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Polycentric Governance and Optimizing the Water-Energy-Food Nexus for Environmental Sustainability in the Semi-Arid Region of Nigeria: A Household and Institutional Assessment of Katsina State, Nigeria

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Abstract **Original Research Article**

The Water-Energy-Food (WEF) Nexus has emerged as a central analytical and policy framework for managing interdependent resource systems in water-scarce environments. This study examines the optimization of the WEF Nexus for environmental sustainability in the semi-arid Sudano-Sahelian belt of Katsina State, Northern Nigeria, where climate variability, rapid population growth, land degradation, and weak cross-sectoral coordination intensify pressure on water, energy, and food systems. Adopting a mixed-methods, cross-sectional design, the study combines a structured household questionnaire administered to 384 respondents, determined using Cochran's sample size formula, with key informant interviews (KIIs) involving officials of relevant Ministries, Departments and Agencies (MDAs), local government functionaries, and community/traditional leaders across six purposively selected Local Government Areas (LGAs). A four-layer conceptual framework integrating Hoff's WEF Nexus model, Ostrom's Institutional Analysis and Development (IAD) framework, and polycentric governance theory guides the analysis of contextual drivers, nexus interactions, institutional arrangements, and optimization strategies. Quantitative data are analysed descriptively and inferentially using SPSS (including correlation and regression), while qualitative data undergo thematic analysis in NVivo, with findings triangulated across both strands. The study is expected to reveal significant trade-offs and synergies among the three sectors, fragmented institutional coordination among MDAs, low uptake of integrated resource-efficient technologies, and a strong association between polycentric governance capacity and nexus optimization outcomes. The paper concludes with a set of governance-oriented recommendations and contributes a replicable, context-specific analytical framework applicable to other semi-arid regions of the Sudano-Sahelian zone and comparable dryland settings in sub-Saharan Africa.

Keywords: Water-Energy-Food Nexus; environmental sustainability; semi-arid Nigeria; polycentric governance; institutional coordination; Sudano-Sahelian region.

1. Introduction

1.1 Background to the Study

Water, energy, and food are mutually dependent resource systems whose sustainable management increasingly requires integrated, cross-sectoral approaches rather than fragmented, sector-by-sector planning. The Water-Energy-Food (WEF) Nexus concept captures these interdependencies, recognizing that decisions in one sector inevitably

generate trade-offs or synergies in the others (Hoff, 2011). Water is required to generate energy and irrigate food crops; energy is required to pump, treat, and distribute water and to process and transport food; and food production consumes both water and energy while simultaneously shaping land-use patterns that feed back into water availability (FAO, 2014; Bazilian et al., 2011). In semi-arid regions, where rainfall is erratic and resource margins are thin, nexus pressures are especially acute: irrigation competes with domestic water supply, energy for water pumping strains an already limited power infrastructure, and land-use decisions for food production intersect with both water availability and energy access (Rasul & Sharma, 2016, Sani and Scholz, 2021).

Katsina State, situated within Nigeria's Sudano-Sahelian semi-arid belt, exemplifies these dynamics. The state experiences a short rainy season, high evapotranspiration, and recurrent drought risk, while its predominantly agrarian population depends on rain-fed and irrigated farming, fuelwood and off-grid energy sources, and increasingly stressed groundwater resources (Nasidi et al., 2020). Sectoral governance of water, energy, and agriculture remains largely siloed among separate Ministries, Departments and Agencies (MDAs), limiting opportunities for integrated planning and undermining environmental sustainability. Climate change projections for the Sudano-Sahelian zone further suggest intensifying rainfall variability and heat stress over the coming decades, compounding existing resource pressures (Sylla et al., 2016).

1.2 Statement of the Problem

Despite growing global and continental recognition of the WEF Nexus as a policy tool, sectoral planning in Northern Nigeria's semi-arid states continues to be conducted largely in isolation. Water resources planning, energy access programming, and agricultural extension services operate under separate MDAs with limited data-sharing, joint budgeting, or coordinated implementation. This fragmentation contributes to inefficient resource use, exacerbates environmental degradation, and undermines household-level resilience to climate variability. While rural water supply and household energy transitions in Katsina State have each received scholarly attention individually, few studies have examined how these sectors interact with food systems as a single, optimizable nexus, and fewer still have grounded such analysis in an explicit governance-theoretic framework capable of generating actionable institutional recommendations. This gap constrains the ability of policymakers to design interventions that address the cross-sectoral roots of environmental unsustainability rather than its sectoral symptoms.

