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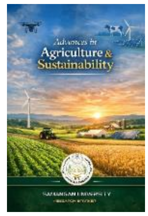

Stakeholders' Perspectives on Technological and Policy Approaches to Climate Resilience and Sustainable Development in Crop–Livestock Systems

Mohammad Daud Surkhabi [1], Besmullah Musammim [1*], Mohammad Qaseem [1], Sayed Noorullah Sadat [1]
[1] *Animal Science, Agriculture, Balkh University*
[*] *Corresponding Author:* Besmullahmusammim012@gmail.com

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Agricultural policy; Climate resilience; Crop–livestock systems; Food security; Stakeholder perception; Sustainable agriculture; Technology adoption

Research/Review Article

Abstract

Climate change is one of the most critical challenges facing crop–livestock systems, posing significant risks to food security and sustainable agricultural production. Despite growing research on agricultural adaptation, limited studies have examined stakeholders' perspectives on technological innovations and policy approaches for enhancing climate resilience in integrated crop–livestock systems, particularly in the study region. This study aimed to address this gap by investigating these perspectives using a survey-based design with a structured questionnaire. The study population included agricultural experts, livestock specialists, researchers, faculty members, and policymakers, with a total of 385 respondents. Data were analyzed using SPSS software through descriptive statistics, including mean, standard deviation, frequency, and percentage. The findings suggest that respondents perceive current agricultural systems as vulnerable to climate change (Mean = 4.52) and strongly support the necessity of climate resilience (Mean = 4.56), the role of modern technologies (Mean = 4.26), the importance of economic incentives (Mean = 4.45), and the alignment of agricultural policies with Sustainable Development Goals (Mean = 4.34). These results indicate that integrating technology, economic instruments, and institutional policy coordination may help reduce production vulnerability and enhance food security. Overall, the study provides evidence-based insights that can inform the design of sustainable agricultural policies in similar contexts

1. Introduction

Integrated crop–livestock systems are particularly vulnerable to climate variability because they rely simultaneously on soil fertility, water availability, feed resources, and animal health, creating multiple exposure pathways to climatic shocks. Unlike specialized monocropping systems, these integrated systems depend on complex ecological feedback loops between crop residues, forage production, manure recycling, and livestock performance. Climate-induced disruptions in any single component can cascade through the entire production cycle. Recent empirical assessments highlight that soil degradation, accelerated nutrient depletion, and declining organic matter content are increasingly observed under conditions of prolonged drought and erratic rainfall *(Herrero et al., 2021).* These soil changes directly affect crop productivity while also limiting forage availability, thereby constraining livestock feeding systems.

Livestock heat stress has emerged as another critical concern. Rising temperatures alter animal physiology, reduce feed intake, impair reproductive performance, and increase disease susceptibility. In semi-arid and arid regions, the combined effects of thermal stress and water scarcity create compounding risks, leading to simultaneous reductions in crop yields and animal productivity *(Thornton et al., 2021).* Such dual impacts weaken income stability, reduce farm resilience, and heighten vulnerability among rural households. Importantly, these risks are not evenly distributed; smallholders and resource-constrained farmers often lack the adaptive capacity needed to buffer against climate variability.

In response to these growing vulnerabilities, recent literature increasingly emphasizes systemic agricultural transitions rather than incremental adjustments. Climate-smart and regenerative agriculture frameworks propose integrated strategies that simultaneously enhance productivity, strengthen adaptive capacity, and mitigate environmental impacts *(Campbell et al., 2020).* These approaches promote diversification, improved soil management, agroecological practices, and adaptive livestock feeding strategies. Digital agriculture tools—including remote sensing, climate forecasting platforms, precision irrigation systems, and data-driven livestock monitoring—are increasingly recognized as transformative instruments for reducing production risk *(World Bank, 2021).* By improving decision-making accuracy and resource efficiency, such technologies can enhance both short-term responsiveness and long-term resilience.

However, technological innovation alone does not guarantee sustainable transformation. Scaling these innovations requires enabling policy environments, access to finance, institutional trust, and well-designed extension systems. Evidence suggests that adoption rates are strongly influenced by economic incentives, risk-sharing mechanisms, and access to reliable information networks. Without targeted policy support, technological advancements often remain confined to pilot projects or resource-rich producers.

