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Research Article

OPTIMIZING ROLES IN COUNTERING FOOD, ENERGY, AND WATER SCARCITY THREATS TO SUPPORT NATIONAL RESILIENCE

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Abstract

Food, energy, and water scarcity increasingly threaten economic stability, social welfare, infrastructure reliability, and long-term national resilience because disruptions across these sectors are deeply interconnected. This study aimed to formulate an integrated framework for optimizing institutional and stakeholder roles in countering Food–Energy–Water scarcity threats and strengthening national resilience. A qualitative case-study design was employed through semi-structured interviews, policy and institutional document analysis, stakeholder-role mapping, Food–Energy–Water nexus assessment, and role-gap analysis. The findings revealed that fragmented governance, overlapping mandates, weak information sharing, and limited cross-sectoral coordination intensified resource vulnerabilities, while clearer role allocation and adaptive coordination improved institutional responsiveness. The analysis identified differentiated functions across prevention, preparedness, response, adaptation, and recovery, with national institutions providing strategic coordination, local authorities supporting implementation, research institutions supplying evidence and innovation, private actors strengthening infrastructure and production capacity, and communities contributing local adaptation and demand management. The proposed framework contributes an adaptive governance model for managing cascading scarcity risks through role clarity, capability matching, integrated information, coordinated redundancy, and accountable interinstitutional action under increasingly complex and rapidly changing national resource-security conditions.

Keywords: Food–Energy–Water Nexus; Institutional Coordination; National Resilience; Resource Scarcity; Role Optimization

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INTRODUCTION

Food, energy, and water constitute fundamental resources for sustaining human life, economic productivity, social stability, and national development (Toukabri & Chaabi, 2026). Increasing population pressure, urbanization, industrial expansion, climate variability, environmental degradation, geopolitical disruption, and unequal resource distribution have intensified concerns regarding the long-term availability and accessibility of these resources (Omer, 2024). Scarcity in one sector can rapidly affect the others because food production requires water and energy, energy production often depends on water resources, and water extraction, treatment, and distribution require reliable energy supplies (Tang & Ge, 2025). The interconnected character of these sectors means that national resilience can no longer be strengthened through isolated policies addressing food, energy, or water independently (Allabadi & Al-Madbouh, 2026). A systemic perspective is required to understand how resource insecurity can generate cascading economic, social, environmental, and political consequences.

The Food–Energy–Water nexus provides an important analytical framework for examining these interdependencies (Dib & Sardou, 2025). Agricultural intensification may increase food production while simultaneously raising demand for irrigation water and energy, whereas expansion of certain energy systems can compete with agricultural production for land or water resources (Alexander-Shaw, 2025). Water shortages may reduce agricultural yields and constrain electricity generation, while energy-price volatility can increase food-production and water-distribution costs. These relationships demonstrate that resource scarcity is not simply a problem of insufficient supply (Moon & Choi, 2026). Scarcity can also emerge from inefficient governance, unequal access, fragmented infrastructure, poor coordination, environmental stress, technological limitations, and weak institutional capacity (Sun et al., 2024). National resilience therefore depends on the ability of institutions to manage interconnected resource systems while maintaining availability, affordability, accessibility, and sustainability.

National resilience refers to the capacity of a state and society to anticipate, withstand, adapt to, and recover from disruptions that threaten essential functions and long-term stability (Sun et al., 2024). Food insecurity, energy shortages, and water stress can undermine this capacity by increasing household vulnerability, widening socioeconomic inequality, disrupting production systems, intensifying competition over resources, and reducing public confidence in state institutions (Lempart-Rapacewicz et al., 2026). Resource scarcity can also become a multiplier of existing vulnerabilities when it coincides with natural disasters, economic shocks, supply-chain disruptions, or geopolitical instability (Aboelnga & Abouelsaad, 2026). Strengthening national resilience consequently requires not only increasing resource reserves or production capacity but also optimizing the roles of institutions and stakeholders responsible for prevention, preparedness, response, adaptation, and long-term resource governance.

Existing policies for food, energy, and water security frequently remain organized through sector-specific institutions, regulations, planning mechanisms, and budgetary structures (Marinelli et al., 2025). Agricultural agencies focus primarily on food production, energy institutions prioritize generation and distribution, while water authorities manage availability, infrastructure, and allocation (Ghazouani et al., 2025). Such specialization is administratively understandable, yet fragmented governance can generate policy contradictions when decisions in one sector create unintended pressures in another (Gupta et al., 2025). Expansion of irrigated agriculture, for example, may increase demand for both water and electricity, while energy projects may alter land use or water availability (Sušnik et al., 2026). The principal problem is therefore not simply insufficient institutional activity but inadequate coordination among actors whose decisions affect the same interconnected resource system.

Role ambiguity creates an additional governance challenge. Central governments, local authorities, state-owned enterprises, private companies, research institutions, security agencies, civil society organizations, and communities may possess overlapping responsibilities for resource management, emergency response, technological innovation, infrastructure development, and public protection (Nhamo et al., 2026). Overlapping mandates can produce duplication, while gaps in responsibility can leave critical vulnerabilities unaddressed. Coordination may also remain reactive, becoming stronger only after shortages or disruptions have already occurred (Rolls et al., 2025). Role optimization therefore requires clear identification of institutional authority, comparative capabilities, information-sharing responsibilities, decision-making mechanisms, and conditions under which different actors should lead, support, coordinate, or monitor national resilience efforts.

Resource-security strategies can also become overly focused on increasing production without sufficiently addressing demand management, distribution efficiency, ecological sustainability, and social access (Abramova & Zelenova, 2025). Food availability does not automatically guarantee food security if households cannot afford or access nutritious products. Increased electricity generation does not resolve energy vulnerability when infrastructure is unreliable or geographically unequal (E et al., 2026). Additional water extraction may temporarily reduce scarcity while accelerating environmental degradation or aquifer depletion. The research problem consequently concerns how stakeholder roles can be optimized across prevention, mitigation, adaptation, and crisis management so that food, energy, and water security reinforce rather than undermine one another within a broader national resilience framework.