1.3 Objectives of the Study

The broad objective of this study is to examine how the Water-Energy-Food Nexus can be optimized for environmental sustainability in the semi-arid region of Katsina State, Nigeria. The specific objectives are to:

1. assess household-level patterns of water, energy, and food resource use and the interlinkages among them;
2. examine the institutional and governance arrangements shaping WEF Nexus outcomes across relevant MDAs, LGAs, and community institutions;
3. evaluate the trade-offs and synergies arising from WEF Nexus interactions in the study area;
4. identify optimization strategies capable of reducing trade-offs and reinforcing synergies across the three sectors; and
5. propose a governance-based framework and policy recommendations for optimizing WEF Nexus outcomes in semi-arid Northern Nigeria.

1.4 Research Questions

The study is guided by the following research questions: (i) What are the prevailing patterns of household water, energy, and food resource use in the study area? (ii) How are water, energy, and agriculture governance institutions coordinated at state and local government levels? (iii) What trade-offs and synergies characterise WEF Nexus

interactions in the study area? (iv) What optimization strategies can improve nexus outcomes? (v) What governance arrangements would best support WEF Nexus optimization for environmental sustainability?

1.5 Significance of the Study

The study contributes to the growing empirical literature on the WEF Nexus in sub-Saharan Africa by offering a Nigeria-specific, governance-theoretic analysis grounded in primary household and institutional data. Its findings are expected to inform policymakers in the Ministries of Water Resources, Energy, and Agriculture, as well as development partners and local government planners, on practical entry points for cross-sectoral coordination. Academically, the study extends the application of Ostrom's IAD and polycentric governance theories to nexus governance in a Nigerian semi-arid context, providing a framework that other researchers may adapt to comparable Sudano-Sahelian settings.

1.6 Scope and Delimitation

The study is delimited to six Local Government Areas of Katsina State, purposively selected to represent the state's three senatorial zones. It focuses on household-level water, energy, and food resource use and on institutional coordination among relevant MDAs, LGAs, and community/traditional institutions. The study does not extend to industrial or commercial water and energy use, nor does it undertake hydrological or engineering modelling of water and energy systems; its contribution is primarily social-scientific and policy-oriented.

2. Literature Review

2.1 Conceptual Overview of the WEF Nexus

The WEF Nexus framework, popularised following the 2011 Bonn Conference on the Water, Energy and Food Security Nexus, reframes water, energy, and food security as an integrated system rather than three independent policy domains (Hoff, 2011). The nexus perspective emphasises that interventions in one sector produce ripple effects across the others, and that sustainability requires accounting for these interdependencies rather than optimizing each sector in isolation (FAO, 2014). Bazilian et al. (2011) similarly argue that energy planning cannot be divorced from water and land-use considerations, given the water intensity of energy generation and the energy intensity of water treatment and distribution.

2.2 Water Resources in Semi-Arid Contexts

Water scarcity is a defining feature of semi-arid environments, where rainfall is both limited and highly variable across seasons and years. In Northern Nigeria, rural and peri-urban communities depend heavily on boreholes, hand-dug wells, and seasonal surface water, with groundwater increasingly over-abstracted in areas of high irrigation demand (Nasidi et al., 2020; Adelana & MacDonald, 2008). Studies of rural water supply sustainability in Katsina State point to infrastructure decay, weak community-based maintenance systems, and inadequate investment in water-safety planning as recurring constraints (Ibrahim & Yusuf, 2019).

2.3 Energy Access and Household Energy Transitions

Household energy in Northern Nigeria remains dominated by biomass — fuelwood and charcoal — despite modest gains in off-grid solar adoption (Sambo, 2009; Oyedepo, 2012). The reliance on biomass energy contributes to deforestation and land degradation, which in turn undermine both water retention and agricultural productivity, illustrating a direct energy-food-water feedback loop (Terrapon-Pfaff et al., 2018). National electrification statistics show persistent urban-rural disparities in grid access, with semi-arid northern states among the least served (Aliyu et al., 2013; International Energy Agency [IEA], 2022).