Governance structures and multi-level coordination mechanisms therefore play a decisive role in adaptation success. Climate resilience in integrated systems depends on coherent agricultural, environmental, and economic policies that operate synergistically rather than in isolation. Fragmented governance can lead to contradictory incentives, inefficiencies, and limited scalability of innovations *(Béné et al., 2021).* Furthermore, sustainable agricultural investment is contingent upon economic instruments that reduce uncertainty and encourage long-term planning. Subsidy reforms, climate risk insurance schemes, and green financing initiatives are increasingly viewed as essential tools for supporting system-wide resilience *(Pretty et al., 2021).*

Alignment with the Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger) and SDG 13 (Climate Action), further underscores the need for integrated governance and stakeholder participation *(Sachs et al., 2023).* Achieving these objectives requires more than technological deployment; it demands inclusive policy design, cross-sectoral collaboration, and institutional accountability. Recent global assessments emphasize that agricultural transformation pathways must incorporate local knowledge systems and stakeholder perspectives to ensure legitimacy and long-term effectiveness *(Barrett et al., 2020).*

Despite the expansion of climate modeling and scenario analysis studies, empirical investigations examining how stakeholders perceive the interaction between technology and policy integration remain relatively scarce *(van Dijk et al., 2021).* This gap is particularly significant in integrated crop–livestock systems, where adaptation outcomes depend heavily on coordinated decision-making among producers, experts, and policymakers. Understanding these perceptions is therefore essential for designing context-sensitive, scalable, and socially acceptable resilience strategies.

2. Material and Methods

This study employed a quantitative survey design to explore stakeholders' perceptions of climate resilience, technology adoption, sustainable agriculture, and policy alignment in integrated crop–livestock systems. A structured questionnaire with 18 items was developed by the researchers and used a five-point Likert scale ranging from "strongly disagree" (1) to "strongly agree" (5). The items were organized into four main constructs: climate resilience and vulnerability, technology transfer and innovation adoption, sustainable development and food security, and policy coordination and stakeholder participation. Two additional items assessed general attitudes toward sustainable agriculture. The questionnaire's content validity was confirmed by experts in agriculture and policy, and reliability analysis showed good internal consistency for all constructs (Cronbach's alpha > 0.7).

The study population included agricultural experts, livestock specialists, policymakers, faculty members, and researchers involved in crop–livestock systems. Because the total population size was unknown, a sample of 385 respondents was calculated using Cochran's formula with a 5% margin of error and 95% confidence level. A census approach was employed, in which all selected participants were invited to participate, resulting in a 100% response rate. Most respondents were crop specialists (44.4%) and livestock specialists (33%), with policymakers (11.2%), faculty members (6.8%), and researchers (4.7%) also represented. Regarding education, most had a bachelor's degree (61.6%) or a master's degree (27.8%), and their professional experience ranged from less than five years to over fifteen years in the sector.

Each of the 18 items was treated as a continuous variable, and composite indices for each construct were calculated by averaging the related items. This approach is consistent with standard practice in social science research, where Likert scales with five or more points are often treated as approximately continuous, especially when the data distribution is near-normal (Norman, 2010; Carifio & Perla, 2008). The constructs were defined as follows: climate resilience perception captured stakeholders' views on vulnerability and the importance of resilience; technology adoption perception measured views on advanced technologies, technology transfer, economic incentives, and policy integration; sustainable development perception assessed contributions to food security and rural livelihoods; and policy and institutional coordination measured alignment with Sustainable Development Goals, inter-institutional coordination, and stakeholder participation. These indices served as the basis for further analyses, including correlation and multiple regression, to examine relationships between independent variables (technology, economic incentives, policy) and dependent variables (perceived resilience, sustainable development).

Data were collected using self-administered questionnaires, either online or in paper form. Participation was voluntary, and informed consent was obtained from all respondents. All questionnaires were fully completed, with no missing data (N = 385). Data analysis was performed in SPSS version 26, with descriptive statistics including mean, median, standard deviation, minimum, and maximum calculated for all variables. The dataset was also prepared for SWOT

Composite indices were calculated mathematically as follows:

$$CI_k = \frac{\left(\Sigma_{\{i=1\}}{}^{\{n\}X}_{\{ik\}}\right)}{n} n\,, for\ k\ =\ 1,2,\ldots,5$$

where XikX_{ik}Xik represents the Likert score of respondent iii for item kkk, and nnn is the number of items in that construct. All equations were formatted using MathType or Microsoft Equation Editor and numbered sequentially.