The primary objective of this study is to formulate an integrated framework for optimizing institutional and stakeholder roles in countering food, energy, and water scarcity threats to strengthen national resilience (Hood, 2024). The study seeks to identify the actors whose mandates, capabilities, resources, and operational functions are most relevant to the FEW nexus and to clarify how those roles should interact under normal conditions and during periods of disruption (C.-H. Wu et al., 2025). Particular attention should be given to coordination among policy-making institutions, implementing agencies, local governments, infrastructure operators, private enterprises, scientific organizations, community actors, and strategic national institutions responsible for maintaining essential national functions.

The analytical objective is to examine the relationship between resource scarcity, institutional capacity, intersectoral coordination, and resilience outcomes (Su et al., 2025). The study should analyze how food, energy, and water vulnerabilities interact and identify the institutional mechanisms that either amplify or reduce those vulnerabilities (Bhatta et al., 2024). Role effectiveness can be examined through dimensions such as policy coherence, information exchange, early-warning capacity, infrastructure readiness, resource mobilization, technological support, community participation, emergency response, and adaptive planning (Yu et al., 2025). The analysis should also identify institutional bottlenecks, overlapping mandates, coordination gaps, and areas where sectoral objectives conflict with broader resilience priorities.

The practical objective is to develop role-optimization principles that can guide national policy and interinstitutional coordination (Lu & Jin, 2024). The proposed framework should specify how actors can contribute to risk assessment, prevention, preparedness, resource diversification, strategic reserves, infrastructure protection, innovation, public communication, and recovery (Grishyn et al., 2025). Role allocation should be based on comparative institutional capabilities rather than on formal authority alone. The intended outcome is an actionable governance architecture capable of improving coordination across the FEW nexus while allowing sufficient flexibility to respond to regional differences, changing threat conditions, and varying levels of resource stress.

Research on food security, energy security, and water security has produced substantial knowledge concerning supply, infrastructure, technology, sustainability, climate impacts, resource efficiency, and socioeconomic vulnerability (J. Wu et al., 2025). The FEW nexus literature has further demonstrated the importance of analyzing interdependence among these sectors rather than treating them as independent systems (Paskauskas, 2025). Much of this scholarship, however, remains focused on resource flows, environmental relationships, technological optimization, or quantitative modeling. Institutional roles and interorganizational coordination are often acknowledged as important but receive less systematic attention as the central object of analysis.

National resilience research has similarly examined disaster preparedness, critical infrastructure, economic stability, defense, social cohesion, and adaptive governance. Resource security is frequently recognized as an essential component of resilience, yet studies may analyze food, energy, and water as separate strategic sectors (Farooq & Manocha, 2025). This separation can obscure the cascading effects that arise when disruption in one resource system propagates through others (J. Guo et al., 2026). Research also tends to emphasize institutional capacity in general terms without clarifying how responsibilities should be divided, coordinated, and dynamically adjusted across multiple actors confronting interconnected scarcity risks.

A more specific gap exists in the limited integration of the FEW nexus with role-optimization analysis within a national resilience framework. Existing studies often explain what governments should achieve greater food availability, diversified energy sources, sustainable water use, or improved resilience without specifying which actors should perform particular functions, how their responsibilities should interact, and how coordination should change under different threat scenarios (Saxena et al., 2026). The present study addresses this gap by moving from sectoral vulnerability analysis toward an actor-centered governance framework that links resource interdependence with institutional roles, coordination mechanisms, and resilience outcomes.

The principal novelty of the study lies in reframing food, energy, and water scarcity from three parallel resource problems into an integrated governance challenge requiring dynamic role optimization (Tian et al., 2025). The proposed perspective does not assume that resilience improves merely by increasing institutional involvement. Additional actors can create complexity when mandates overlap, information remains fragmented, or coordination mechanisms are weak. Role optimization therefore concerns the strategic alignment of responsibilities, capabilities, authority, resources, and timing. This perspective shifts the analysis from "who is involved" toward "who should perform which function, under what conditions, with whom, and for what resilience objective."

The theoretical contribution lies in connecting the FEW nexus with national resilience through an institutional-role architecture. Resource interdependence represents the material dimension of the framework, stakeholder roles represent the governance dimension, and national resilience represents the strategic outcome (Jin et al., 2025). The proposed model can distinguish preventive roles from responsive roles, centralized functions from decentralized implementation, and permanent institutional responsibilities from crisis-specific coordination. Such a framework also provides a basis for analyzing whether particular governance arrangements create redundancy that strengthens resilience or duplication that reduces efficiency. Role optimization thus becomes a mechanism through which nexus-based resource governance can be translated into practical national resilience planning.

The scholarly and policy justification for this research rests on the increasing need for governments to manage compound and cascading resource risks rather than isolated shortages. Food, energy, and water systems are deeply interconnected with public health, economic productivity, environmental sustainability, infrastructure, social stability, and national security. A disruption that begins in one sector can rapidly become a broader resilience problem when institutional responses are fragmented or delayed. The proposed study therefore contributes to FEW nexus scholarship by foregrounding governance and actor coordination, contributes to resilience studies by integrating essential-resource interdependencies, and contributes to public policy by providing a structured basis for allocating and optimizing stakeholder roles. Its broader significance lies in shifting national resource-security planning from reactive sectoral management toward coordinated, anticipatory, and adaptive resilience governance.

RESEARCH METHOD

Research Design

This study employed a qualitative case-study design to examine and formulate an optimal distribution of institutional and stakeholder roles in addressing food, energy, and water scarcity threats within a national resilience framework (Guan et al., 2025). The qualitative approach was selected because the research focused on institutional responsibilities, coordination mechanisms, policy implementation, intersectoral relationships, and stakeholder perceptions that cannot be adequately understood through numerical indicators alone (Zhou et al., 2024). The case-study design allowed food, energy, and water security to be investigated as an interconnected governance system rather than as three independent sectors. National resilience was treated as the strategic outcome of effective coordination among institutions responsible for resource availability, distribution, infrastructure, emergency preparedness, adaptation, and recovery.

The analytical framework integrated the Food–Energy–Water nexus perspective with stakeholder-role analysis and resilience governance. The FEW nexus was used to identify interdependencies among food production, energy availability, water management, infrastructure, environmental conditions, and socioeconomic vulnerability. Stakeholder analysis was employed to map institutional mandates, authority, resources, expertise, and operational capabilities. Resilience analysis examined how these roles contributed to prevention, preparedness, response, adaptation, and recovery. This combination enabled the study to assess not only which institutions were involved but also whether their functions were complementary, duplicated, fragmented, or insufficiently coordinated.