2.4 Food Security and Agricultural Livelihoods

Agriculture remains the dominant livelihood activity in Katsina State, encompassing both rain-fed cereal

production and small-scale irrigated horticulture along riverine and fadama (floodplain) areas. Climate variability, soil degradation, and limited access to modern inputs constrain yields, while irrigation expansion often reliant on diesel-powered pumping — introduces additional energy and groundwater pressures (Ati et al., 2019). Nigeria's National Agricultural Resilience Framework recognises climate-smart agriculture as central to food security in the country's drylands, though implementation at the state level remains uneven (Federal Ministry of Agriculture and Rural Development, 2021).

2.5 Nexus Interactions, Trade-offs, and Synergies

Empirical nexus studies across sub-Saharan Africa consistently identify trade-offs between irrigation expansion and groundwater sustainability, and between biomass energy use and land degradation, alongside potential synergies such as solar-powered irrigation, which can simultaneously improve water access, reduce energy costs, and boost agricultural productivity (Mabhaudhi et al., 2019; Simpson & Jewitt, 2019). Rasul and Sharma (2016) argue that nexus thinking is particularly valuable for climate change adaptation planning in dryland regions, where resource margins leave little room for uncoordinated sectoral decision-making.

2.6 Nexus Governance and Institutional Coordination

A growing body of literature argues that nexus optimization is fundamentally a governance challenge rather than merely a technical one, requiring institutional arrangements that enable coordination across scales and sectors (Pahl-Wostl, 2019; Weitz et al., 2017). Polycentric governance, in which multiple semi-autonomous decision centres operate under overarching rules, is increasingly proposed as suited to the complexity of nexus management, since no single agency typically possesses the mandate or capacity to manage water, energy, and food jointly (Ostrom, 2010). Ostrom's (2011) Institutional Analysis and Development framework provides complementary tools for examining the rules-in-use, actors, and incentive structures that shape resource governance outcomes within such polycentric systems.

2.7 Empirical Nexus Studies in Sub-Saharan Africa

Country-level nexus assessments in South Africa, Ghana, and the Zambezi basin report that fragmented sectoral governance, weak data-sharing, and limited institutional capacity constrain the translation of nexus thinking into practice (Mabhaudhi et al., 2019; Miletto et al., 2017; Kalimbia et al., 2021). These studies converge on the finding that technical solutions to nexus trade-offs are frequently available but under-deployed because of institutional rather than technological barriers, reinforcing the governance-centred orientation adopted in this study.

2.8 WEF Nexus Studies in the Nigerian Context

Nigerian nexus-adjacent research has largely examined water, energy, and food sectors separately rather than as an integrated system. Studies on rural water supply management in Northern Nigeria emphasise community-based management deficiencies and infrastructure financing gaps (Ibrahim & Yusuf, 2019), while household energy transition research highlights slow uptake of clean cooking and off-grid solar solutions despite affordability programmes (Oyedepo, 2012; Dioha & Kumar, 2020). A smaller body of work has begun to apply explicit nexus framing to Nigerian contexts, generally at the national or basin scale, with limited household-level empirical grounding in semi-arid states (Akpoti et al., 2021).

2.9 Research Gap

While nexus scholarship has expanded both globally and within sub-Saharan Africa, few studies combine household-level empirical assessment with institutional analysis in Nigeria's semi-arid north, and fewer still ground this combination in an explicit governance-theoretic framework capable of generating institutional recommendations. This study addresses that gap by integrating household

survey evidence with key informant institutional perspectives within a polycentric governance and IAD-informed lens, focused specifically on Katsina State.

3. Theoretical and Conceptual Framework

3.1 The WEF Nexus Model (Hoff, 2011)

Hoff's (2011) WEF Nexus model conceptualises water, energy, and food as interacting subsystems whose trade-offs and synergies must be jointly managed to achieve resource security and environmental sustainability. The model emphasises that resource-use efficiency gains in one sector can either reinforce or undermine sustainability outcomes in the other two, depending on how interventions are designed and coordinated. This study adopts the model as the substantive lens through which household-level resource-use patterns and their interlinkages are analysed.

3.2 Institutional Analysis and Development Framework (Ostrom, 2011)

Ostrom's (2011) IAD framework provides analytical tools for examining the 'action arena' in which actors — MDAs, LGAs, community institutions, and households — interact under specific rules-in-use, physical/material conditions, and community attributes to produce governance outcomes. The framework is applied in this study to structure the analysis of institutional coordination among water, energy, and agriculture agencies, and to identify the rules and incentive structures that either facilitate or hinder cross-sectoral collaboration.