Overall, this methodology was designed to be transparent, reproducible, and aligned with international journal standards, allowing other researchers to replicate the study under similar conditions. It also ensures that the data are ready for advanced analyses to explore the interactions among technology, policy, and climate-resilient practices in crop–livestock systems.

3. Results

Most respondents held a bachelor's degree (61.6%), and the majority were crop or livestock specialists (77.4%). Professional experience was distributed across all categories, with roughly one-third of respondents in both the <5 years and >15 years groups. These characteristics indicate that the insights collected come primarily from experienced practitioners in crop–livestock systems, providing a solid foundation for understanding stakeholders' perceptions and attitudes. . The following table (Table 1) summarizes these results.

Table 1. Demographic and Professional Characteristics of Respondents

Variable	Category	N	%
Education	Bachelor	237	61.6
	Master	107	27.8
	PhD	40	10.4
	Postdoctoral	1	0.3
Professional Background	Crop Specialist	171	44.4
	Livestock Specialist	127	33.0
	Policy Maker	43	11.2
	Faculty Member	26	6.8
	Researcher	18	4.7
Experience in Crop–Livestock Sector	<5 years	130	33.8
	5–10 years	52	13.5
	10–15 years	76	19.7
	>15 years	127	33.0

The demographic profile shows a predominance of bachelor's degree holders and field specialists, with balanced professional experience across early- and late-career participants. These characteristics provide context for interpreting the subsequent perception and attitude data.

Respondents strongly agreed that current crop–livestock systems are vulnerable to climate change and that climate resilience is essential for sustainable crop production. They also recognized climate change as a serious threat to food security and highlighted the key role of advanced technologies and climate-smart agriculture in reducing production risks. These findings indicate a clear consensus among stakeholders on the importance of adaptive measures in integrated crop–livestock systems. The following table (Table 2) summarizes these results.

Table 2: Climate Resilience and Vulnerability Perceptions

Statement	Mean ± SD	Strongly disagree (N, %)	Disagree (N, %)	Neutral (N, %)	Agree (N, %)	Strongly agree (N, %)
Current crop–livestock systems are vulnerable to climate change	4.25 ± 0.60	2 (0.5%)	0 (0.0%)	20 (5.2%)	134 (34.8%)	229 (59.5%)
Climate resilience is essential for sustainable crop production	4.37 ± 0.61	4 (1.0%)	0 (0.0%)	21 (5.5%)	114 (29.6%)	246 (63.9%)
Climate change is a serious threat to food security	4.40 ± 0.58	8 (2.1%)	0 (0.0%)	22 (5.7%)	96 (24.9%)	259 (67.3%)
Advanced technologies play a key role in enhancing resilience	4.27 ± 0.72	9 (2.3%)	0 (0.0%)	52 (13.5%)	152 (39.5%)	172 (44.7%)
Climate-smart agriculture can reduce production risks	4.27 ± 0.74	14 (3.6%)	23 (6.0%)	19 (4.9%)	159 (41.3%)	170 (44.2%)

The results show a strong consensus among respondents regarding the vulnerability of crop–livestock systems, the importance of climate resilience, and the role of advanced technologies and climate-smart agriculture in reducing production risks.

Respondents demonstrated a strong positive perception of technology transfer, economic incentives, and the integration of technology, economy, and policy in promoting sustainable agricultural innovations. High agreement suggests that both financial and institutional support are considered critical for effective adoption of new technologies in crop–livestock systems. . The following table (Table 3) summarizes these results.

Table 3: Technology Transfer and Innovation Adoption

Statement	Mean ± SD	Strongly disagree (N, %)	Disagree (N, %)	Neutral (N, %)	Agree (N, %)	Strongly agree (N, %)
Technology transfer to farmers is as important as technology production	4.41 ± 0.63	4 (1.0%)	0 (0.0%)	32 (8.3%)	151 (39.2%)	198 (51.4%)
Economic incentives increase adoption of agricultural innovations	4.50 ± 0.57	2 (0.5%)	4 (1.0%)	12 (3.1%)	165 (42.9%)	202 (52.5%)
Investment in sustainable agriculture is economically justified	4.53 ± 0.56	7 (1.8%)	13 (3.4%)	0 (0.0%)	158 (41.0%)	207 (53.8%)
Integration of technology, economy, and policy is the pathway to sustainable R&D	4.52 ± 0.60	16 (4.2%)	26 (6.8%)	0 (0.0%)	126 (32.7%)	217 (56.4%)

The results indicate a strong positive perception of technology transfer, economic incentives, and integrated policy frameworks in promoting adoption of sustainable agricultural innovations. High agreement suggests that both economic and institutional support are critical for effective innovation uptake.