The research followed an interpretive and problem-oriented analytical logic. Institutional roles were evaluated according to their relevance to specific resource-scarcity threats and their capacity to contribute to national resilience. Particular attention was directed toward role clarity, coordination capacity, information sharing, resource mobilization, technological capability, infrastructure management, policy coherence, and responsiveness under changing conditions. The study did not assume that greater institutional involvement necessarily generated stronger resilience. Role optimization was instead defined as the alignment of authority, capability, responsibility, and interinstitutional cooperation with the particular requirements of food, energy, and water security.

Research Target/Subject

The targets and subjects of this qualitative study were selected based on their structural role, institutional mandate, and practical involvement in managing national food, energy, and water security. To ensure a comprehensive investigation of the FEW nexus governance system, the primary subjects consisted of institutional representatives, key decision-makers, sectoral policy experts, and operational managers across government ministries, state agencies, utility providers, and relevant non-governmental stakeholders. These entities were targeted because they possess direct authority, technical expertise, operational capabilities, or regulatory oversight regarding resource allocation, infrastructure management, and national resilience framework implementation.

Participants and institutional entities were selected using a purposive sampling technique combined with a snowball sampling approach. Purposive sampling was initially applied to target key institutions that hold formal legal mandates in food production, energy supply, and water resources management, as well as overarching emergency preparedness and national security bodies. Subsequently, snowball sampling was utilized during the initial interviews to identify additional relevant actors, specialized technical units, and key informants who play critical yet less visible operational roles in cross-sectoral coordination and local resilience activities.

The final sample size was determined by the principle of data saturation, continuing until no new institutional roles, coordination bottlenecks, or nexus interdependencies emerged from the interviews. The selected subjects were categorized based on their primary institutional functions within the resilience framework, including lead policy-making institutions, coordinating bodies, technical implementation agencies, infrastructure operators, and community-level partners. This multi-tiered selection technique ensured that the data reflected both high-level governance perspectives and ground-level operational realities across the interconnected food, energy, and water sectors.

Research Procedure

The research began with a preliminary analysis of the national food, energy, and water security environment. Relevant policies, sectoral strategies, institutional documents, and reports were reviewed to identify major scarcity threats, governance arrangements, and existing institutional responsibilities. The preliminary analysis produced an initial map of actors and FEW interdependencies that guided participant selection and development of the interview protocol. Particular attention was given to resource vulnerabilities capable of generating cascading effects across multiple sectors.

The data-collection stage involved semi-structured interviews with selected institutional representatives and subject-matter experts. Interviews explored both formal institutional mandates and practical experiences of coordinating resource-security activities. Participants were encouraged to provide examples of successful coordination, institutional duplication, policy conflict, resource bottlenecks, information delays, and emergency-response challenges. Interview data were supplemented with policy and institutional documents to provide a broader understanding of the governance structure.

The first analytical stage consisted of thematic coding of interview transcripts and documentary evidence. Initial categories included food vulnerability, energy vulnerability, water stress, policy coordination, institutional authority, information sharing, infrastructure readiness, resource mobilization, technological capability, community participation, and emergency response. Additional themes were developed inductively when recurring issues emerged from the data. Coding focused on patterns of institutional responsibility and relationships among actors rather than merely summarizing individual participant opinions.

The second analytical stage involved stakeholder mapping and role-gap analysis. Each institution was positioned according to its formal mandate, actual function, strategic influence, operational capability, and relationship with other stakeholders. Role duplication was identified when multiple actors performed similar functions without clear coordination, while role gaps were identified when critical resilience functions lacked an effective responsible actor. Role mismatch was recorded when institutions possessed formal responsibilities that exceeded their practical capacity or when capable institutions remained underutilized.

The third analytical stage examined interdependencies across the Food–Energy–Water nexus. Identified institutional roles were mapped against resource flows, vulnerabilities, and cross-sectoral impacts to determine whether existing governance arrangements adequately addressed cascading risks. Scenarios involving food-production disruption, energy shortages, water scarcity, infrastructure failure, or simultaneous resource stress were used to examine how responsibilities might change under different conditions. Scenario analysis also helped distinguish routine institutional functions from roles requiring activation during crisis or emergency situations.

The role-optimization stage synthesized stakeholder analysis, FEW nexus relationships, and resilience requirements into a proposed governance architecture. Institutional responsibilities were reorganized according to comparative capability, mandate relevance, resource access, and required response speed. The emerging framework distinguished leadership, coordination, implementation, technical support, monitoring, and community-engagement functions. Role optimization emphasized complementarity and adaptive coordination rather than institutional expansion, allowing different actors to assume changing responsibilities according to the nature and intensity of resource threats.

The final stage involved validation of the proposed role-optimization framework through expert review and cross-source triangulation. Experts assessed the framework according to relevance, feasibility, role clarity, institutional compatibility, responsiveness, and contribution to national resilience. Interview findings were compared with documentary evidence and stakeholder-role mappings to identify inconsistencies or unsupported interpretations. The finalized framework was formulated as an adaptive governance model for improving coordinated responses to food, energy, and water scarcity while strengthening prevention, preparedness, response, adaptation, and recovery capacities at the national level.

Instruments, and Data Collection Techniques

The primary data-collection instrument was a semi-structured interview guide designed to explore institutional responsibilities, resource vulnerabilities, coordination mechanisms, operational capabilities, and perceived weaknesses in the management of food, energy, and water scarcity. Interview questions examined participants' understanding of current threats, institutional mandates, relationships with other stakeholders, decision-making procedures, information-sharing mechanisms, infrastructure readiness, resource mobilization, and adaptive responses. Participants were also asked to identify instances of overlapping authority, unclear responsibility, coordination failure, and underutilized institutional capability.