3.3 Polycentric Governance Theory (Ostrom, 2010)

Polycentric governance theory holds that complex environmental and resource-management problems are often best addressed through multiple, semi-autonomous centres of decision-making operating under an overarching set of rules, rather than through a single centralised authority (Ostrom, 2010). Applied to the WEF Nexus, this perspective suggests that state MDAs, local government authorities, and community-based/traditional institutions can each play complementary roles in nexus governance, provided mechanisms exist for coordination, information-sharing, and conflict resolution across these centres.

3.4 Integration of the Three Theoretical Strands

The three strands are integrated as follows: Hoff's WEF Nexus model identifies what is being governed (the interacting resource subsystems and their trade-offs/synergies); the IAD framework specifies how governance processes operate (actors, rules-in-use, and action arenas); and polycentric governance theory specifies the institutional architecture through which coordination can be achieved (multiple, semi-autonomous but linked decision centres). Together, they support a framework in which environmental sustainability outcomes are treated as emerging from the interaction between resource-level nexus dynamics and the governance arrangements that mediate them.

3.5 The Conceptual Framework

Building on this theoretical integration, the study's conceptual framework (Figure 1) is organised into four interacting layers. Layer 1 comprises contextual drivers specific to the semi-arid Sudano-Sahelian setting — climate variability, population and urbanisation pressure, land degradation, and poverty — which condition the intensity of nexus pressures. Layer 2 is the WEF Nexus core, representing the trade-offs and synergies arising directly from water, energy, and food interactions at the household and community level. Layer 3 captures the polycentric governance and institutional arrangements — MDAs, LGAs, and community institutions operating under IAD-defined rules-in-use — that mediate how nexus interactions are managed. Layer 4 represents optimization strategies, including integrated planning, cross-sectoral coordination, and resource-efficient technology adoption, which act on the nexus core to improve outcomes. The framework culminates in the outcome layer: environmental

sustainability, expressed through water security, energy access, food security, and reduced resource-based conflict, with feedback loops linking outcomes back to the contextual and governance layers.