Respondents recognized that sustainable crop–livestock systems contribute to improving rural livelihoods, strengthening food security, and reducing the vulnerability of production systems. High levels of agreement indicate a clear consensus among stakeholders on the importance of sustainable practices for promoting both socio-economic and ecological resilience. . The following table (Table 4) summarizes these results.

Table 4: Sustainable Development and Food Security

Statement	Mean ± SD	Strongly disagree (N, %)	Disagree (N, %)	Neutral (N, %)	Agree (N, %)	Strongly agree (N, %)
Sustainable crop–livestock systems improve rural livelihoods	4.38 ± 0.57	2 (0.5%)	9 (2.3%)	9 (2.3%)	113 (29.4%)	261 (67.8%)
Sustainable crop–livestock development strengthens food security	4.61 ± 0.55	2 (0.5%)	1 (0.3%)	11 (2.9%)	122 (31.7%)	249 (64.7%)
This approach reduces vulnerability of production systems	4.36 ± 0.66	10 (2.6%)	60 (15.6%)	0 (0.0%)	142 (36.9%)	173 (44.9%)

High agreement among respondents highlights the positive role of sustainable crop–livestock systems in enhancing rural livelihoods, strengthening food security, and reducing production vulnerabilities, emphasizing their importance for socio-economic and ecological resilience.

Respondents emphasized the importance of aligning agricultural policies with global Sustainable Development Goals (SDGs), promoting institutional coordination, and ensuring active participation of faculty and experts in policymaking. These findings suggest a consensus that coordinated policy frameworks and stakeholder engagement are crucial for enhancing climate resilience and sustainable development in crop–livestock systems. The following table (Table 5) summarizes these results.

Table 5: Policy, Institutional Coordination, and Stakeholder Participation

Statement	Mean ± SD	Strongly disagree (N, %)	Disagree (N, %)	Neutral (N, %)	Agree (N, %)	Strongly agree (N, %)
Agricultural policies should align with global SDGs	4.38 ± 0.61	1 (0.3%)	11 (2.9%)	25 (6.5%)	165 (42.9%)	183 (47.5%)
Institutional coordination is necessary to tackle climate change	4.38 ± 0.59	2 (0.5%)	2 (0.5%)	32 (8.3%)	154 (40.0%)	195 (50.6%)
Participation of faculty and experts in agricultural policymaking is crucial	4.36 ± 0.60	0 (0.0%)	0 (0.0%)	32 (8.3%)	106 (27.5%)	247 (64.2%)

Respondents showed strong agreement on the need for policy alignment with SDGs, institutional coordination, and expert participation in agricultural policymaking, highlighting the critical role of coordinated policies and stakeholder engagement in promoting climate resilience and sustainable crop–livestock systems.

Data were analyzed using IBM SPSS Statistics Version 26 (IBM Corp., 2024).

The distribution of responses shows that the majority of respondents selected "Agree," indicating strong support for the statement. Smaller proportions chose "Neutral," "Disagree," or "Strongly Disagree," reflecting limited disagreement or uncertainty among stakeholders.

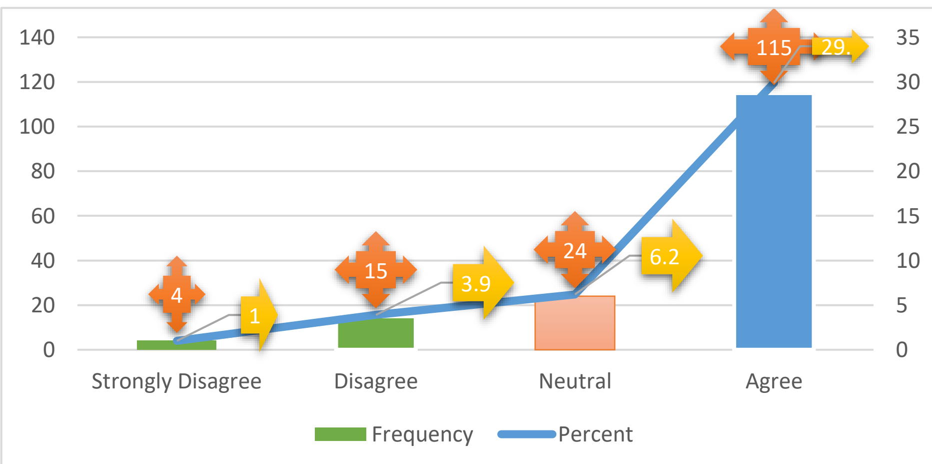

Figure 1: Policy Support for Climate Adaptation

Most stakeholders agree or strongly agree that government policies effectively support climate-resilient practices in crop–livestock systems.