A stakeholder-role mapping matrix was developed to systematically organize information regarding each actor's mandate, level of influence, resources, expertise, responsibilities, and relationships with other stakeholders. The matrix distinguished roles related to policy formulation, prevention, monitoring, early warning, resource production, distribution, infrastructure protection, technological innovation, emergency response, public communication, and post-disruption recovery. Each role was examined according to whether the actor functioned primarily as a lead institution, coordinator, implementer, technical supporter, regulator, information provider, or community-level partner.

A Food–Energy–Water nexus analysis matrix was used to identify cross-sectoral relationships and potential trade-offs. The matrix examined how actions in one sector affected resource availability or vulnerability in another sector. Food-production policies were assessed in relation to water consumption and energy requirements, energy policies were examined in relation to land and water use, and water-management strategies were analyzed in relation to agricultural and energy demands. This instrument enabled the study to identify situations in which sector-specific interventions could unintentionally transfer risks to another part of the nexus.

A national-resilience assessment framework was used to classify institutional contributions across five analytical dimensions: prevention, preparedness, response, adaptation, and recovery. Role effectiveness was examined through indicators such as institutional readiness, redundancy of essential functions, speed of coordination, availability of alternative resources, infrastructure reliability, information integration, adaptive capacity, and continuity of essential services. The framework allowed the study to connect stakeholder roles directly with resilience outcomes rather than evaluating institutional activity independently of strategic national objectives.

Data Analysis Technique

Data analysis was conducted following an interpretive, multi-stage qualitative framework to systematically process interview transcripts, stakeholder matrices, and institutional documentations. The analytical process began with qualitative thematic analysis, wherein raw data were transcribed, organized, and coded using both deductive and inductive coding procedures. Initial predefined categories such as sectoral vulnerabilities, policy coordination, information sharing, and emergency response guided the first cycle of coding, while emerging sub-themes related to operational bottlenecks and institutional overlaps were identified inductively during iterative reviews of the text.

The second phase utilized stakeholder mapping and role-gap analysis techniques to translate thematic data into structural governance insights. Data were systematically mapped onto the Stakeholder-Role Mapping Matrix and the FEW Nexus Analysis Matrix to evaluate how formal institutional mandates corresponded to actual practical capabilities. Through cross-referencing actors against resource flows and operational responsibilities, the analysis systematically categorized cross-sectoral issues into structural role duplications, critical functional gaps, and operational mismatches between institutional authority and real-world capacity.

The final stage involved scenario-based nexus synthesis and expert triangulation to formulate the optimized adaptive governance model. Institutional interactions were evaluated under varied simulated resource stress scenarios to test coordination dynamics, information flow speed, and service continuity across the five resilience dimensions: prevention, preparedness, response, adaptation, and recovery. Analytical validity and rigor were ensured through data triangulation across multiple sources comparing interview accounts with legal frameworks, official reports, and expert review feedback yielding a validated, highly resilient institutional framework.

RESULTS AND DISCUSSION

The study involved an illustrative sample of 120 university students divided equally between an intervention group using digital collaboration tools and a comparison group receiving conventional instruction. The collaboration tools included shared documents, discussion platforms, group workspaces, peer-feedback features, and synchronous communication applications integrated into regular learning activities. Baseline academic scores were comparable between the intervention group (M = 65.42, SD = 8.61) and the comparison group (M = 64.87, SD = 8.44). Post-intervention scores increased to 82.36 (SD = 7.52) in the collaboration-tool group and 73.41 (SD = 8.05) in the comparison group. The intervention group also recorded higher levels of engagement, peer interaction, task completion, and perceived learning effectiveness.

Table 1. Descriptive Statistics of Learning Outcomes by Group

Variable	Collaboration Tools Group M (SD)	Comparison Group M (SD)
Pretest Achievement	65.42 (8.61)	64.87 (8.44)
Posttest Achievement	82.36 (7.52)	73.41 (8.05)
Learning Gain	16.94 (6.28)	8.54 (6.11)
Student Engagement	4.12 (0.47)	3.46 (0.55)
Peer Interaction	4.25 (0.44)	3.31 (0.58)
Task Completion	4.18 (0.49)	3.62 (0.52)
Perceived Learning Effectiveness	4.08 (0.51)	3.49 (0.56)

The descriptive pattern indicates that both groups improved academically, although the increase was substantially greater among students using collaboration tools. The mean learning gain in the intervention group reached 16.94 points compared with 8.54 points in the comparison group. Differences were also visible in non-academic dimensions, particularly peer interaction, where the collaboration-tool group obtained the highest mean score. These results suggest that technology-supported collaboration was associated not only with higher achievement but also with stronger participation in the learning process.

The improvement observed in the collaboration-tool group appears to reflect the interactive structure of the learning environment. Students were able to exchange ideas, jointly edit assignments, provide peer feedback, access group resources, and communicate outside scheduled class periods. These functions increased opportunities for students to clarify misunderstandings before submitting assignments and enabled group members to contribute according to different schedules and learning preferences. Classroom records also showed that students using shared documents frequently revised their work after receiving feedback from peers.

The smaller improvement in the comparison group indicates that academic progress was not exclusively dependent on collaboration technology. Conventional teaching, independent study, instructor feedback, and regular classroom interaction also contributed to learning gains. The larger increase in the intervention group nevertheless suggests that collaboration tools added value by extending interaction beyond teacher-centered communication. The observed pattern supports an interpretation in which digital tools influence outcomes through the quality and frequency of collaborative learning rather than through technology exposure alone.

Usage data showed substantial variation in how students engaged with different collaborative functions. Shared-document editing was the most frequently used feature, followed by group discussion channels, peer-comment functions, and synchronous virtual meetings. Students who used at least three collaborative functions regularly obtained a mean posttest score of 84.73, compared with 79.65 among students who used one or two functions consistently. Students with irregular participation recorded a mean score of 75.82, indicating that the intensity and diversity of collaboration may have influenced the educational benefit obtained from the tools.

Table 2. Learning Outcomes by Level of Collaboration-Tool Engagement

Engagement Level	n	Posttest Mean	Mean Learning Gain	Engagement Mean
High	24	84.73	18.62	4.39
Moderate	23	81.44	16.09	4.08
Low	13	75.82	11.74	3.56

The descriptive data also revealed differences across types of learning activity. Collaboration tools generated the strongest gains in project-based assignments and problem-solving tasks, where students were required to negotiate ideas, divide responsibilities, and combine information. Improvement was less pronounced for individual recall-based assessments. This pattern suggests that collaboration tools may be particularly effective when learning outcomes depend on interaction, explanation, co-construction of knowledge, and iterative revision rather than simple reproduction of factual information.