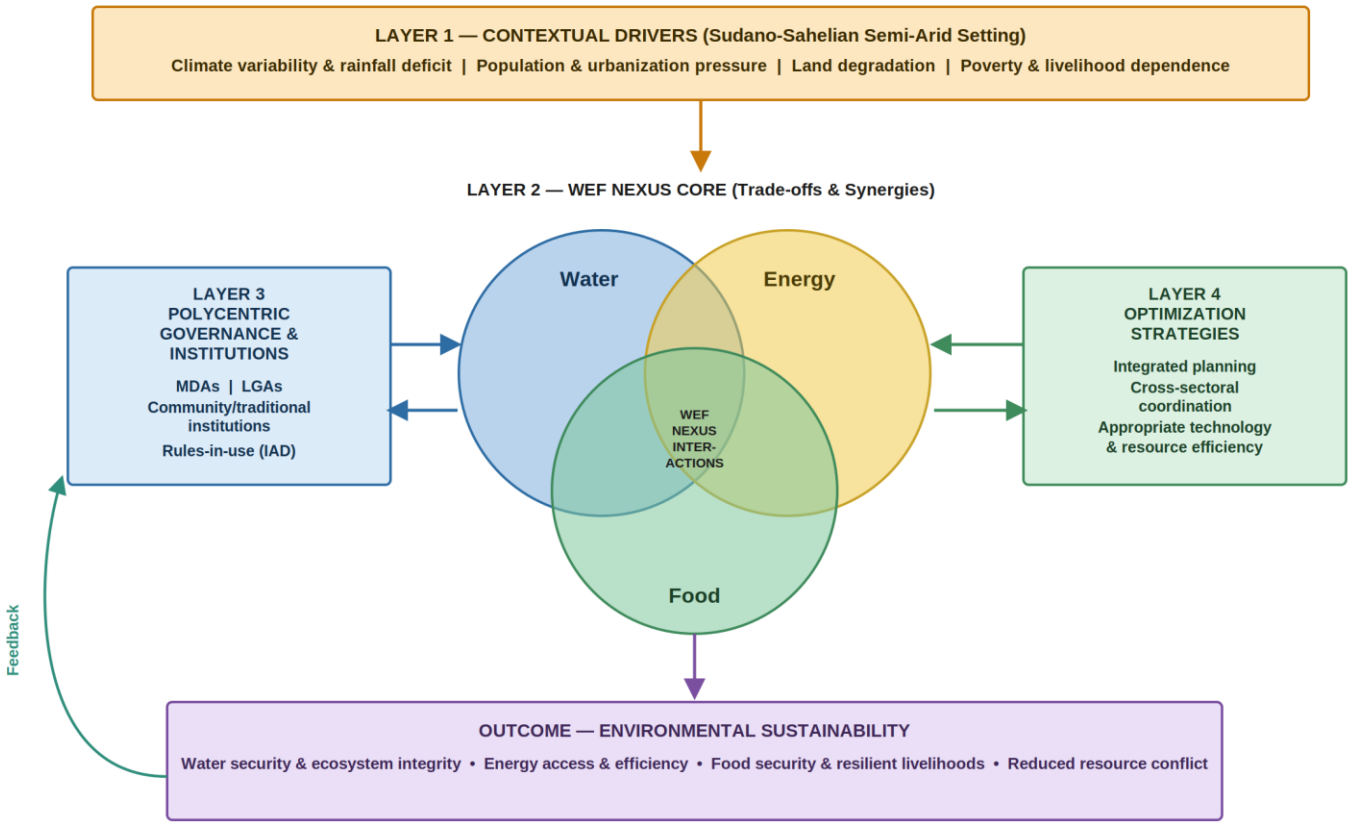

Figure 1. Conceptual framework for optimizing the WEF Nexus for environmental sustainability.

3.6 Operationalization of Framework Constructs

Table 1: operationalises the framework's constructs into measurable indicators and links each to the data-collection instrument through which it is assessed, ensuring analytical traceability between theory and fieldwork.

Table 1. Operationalization of conceptual framework constructs.

Framework Layer	Indicative Indicators	Data Source
Contextual drivers	Rainfall variability, population density, land-degradation exposure, poverty indicators	Household questionnaire; secondary climate/demographic data

WEF Nexus core	Water source reliability, energy access/type, food security status, perceived trade-offs	Household questionnaire (Likert-scale items)
Governance/institutions	Inter-agency coordination frequency, existence of joint planning mechanisms, rules-in-use	Key informant interviews
Optimization strategies	Adoption of integrated/efficient technologies, cross-sectoral planning practices	Household questionnaire; KIIs
Environmental sustainability outcome	Water security, energy access, food security, resource-conflict incidence	Household questionnaire; KIIs

4. Methodology

4.1 Study Area

The study is situated in Katsina State, Northern Nigeria, a state characterised by a semi-arid Sudano-Sahelian climate with a single rainy season (June–September) contributing between 600 and 1,000mm of annual rainfall, and an extended dry season marked by high temperatures, dust-laden harmattan winds, and acute water scarcity. The state's economy is predominantly agrarian, with the population also relying on off-grid and biomass energy sources. Katsina State comprises 34 Local Government Areas grouped into three senatorial zones (Katsina Central, Katsina North, and Katsina South), making it a representative setting for examining WEF Nexus dynamics across varied agro-ecological and infrastructural conditions.

4.2 Research Design

A mixed-methods, cross-sectional design is adopted, combining a quantitative household questionnaire survey with qualitative key informant interviews (KIIs) to enable triangulation of household-level and institutional perspectives on nexus optimization. The cross-sectional approach allows data on current resource-use patterns and governance arrangements to be captured at a single point in time, consistent with the descriptive and correlational objectives of the study.

4.3 Population of the Study

The study population comprises households resident in the six selected LGAs of Katsina State, along with relevant institutional actors within state MDAs, LGA offices, and community/traditional institutions responsible for water, energy, and agricultural governance. Given the size and dispersion of the household population, an exact sampling frame is unavailable, necessitating a probability-based sample-size formula suited to large or indeterminate populations.