The distribution of responses indicates that most participants selected "Strongly Agree," suggesting very high support for the statement. Smaller percentages chose "Agree," "Neutral," "Disagree," or "Strongly Disagree," indicating limited disagreement.

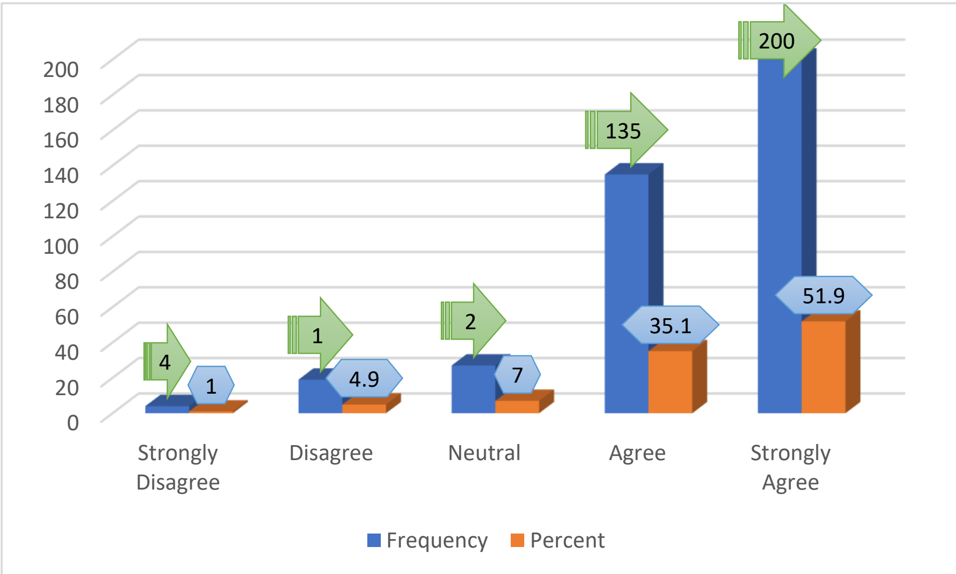

Figure 2: Stakeholder Collaboration

Over 85% of respondents believe that collaboration among farmers, researchers, and policymakers is sufficient to implement sustainable agricultural innovations.

Table 6. One-Sample t-test for Climate Resilience Perceptions

Statement	Mean	SD	Test Value = 3	t-value	p-value
Vulnerability of crop–livestock systems	4.25	0.60	3	28.4	<0.001
Importance of climate resilience	4.37	0.61	3	30.9	<0.001
Climate change threat to food security	4.40	0.58	3	32.5	<0.001
Role of advanced technologies	4.27	0.72	3	24.7	<0.001
Climate-smart agriculture reduces risk	4.27	0.74	3	23.9	<0.001

The one-sample t-test results (Table 6) show that all mean scores were significantly higher than the neutral value of 3 ($p < 0.001$), indicating strong agreement among respondents. Participants perceived high vulnerability of crop–livestock systems (M = 4.25, SD = 0.60) and emphasized the importance of climate resilience (M = 4.37, SD = 0.61) and threats to food security (M = 4.40, SD = 0.58). They also recognized the role of advanced technologies (M = 4.27, SD = 0.72) and climate-smart agriculture (M = 4.27, SD = 0.74) in reducing climate-related risks. Overall, these results reflect strong awareness and positive attitudes toward adopting adaptive strategies to enhance climate resilience.