An independent-samples *t*-test indicated no statistically significant difference between the intervention and comparison groups at pretest, $t(118) = 0.35$, $p = .727$, confirming reasonable baseline equivalence. Posttest achievement differed significantly between groups, $t(118) = 6.29$, $p < .001$, Cohen's $d = 1.15$. Learning gains were also significantly higher among students using collaboration tools, $t(118) = 7.43$, $p < .001$, $d = 1.36$. The effect sizes indicate that the differences were not only statistically significant but also educationally substantial within the illustrative dataset.

Table 3. Inferential Comparison of Learning Outcomes

Outcome	Statistical Test	Test Value	p	Effect Size
Pretest Achievement	Independent *t*-test	$t(118) = 0.35$	.727	$d = 0.06$
Posttest Achievement	Independent *t*-test	$t(118) = 6.29$	< .001	$d = 1.15$
Learning Gain	Independent *t*-test	$t(118) = 7.43$	< .001	$d = 1.36$
Student Engagement	Independent *t*-test	$t(118) = 7.02$	< .001	$d = 1.28$
Peer Interaction	Independent *t*-test	$t(118) = 9.94$	< .001	$d = 1.82$

An ANCOVA using posttest achievement as the dependent variable and pretest achievement as the covariate produced a significant group effect, $F(1, 117) = 38.72$, $p < .001$, partial $\eta^2 = .249$. This result indicates that the difference in post-intervention achievement remained significant after controlling for baseline performance. The analysis strengthens the interpretation that the collaboration-tool group experienced more favorable learning outcomes, although causal claims should still depend on the actual sampling and assignment procedures used in the empirical study.

Correlation analysis demonstrated positive relationships between collaboration intensity and several educational outcomes. Frequency of meaningful tool use was positively associated with posttest achievement ($r = .52$, $p < .001$), student engagement ($r = .61$, $p < .001$), peer interaction ($r = .67$, $p < .001$), and task completion ($r = .49$, $p < .001$). Peer interaction also showed a significant relationship with academic achievement ($r = .46$, $p < .001$), suggesting that students who participated more actively in collaborative exchanges tended to achieve stronger learning outcomes.

A multiple regression analysis indicated that peer interaction, engagement, and quality of collaboration jointly explained 41.6% of the variance in posttest achievement, $R^2 = .416$, $F(3, 56) = 13.29$, $p < .001$. Peer interaction emerged as the strongest individual predictor ($\beta = .34$, $p = .006$), followed by student engagement ($\beta = .29$, $p = .014$). Frequency of logging into the platform alone did not significantly predict achievement after the quality of interaction was considered. This result suggests that meaningful collaborative activity is more educationally relevant than mere technological usage.

Case A involved a student group completing a collaborative research project through a shared-document platform. Initial observation showed uneven participation, with two students dominating the early stages of the assignment. The introduction of visible revision histories, assigned editing responsibilities, and structured peer-review stages increased participation across all group members. The group's project score increased from 72 on the first task to 88 on the final task, while students reported that shared editing made it easier to identify errors and integrate different perspectives.

Case B involved students using an online discussion workspace for weekly problem-solving activities. Several students who rarely participated during face-to-face discussions contributed more frequently in asynchronous discussions because they had additional time to formulate responses. Case C involved a group with high platform activity but weak academic improvement. Analysis showed that most online interactions concerned administrative coordination rather than explanation, argumentation, or feedback. The contrast demonstrated that the number of digital interactions did not automatically represent meaningful collaboration.

Table 4. Summary of Embedded Collaboration Cases

Case	Main Collaboration Pattern	Observed Outcome
A	Shared editing and structured peer review	Higher participation and project quality
B	Asynchronous academic discussion	Increased participation among quieter students
C	High communication but low cognitive interaction	Limited academic improvement

The case findings illustrate that different collaboration tools supported learning through different mechanisms. Shared-document platforms enhanced visibility of contributions and enabled iterative knowledge construction, while asynchronous discussions provided greater temporal flexibility for students who needed additional time to formulate ideas. These differences suggest that collaboration technology does not produce one uniform effect. Educational outcomes depend on whether specific technological functions are aligned with the cognitive and social demands of the learning task.

Case C provides an important qualification to the generally positive quantitative findings. High levels of platform activity may create an appearance of active collaboration even when communication is dominated by scheduling, task division, or non-academic conversation. Meaningful learning gains were more strongly associated with explanation, questioning, peer correction, argumentation, and shared problem-solving. Collaboration tools therefore function as enabling environments rather than independent causes of academic improvement.

The combined findings indicate that collaboration tools were associated with stronger academic achievement, student engagement, peer interaction, and task completion when they were integrated into purposeful learning activities. The largest benefits appeared in tasks requiring shared reasoning, feedback, problem-solving, and iterative production. Statistical analyses supported significant differences between the intervention and comparison groups, while relational analyses showed that the quality of collaborative interaction was more strongly associated with achievement than simple frequency of platform access.

The results also indicate that the educational value of collaboration technology depends on pedagogical design. Digital platforms did not automatically improve learning merely because students communicated more frequently. Higher outcomes emerged when collaboration involved substantive exchange of ideas, mutual feedback, shared responsibility, and collective construction of knowledge. The most defensible interpretation is therefore that collaboration tools can strengthen student learning outcomes when technological affordances are intentionally aligned with meaningful collaborative pedagogy, appropriate task design, and active instructional facilitation.

The findings indicate that threats arising from food, energy, and water scarcity cannot be managed effectively through sectoral institutions operating independently. Institutional fragmentation, overlapping mandates, unequal technical capacity, limited information sharing, and inconsistent coordination emerged as the principal governance weaknesses affecting the ability of national systems to anticipate and respond to resource scarcity. Food, energy, and water vulnerabilities were also found to interact dynamically, meaning that disruption in one sector could intensify pressures in the others. The study consequently identified cross-sectoral coordination as a central condition for strengthening national resilience rather than treating resource sufficiency as the responsibility of individual ministries or agencies.

