary farming systems.

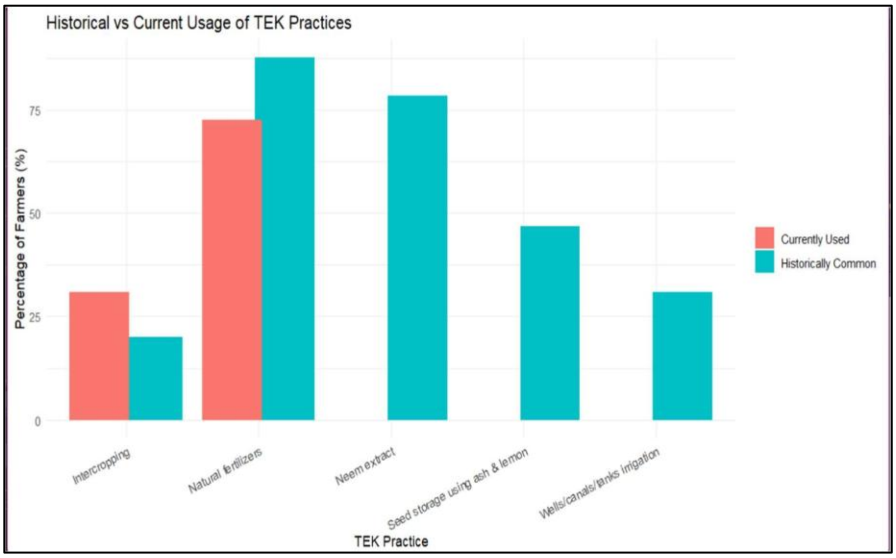

Figure 12: Historical vs Current Usage of TEK Practices

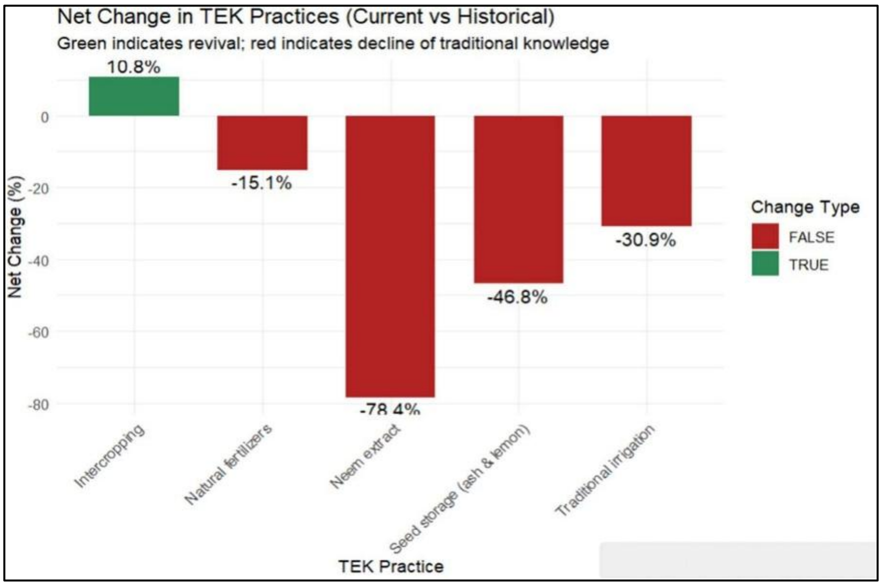

Figure 13: Net Change in TEK Practices

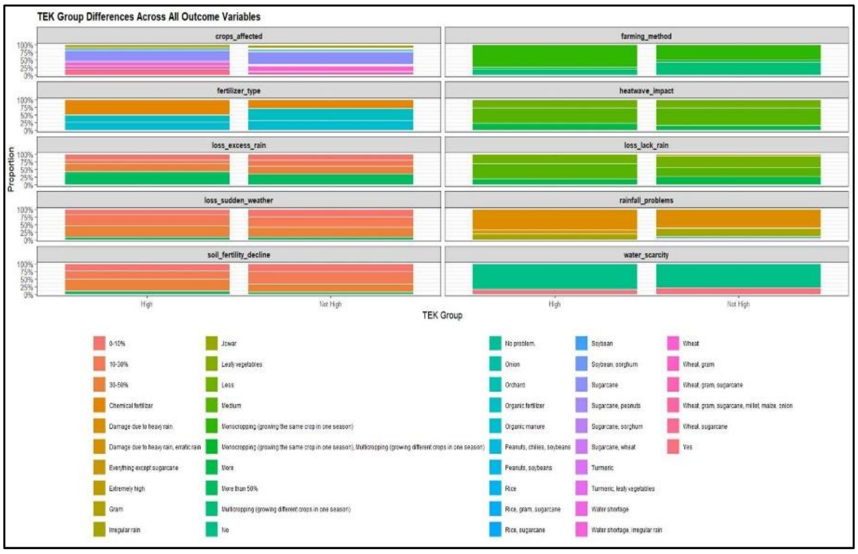

Figure 14: TEK Intensity × Climate and Farm Outcomes

Policy Effectiveness and Inclusivity

Evaluation of government schemes reveals a clear implementation gap. Although policy awareness among farmers is relatively high, it rarely translates into actual access or perceived benefit. Drop-offs across policy stages indicate weak targeting and limited inclusivity, especially for small and marginal farmers. Statistical tests show uneven participation and outcomes across landholding categories, pointing to structural exclusion rather than information deficits. Overall, policy effectiveness is constrained by delivery mechanisms and institutional reach, limiting the ability of existing schemes to meaningfully offset climate vulnerability.