Table7. ANOVA Results by Education Level and Experience

Dependent Variable	Factor	F-value	p-value	Interpretation
Climate vulnerability perception	Education	4.12	0.007	Significant
Climate vulnerability perception	Experience	3.45	0.016	Significant
Technology adoption attitude	Education	5.26	0.002	Significant
Technology adoption attitude	Experience	2.18	0.089	Not significant
Sustainable development perception	Education	3.98	0.009	Significant
Sustainable development perception	Experience	2.64	0.051	Marginal

The ANOVA results (Table 7) show that education level significantly influenced respondents' perceptions and attitudes. Specifically, differences across education levels were observed for climate vulnerability perception ($F = 4.12$, $p = 0.007$), technology adoption attitude ($F = 5.26$, $p = 0.002$), and sustainable development perception ($F = 3.98$, $p = 0.009$), indicating that higher education is associated with greater awareness of climate risks, stronger support for adopting technologies, and more positive views on sustainable development. In contrast, professional experience had a weaker impact: it significantly affected climate vulnerability perception ($F = 3.45$, $p = 0.016$), showed a marginal effect on sustainable development perception ($F = 2.64$, $p = 0.051$), and was not significant for technology adoption attitude ($F = 2.18$, $p = 0.089$). Overall, these findings suggest that formal education plays a more decisive role than experience in shaping respondents' understanding and proactive attitudes toward climate resilience and sustainable practices.

Table 8. Multiple Regression Analysis for Innovation Adoption

Independent Variable	Beta (β)	Std. Error	t-value	p-value
Education level	0.21	0.05	4.20	<0.001
Professional experience	0.12	0.04	2.85	0.005
Climate vulnerability perception	0.39	0.06	6.50	<0.001
Professional background	0.06	0.03	1.80	0.073
Constant	—	—	—	—

Model Summary

R	R²	Adjusted R²	F-value	p-value
0.62	0.38	0.36	45.7	<0.001

The results of the multiple regression analysis (Table 8) indicate that climate vulnerability perception ($\beta = 0.39$, $p < 0.001$) and education level ($\beta = 0.21$, $p < 0.001$) were significant predictors of innovation adoption. Professional experience also had a positive and significant effect ($\beta = 0.12$, $p = 0.005$), while professional background was not a significant predictor ($\beta = 0.06$, $p = 0.073$). The overall model was statistically significant ($F = 45.7$, $p < 0.001$) and explained 38% of the variance in innovation adoption ($R^2 = 0.38$, Adjusted $R^2 = 0.36$), suggesting that respondents' awareness of climate vulnerability and educational attainment are the primary drivers influencing their adoption of innovative practices.

Table 9. Independent t-test between Crop and Livestock Specialists

Variable	Group	Mean	SD	t-value	p-value
Policy perception	Crop specialists	4.34	0.58	1.12	0.262
	Livestock specialists	4.29	0.61		
Technology adoption	Crop specialists	4.42	0.55	0.94	0.347
	Livestock specialists	4.38	0.57		

The independent t-test results (Table 9) show no significant differences between crop and livestock specialists in either policy perception or technology adoption. Crop specialists reported a mean policy perception of 4.34 (SD = 0.58) compared to 4.29 (SD = 0.61) for livestock specialists (t = 1.12, p = 0.262). Similarly, technology adoption scores were 4.42 (SD = 0.55) for crop specialists and 4.38 (SD = 0.57) for livestock specialists (t = 0.94, p = 0.347). These findings suggest that professionals across both sectors share a consistent perspective regarding policy and the adoption of innovative practices.

Table 10. Pearson Correlation Matrix

Variables	Climate resilience	Technology adoption	Sustainable development	Food security
Climate resilience	1	0.64**	0.58**	0.61**
Technology adoption	0.64**	1	0.69**	0.55**
Sustainable development	0.58**	0.69**	1	0.72**
Food security	0.61**	0.55**	0.72**	1

The Pearson correlation analysis (Table 10) revealed strong and significant positive relationships among climate resilience, technology adoption, sustainable development, and food security (r = 0.55–0.72, p < 0.01). Climate resilience was strongly correlated with technology adoption (r = 0.64), sustainable development (r = 0.58), and food security (r = 0.61). Similarly, sustainable development showed the highest correlation with food security (r = 0.72). These findings indicate that improvements in one domain are closely associated with positive outcomes in the others, highlighting the interlinked nature of climate resilience, innovation, and sustainable food systems.