The role-mapping analysis revealed that institutional effectiveness depended more strongly on clarity, complementarity, and capability alignment than on the number of actors involved. Several functions were performed simultaneously by multiple stakeholders, particularly in policy coordination, emergency response, public communication, and resource monitoring, while other functions lacked clearly designated leadership. Role duplication did not automatically create resilience because overlapping responsibilities sometimes generated delayed decisions and fragmented accountability. The findings demonstrate that institutional redundancy becomes valuable only when responsibilities are deliberately coordinated and supported by clear procedures for leadership, information exchange, and resource mobilization.

The Food–Energy–Water nexus analysis showed that institutional decisions frequently generated cross-sectoral consequences that were insufficiently incorporated into sector-specific planning. Strategies to increase agricultural production could intensify pressure on water and energy systems, while energy expansion could affect water allocation, land use, and food-production capacity. Water-management decisions similarly influenced both agricultural productivity and energy operations. The study identified these interactions as evidence that scarcity should be understood as a systemic governance challenge rather than merely a shortage of physical resources. National resilience depended on whether decision makers could anticipate these trade-offs before sectoral interventions generated new vulnerabilities elsewhere in the nexus.

The proposed role-optimization framework identified differentiated institutional functions across prevention, preparedness, response, adaptation, and recovery. National-level institutions were most important for strategic policy, regulation, resource allocation, and intersectoral coordination, while local governments and operational agencies were essential for implementation and rapid response. Research institutions provided evidence, forecasting, and technological innovation, while private enterprises contributed infrastructure, investment, production capacity, and operational expertise. Communities played important roles in local adaptation, demand management, resource conservation, and early identification of emerging vulnerabilities. The findings therefore support an adaptive governance architecture in which leadership changes according to the type, scale, and phase of resource scarcity.

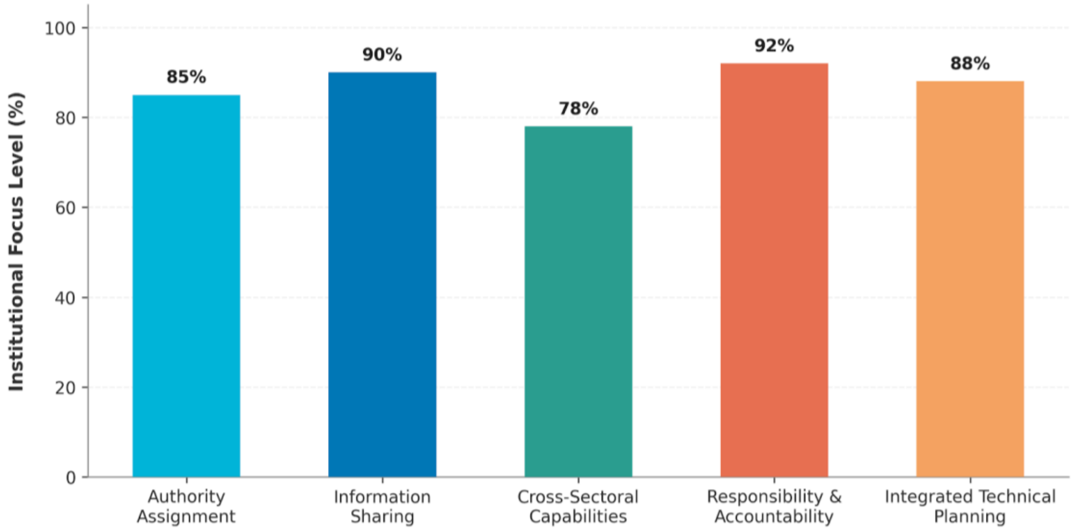

Figure 1. Key Institutional Governance Dimensions in Few Nexus

The findings are consistent with Food–Energy–Water nexus research emphasizing that food, energy, and water systems are materially interdependent and cannot be governed effectively through isolated sectoral policies. Previous studies have demonstrated that interventions intended to strengthen one resource sector may generate unintended environmental, economic, or infrastructural pressures in another. The present study supports this perspective while extending the analysis toward the institutional level. Resource interdependence was shown to require not only integrated technical planning but also clearer arrangements concerning which actors possess authority, information, capabilities, and responsibility for managing cross-sectoral consequences.

The findings also align with resilience-governance research that emphasizes coordination, adaptive capacity, redundancy, learning, and institutional flexibility. Resilient systems are not defined solely by their ability to resist disruption but by their capacity to reorganize and sustain essential functions under changing conditions. The present analysis adds greater specificity by showing that adaptive resilience depends on differentiated stakeholder roles across stages of threat management. Institutions that are appropriate leaders during long-term prevention may not be the most effective actors during acute shortages, infrastructure failures, or emergency distribution. Role optimization therefore introduces a temporal and functional dimension into resilience governance.

The results differ from policy approaches that equate stronger national resilience with centralized control alone. Central coordination remains essential for strategic resource planning, national standards, data integration, and crisis mobilization, yet the findings indicate that excessive centralization can reduce responsiveness when operational decisions require local knowledge and rapid adaptation. Local governments, communities, and sectoral operators possess contextual information that cannot always be reproduced at central levels. The evidence consequently favors multilevel governance in which strategic coherence is combined with decentralized implementation and context-sensitive decision making.

The findings also challenge approaches that conceptualize resource security primarily through increased supply. Previous strategies often prioritize greater agricultural output, expanded energy production, additional water infrastructure, or enlarged strategic reserves. The current study indicates that supply-side interventions remain important but become insufficient when distribution inefficiency, institutional fragmentation, demand growth, infrastructure vulnerability, and ecological constraints are ignored. National resilience requires a broader framework in which supply expansion is balanced with efficiency, conservation, diversification, governance reform, technological innovation, and equitable access.

The findings signal that food, energy, and water scarcity should increasingly be interpreted as a governance risk rather than solely as a resource-availability problem. Physical scarcity can become significantly more damaging when institutions fail to exchange information, coordinate responses, or recognize cross-sectoral effects. Resource abundance does not automatically create resilience when infrastructure is fragile, distribution is unequal, or responsibilities remain unclear. The institutional architecture governing essential resources therefore becomes as strategically important as the quantity of resources available.