Role of Krishi Vigyan Kendras (KVKs) and Knowledge Transfer

Engagement with Krishi Vigyan Kendras exerts a strong and statistically significant influence on adaptive behaviour. KVK-aware farmers show substantially higher adoption of improved water management, diversified cropping systems, climate adaptation actions, and sustainable fertilizer use, with adoption rates 30–45% higher across key practices ($p < 0.01$). Unlike general policy awareness, KVK engagement generates tangible behavioural change, underscoring the effectiveness of localized, continuous extension services in strengthening climate resilience where policy-based mechanisms fall short.

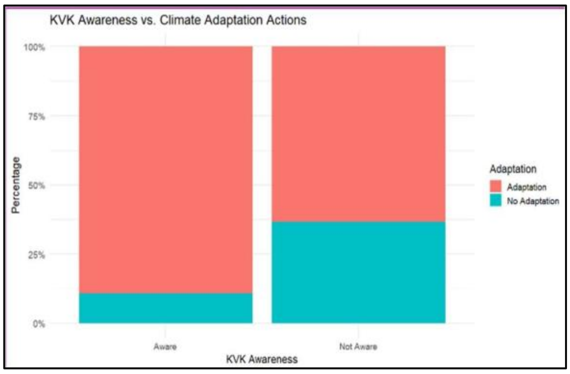

Figure 15: KVK Awareness × Climate Adaptation

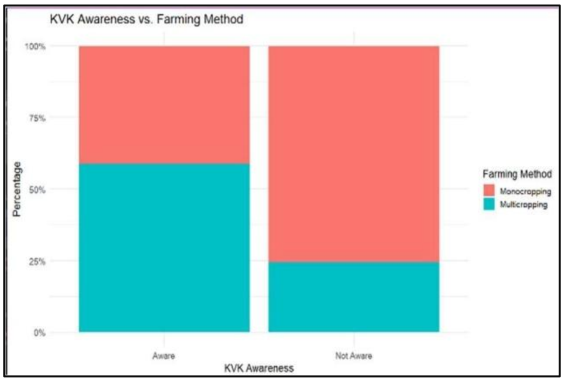

Figure 16: KVK Awareness × Farming Method

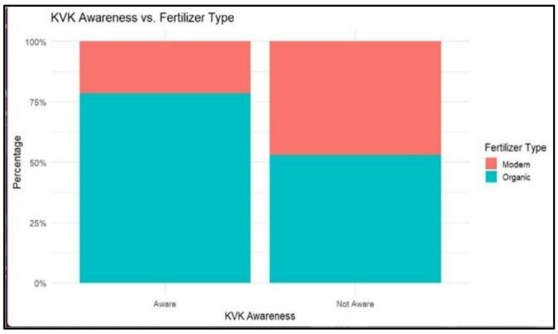

Figure 17: KVK Awareness × Fertilizer Type

VII. CONCLUSION

The results from the study revealed that global warming has changed current growing conditions in the agricultural area of western Maharashtra, with the greatest impacts including extreme heat events or periods of no rainfall (drought) and lack of available water. Together, these three phenomena are causing many farmers within this region to have decreased production; loss of soil quality; and ultimately loss of revenues and livelihoods. The most vulnerable groups were smallholders and marginal farmers, but the groups most at risk are also farmers relying on climate-dependent crops. Adaptation efforts exist within the region, but are not uniformly occurring, creating additional gaps in resilience strategies. Furthermore, TEK is declining as an effective avenue to increase sustainable agricultural production; while the government-sponsored agricultural research stations (KVK) are an increasing source of support for many vulnerable farmers who are attempting to adapt. Therefore, the presence of climate change will lead to an increase in vulnerability in the western Maharashtra agricultural sector, which will require an integrated and inclusive response by policymakers based on the four components mentioned above.

VIII. POLICY RECOMMENDATIONS

1. Prioritize water-centric adaptation through expanded drip irrigation, rainwater harvesting, and groundwater recharge, with higher subsidies for small farmers.
2. Promote crop diversification away from high-risk crops toward drought-resilient alternatives, supported by price incentives and market assurance.
3. Target small and marginal farmers with climate-adaptation credit, insurance, and input support.
4. Revive and integrate TEK into extension systems through documentation and scientific validation.
5. Strengthen KVKs via increased staffing, regular field demonstrations, and follow-up support.
6. Improve scheme implementation and monitoring, focusing on outcomes rather than enrolment.

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ICAR Agricultural Extension Division: https://icar.org.in/agricultural-extension-division/achievements-agricultural-extension-division

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Fertilizer Subsidy Information: https://www.fert.nic.in/fertilizer-subsidy
Bank of Maharashtra – Agriculture Loans: https://bankofmaharashtra.in/agricultures