4. Conclusion and Discussion

This study explored stakeholders' perspectives on the role of technological innovations and policy interventions in enhancing climate resilience and sustainable development within integrated crop–livestock systems. The findings indicate that stakeholders perceive climate change as a growing structural threat to agricultural production and economic sustainability, which aligns with global assessments highlighting the increasing frequency and severity of climate-related hazards in agriculture *(IPCC, 2022; FAO, 2023).* The study underscores that vulnerability in integrated crop–livestock systems arises from the complex interactions among soil, water, crops, and livestock. This perspective aligns with socio-ecological system frameworks, which conceptualize agriculture as a dynamic system shaped by both ecological and social factors *(Herrero et al., 2021; Lal, 2021).* Stakeholders specifically emphasized the dual stress of declining crop yields and livestock heat stress, reflecting the compounded risks reported in semi-arid and marginal agroecological regions *(Thornton et al., 2021; Mbow et al., 2021).* These findings suggest that resilience strategies need to account for simultaneous multi-dimensional pressures rather than focusing on individual components. Respondents recognized climate-smart agricultural practices, precision management of inputs, and digital monitoring tools as critical means of mitigating production risks. These perceptions corroborate research emphasizing the potential of digital tools and technological innovations to enhance efficiency, reduce uncertainty, and promote sustainable management practices *(Campbell et al., 2020; World Bank, 2021).* However, stakeholders highlighted that technological solutions alone are insufficient without an enabling policy environment, echoing literature on institutional transitions and the importance of integrating technology within broader governance frameworks *(Dinesh et al., 2020; Carter et al., 2021).* Economic incentives, climate risk insurance, and green credit facilities were identified as essential drivers for technology adoption. This finding aligns with agricultural economics research that underscores the role of risk aversion and financial tools in shaping farmers' decisions under uncertainty *(Arslan et al., 2020; Falco & Veronesi, 2021).* Additionally, social capital and institutional trust emerged as key enablers of innovation uptake, supporting evidence that stakeholder networks and governance legitimacy are central to the effectiveness of adaptation interventions *(Meijer et al., 2021; Hornsey et al., 2021).* The results also highlight the need for policy coherence across agricultural, environmental, and rural development sectors to facilitate scaling of adaptation strategies. Lack of coordination at institutional levels can hinder innovation diffusion and the broader sustainability transition *(Béné et al., 2021; Pretty et al., 2021).* Alignment with the Sustainable Development Goals, particularly SDG 2 (Zero Hunger) and SDG 13 (Climate Action), requires inclusive decision-making processes, active stakeholder participation, and integration of scientific knowledge with local perceptions *(Sachs et al., 2023; Barrett et al., 2020).* Unlike many modeling-focused studies that primarily assess projected climate scenarios *(van Dijk et al., 2021),* this research emphasizes the mediating role of stakeholder perceptions in bridging technology and policy. The findings demonstrate that the success of climate interventions depends not only on technological efficacy but also on trust, understanding, and active engagement of stakeholders. This highlights a critical gap in previous research and underscores the need to integrate socio-cognitive dimensions into adaptation planning. Limitations of the study include reliance on perception-based survey data, which may introduce response biases, and the cross-sectional design, which limits the ability to examine changes in attitudes and adaptive behaviors over time. The findings suggest designing integrated policy frameworks that combine targeted financial support, extension services, and digital infrastructure development. Establishing risk reduction mechanisms, such as climate insurance schemes and decision-support tools, can further incentivize investment in sustainable technologies *(Falco & Veronesi, 2021)*. Building institutional trust and fostering social networks are equally important for enhancing adoption rates and sustaining resilience interventions. Future studies should employ longitudinal designs to capture dynamic adaptation processes and changes in stakeholder perceptions over time. Comparative analyses across diverse agroecological and socio-economic contexts could provide insights into context-specific barriers and enablers. Furthermore, combining qualitative and quantitative methods can deepen understanding of the interactions between technology, policy, and stakeholder behavior, offering actionable guidance for resilience planning. Overall, the study highlights that transitioning toward resilient and sustainable crop–livestock systems requires an integrated, multi-level approach where technological innovation, policy frameworks, economic incentives, and social capital interact synergistically. Achieving long-term resilience is not solely a matter of deploying technology but involves creating an enabling environment where stakeholders are informed, engaged, and empowered to participate in sustainable decision-making *(IPCC, 2022; Béné et al., 2021).*

5. Statements and Declarations

5.1 Competing interests

The author(s) declare no competing interests:

5.2 Data availability

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

5.3 Ethics Approval

Ethical Approval: Not Applicable

5.4 Consent to participate/Consent to publish

Consent to Participate/Consent to Publish: Not Applicable

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5.7 Author Contributions

All authors contributed equally to the conceptualization, methodology, investigation, writing, and review of this manuscript.

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