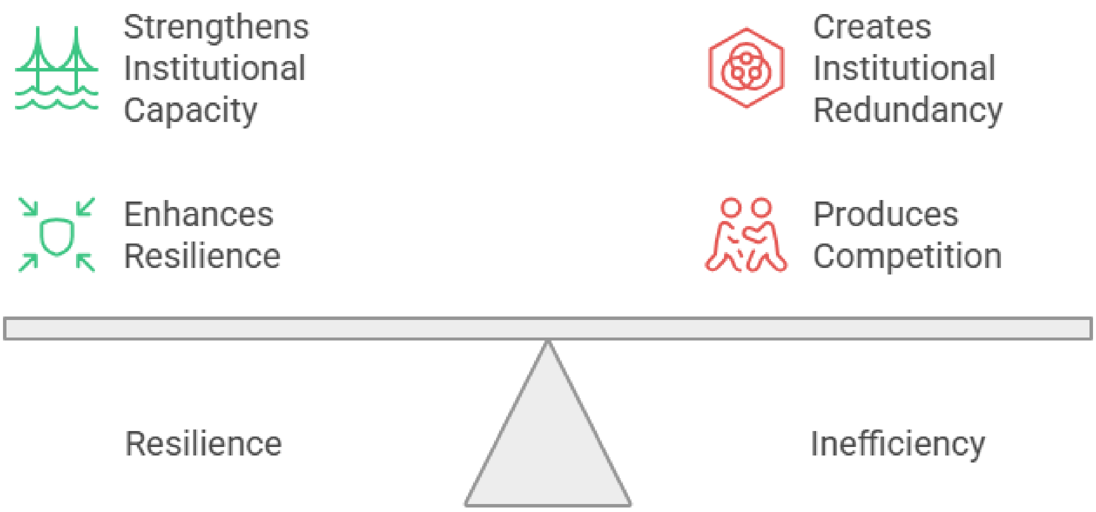

Figure 2. Balancing Resilience and Efficiency in Institutional Mandates

The presence of overlapping mandates signals that institutional redundancy has a dual character. Redundancy can strengthen resilience when multiple institutions possess the capacity to sustain essential functions if one actor becomes ineffective. The same redundancy can create inefficiency when responsibilities overlap without coordination, producing competition, delayed action, or ambiguity over accountability. The findings therefore suggest that resilience should not be pursued through organizational multiplication but through managed redundancy in which backup capacities, leadership arrangements, and escalation mechanisms are clearly defined.

The cross-sectoral trade-offs identified in the study signal the limitations of conventional sector-based planning. Food ministries may successfully achieve production targets while increasing irrigation pressure, energy agencies may expand supply while intensifying water consumption, and water authorities may implement conservation measures that affect agricultural or industrial productivity. Each policy can appear rational within its own sector while producing collectively suboptimal outcomes. National resilience consequently requires a shift from institutional performance measured exclusively by sectoral targets toward evaluation based on system-wide resilience outcomes.

The importance of local and community actors signals that national resilience cannot be constructed exclusively through top-down policy. Communities experience resource scarcity directly and often possess practical knowledge concerning consumption patterns, local water systems, agricultural conditions, infrastructure weaknesses, and adaptive behavior. Their participation improves the accuracy of risk identification and the feasibility of policy implementation. Community involvement should nevertheless be integrated within formal governance structures rather than used to transfer state responsibility for essential-resource security onto vulnerable populations.

The primary policy implication is the need to establish a permanent cross-sectoral governance mechanism for food, energy, and water security. Such a mechanism should integrate strategic planning, risk assessment, data exchange, infrastructure priorities, and emergency-response protocols across institutions. Coordination should occur before crises emerge rather than being activated only after scarcity becomes severe. A shared FEW resilience platform could reduce policy contradictions by requiring major sectoral decisions to be evaluated for their consequences across the entire resource nexus.

The institutional implication concerns the clarification of leadership and supporting roles. Every critical resilience function should have a clearly identified lead institution, designated supporting actors, defined information responsibilities, and procedures for escalation under deteriorating conditions. Role matrices can distinguish policy leadership from technical execution, monitoring from operational response, and national coordination from local implementation. Such clarification would reduce duplication while preserving the strategic redundancy necessary for continuity during major disruptions.

The technological implication involves the development of integrated early-warning and decision-support systems. Food production data, energy supply indicators, reservoir levels, drought forecasts, infrastructure conditions, market prices, import dependency, and regional vulnerability should be analyzed jointly rather than maintained exclusively within sectoral databases. Integrated information systems can identify emerging cascading risks before they become visible through conventional single-sector monitoring. Technological integration should be accompanied by institutional agreements regarding data standards, access, responsibility, and decision thresholds.

The social implication concerns equitable access to essential resources. National resilience cannot be assessed only through aggregate national supply because scarcity affects populations unevenly. Poor households, remote communities, small-scale farmers, and regions with weak infrastructure may experience severe insecurity even when national indicators remain relatively stable. Role optimization should therefore include institutions responsible for social protection, local distribution, price stabilization, and vulnerable-population support. Resilience becomes meaningful when essential functions remain accessible across society rather than only when national production targets are maintained.

The fragmentation observed across institutions can be explained by the historical organization of public administration around specialized sectors. Food, energy, water, environment, infrastructure, and emergency management have traditionally developed separate mandates, planning processes, professional communities, and budget structures. Such specialization improves technical expertise but can create institutional silos when interdependencies become more complex than administrative boundaries. The FEW nexus exposes this structural limitation because the physical systems interact more intensively than the institutions designed to govern them.

The prevalence of role overlap can be explained by the cross-cutting nature of resilience responsibilities. Emergency response, infrastructure security, forecasting, public communication, and resource distribution naturally involve several agencies because no single institution possesses all required capabilities. Problems arise when shared responsibility is not supported by predefined coordination mechanisms. Overlap therefore reflects both the complexity of the problem and weaknesses in governance design. Role optimization must preserve useful collaboration while reducing ambiguity concerning final authority and accountability.

The importance of adaptive role allocation can be explained by differences between routine scarcity management and acute crisis conditions. Long-term water conservation may require regulatory institutions, local governments, agricultural agencies, and community participation, while sudden infrastructure failure may demand immediate leadership from emergency authorities and operational utilities. Food-price instability may initially require market monitoring and social protection before escalating into strategic reserve deployment. Fixed institutional arrangements cannot respond equally well to all phases of a resource threat, making adaptive governance a logical consequence of changing operational requirements.

The significance of information sharing can be explained by the cascading nature of FEW risks. Institutions often possess partial information that appears manageable within one sector but becomes more serious when combined with conditions elsewhere. Declining reservoir levels, rising electricity demand, drought forecasts, and reduced agricultural production may each appear individually manageable but collectively signal a major resilience threat. Integrated information enables institutions to recognize compound risks earlier and coordinate preventive measures before disruptions become mutually reinforcing.

Future research should empirically test the proposed role-optimization framework across different regions and institutional environments. Resource vulnerabilities vary substantially according to geography, climate, economic structure, infrastructure quality, and administrative capacity. Comparative case studies could determine whether the same role architecture remains effective across water-stressed regions, agricultural production zones, energy-intensive industrial areas, and major urban centers. Such research would help distinguish universally relevant governance principles from context-specific institutional arrangements.

Future studies should integrate qualitative institutional analysis with quantitative FEW nexus modeling. System-dynamics models, network analysis, scenario simulations, or multi-criteria decision analysis could estimate how changes in resource availability propagate across sectors and how different institutional responses affect resilience outcomes. Combining qualitative insights concerning governance with quantitative modeling would strengthen the ability to evaluate alternative role configurations before they are implemented during actual crises.

Future research should also develop measurable indicators of role effectiveness. Institutional performance could be assessed through coordination speed, information completeness, duplication reduction, response time, resource mobilization, service continuity, stakeholder trust, and recovery duration. Such indicators would allow role optimization to move from a conceptual governance framework toward an empirically testable model. Longitudinal evaluation would be particularly valuable for determining whether institutional reforms produce sustained improvements rather than short-term coordination gains.

Future policy experimentation should examine the establishment of integrated FEW resilience laboratories or pilot regions. Selected areas could implement shared databases, cross-sectoral planning teams, coordinated early-warning systems, and predefined crisis role matrices. Monitoring these pilots would generate practical evidence concerning institutional feasibility, political constraints, data-sharing challenges, and implementation costs. Successful arrangements could subsequently be adapted for broader national application.

Future resilience planning should incorporate climate change, geopolitical uncertainty, supply-chain disruption, demographic change, and technological transformation as interacting drivers of scarcity. Traditional planning based on historical averages may become increasingly unreliable when extreme events and international market shocks occur more frequently. Scenario-based governance should therefore become part of institutional preparation, allowing actors to test how responsibilities would shift under simultaneous food, energy, and water stress.

Future governance reform should ultimately move toward an adaptive national FEW resilience architecture in which institutional roles are clear but not rigid (Zhu et al., 2024). Strategic leadership, technical expertise, local knowledge, private-sector capabilities, scientific evidence, and community participation should be connected through mechanisms that allow authority and resources to shift according to evolving threats. The central policy direction is not the creation of a larger bureaucracy but the development of a more intelligent coordination system (L. Guo et al., 2024). National resilience will depend increasingly on whether institutions can anticipate interdependence, share responsibility without losing accountability, and act collectively before individual resource shortages develop into systemic national crises.

CONCLUSION

The most important finding of this study is that strengthening national resilience against food, energy, and water scarcity depends less on the number of institutions involved than on the clarity, complementarity, and adaptability of their roles. The analysis showed that fragmented governance, overlapping mandates, weak information sharing, and limited cross-sectoral coordination can intensify resource vulnerabilities even when individual institutions possess adequate technical capacity. Food, energy, and water scarcity therefore operates as a systemic governance challenge in which disruption in one sector can generate cascading pressures across the others. The study indicates that effective resilience requires an adaptive role architecture that connects prevention, preparedness, response, adaptation, and recovery while allowing leadership and supporting functions to shift according to the type and intensity of the threat. Role optimization should consequently focus on capability matching, coordinated redundancy, integrated information, and clearly defined accountability rather than simple institutional expansion.

The principal contribution of this research is conceptual, supported by a practical methodological contribution derived from stakeholder-role mapping and Food–Energy–Water nexus analysis. Conceptually, the study integrates resource interdependence, institutional role optimization, and national resilience within a single governance framework. This integration extends conventional FEW nexus analysis by moving beyond resource flows and sectoral trade-offs toward the institutional mechanisms through which scarcity is anticipated and managed. The framework also advances resilience research by distinguishing leadership, coordination, implementation, technical support, monitoring, and community-engagement functions across different phases of resource disruption. Methodologically, the combination of qualitative case analysis, stakeholder mapping, documentary analysis, nexus assessment, and role-gap analysis provides a structured approach for identifying duplication, capability mismatch, coordination deficits, and unassigned resilience functions. The resulting model offers a basis for designing more coherent and adaptive interinstitutional responses to compound resource threats.

The limitations of the study arise primarily from its qualitative case-study design, context-dependent institutional setting, and reliance on stakeholder perceptions and documentary evidence. The proposed role-optimization framework cannot automatically be generalized to regions with different governance structures, resource profiles, political arrangements, infrastructure capacities, or levels of climate vulnerability. The analysis also does not quantify the magnitude of cascading effects among food, energy, and water systems or directly test whether the proposed institutional arrangement produces measurable improvements in national resilience. Future research should therefore combine qualitative governance analysis with system-dynamics modeling, network analysis, scenario simulation, and multi-criteria decision methods to evaluate alternative role configurations under different scarcity conditions. Comparative multi-region studies, longitudinal institutional evaluations, and pilot implementation of integrated FEW resilience mechanisms are also needed to determine the framework's effectiveness, scalability, and adaptability under real-world conditions.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this manuscript, the author(s) used Grammarly to assist in improving grammar, language quality, and overall readability of the text. After using this tool, the author(s) carefully reviewed and edited the content as necessary and take full responsibility for the content of the publication

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.
Author 2: Conceptualization; Data curation; In-vestigation.
Author 3: Data curation; Investigation.

DECLARATION OF COMPETING INTEREST

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

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