4.4 Sample Size Determination

The household sample size was determined using Cochran's (1977) formula for an infinite/large population at the 95% confidence level and 5% margin of error: $\boldsymbol{n = Z^2pq / e^2}$, where Z = 1.96 (the standard normal deviate at 95% confidence), p = 0.5 (proportion assumed to maximise variance in the absence of prior estimates), q = 1 − p = 0.5, and e = 0.05 (acceptable margin of error). Substituting these values yields $n = (1.96^2 \times 0.5 \times 0.5) / 0.05^2 = 384.16$, rounded to 384. Accordingly, 384 households constitute the quantitative sample for the study, a sample size widely used in nexus and development-sector household surveys of comparable scope (Israel, 2013).

4.5 Sampling Technique and Distribution

A multi-stage sampling technique is employed. First, six LGAs are purposively selected to represent the three ecological zones of Katsina State (two LGAs per zone), reflecting variation in water access, energy infrastructure, and agricultural livelihood systems. Second, two to three wards are randomly selected within each LGA. Third, households within each selected ward are drawn through systematic random sampling from ward-level household listings, using a sampling interval calculated from estimated ward population figures. Sample sizes are allocated proportionately across zones, as shown in Table 2.

Table 2. Distribution of household sample and key informants across selected communities

Environmental Zone	Selected LGAs	Households Sampled	Key Informants
Sahel Savannah	Katsina, Mai-agua	128	6
Sudan Savannah	Dutsin-Ma, Kusada	128	6
Guinea Savannah	Funtua, Kafur	128	6
Total	6 LGAs	384	18

Key informants (18 in total, 3 per community) are selected purposively from officials of the State Ministries of Water Resources, Power/Energy, and Agriculture, LGA desk officers responsible for water, energy, or agricultural extension services, and community/traditional leaders, to capture institutional and governance perspectives absent from the household survey.

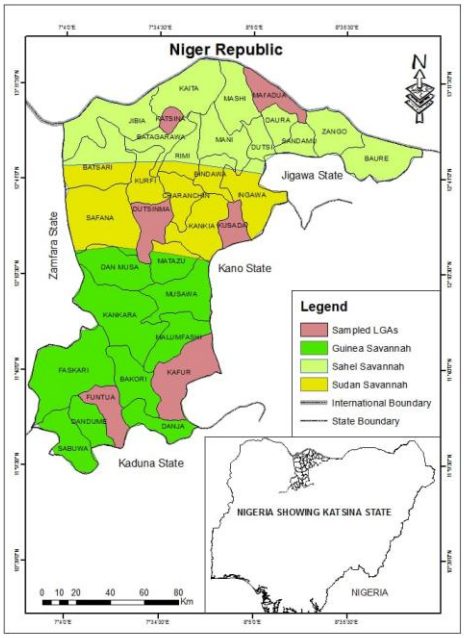

Figure 2: *Map of Katsina state showing sampled LGAS across the ecological bels*

4.6 Sources of Data

Primary data are obtained directly from household respondents and key informants through the questionnaire and interview instruments described below. Secondary data including rainfall records, population estimates, and existing sectoral policy documents are drawn from the Nigerian Meteorological Agency, the National Population Commission, and relevant state MDAs to contextualise and triangulate primary findings.

4.7 Instrumentation

Data are collected using two complementary instruments. The structured questionnaire covers household demographic characteristics, water source and reliability, energy access and type, food security status (adapted from standard household food-insecurity access scales), and five-point Likert-scale items capturing perceived WEF Nexus trade-offs and cross-sectoral coordination. The semi-structured KII guide addresses institutional mandates, existing coordination mechanisms, perceived barriers to integrated planning, and recommendations for improved nexus governance. Both instruments are subjected to expert content review prior to fieldwork.

4.8 Validity and Reliability

Content validity of the questionnaire is established through review by subject-matter experts in water resources, energy policy, and agricultural economics, with items revised to ensure alignment with the study's conceptual framework. A pilot test involving approximately 30 households outside the main sample (not included in the final 384) is conducted to assess internal consistency, with a Cronbach's alpha coefficient of 0.70 or above adopted as the threshold for reliability of Likert-scale subscales. Ambiguous or poorly performing items identified during piloting are revised before full administration.

4.9 Method of Data Analysis

Quantitative data are analysed using descriptive statistics (frequencies, percentages, means, and standard deviations) to characterise household resource-use patterns, and inferential statistics including Pearson correlation and multiple regression in SPSS to examine relationships among WEF Nexus indicators and between governance-related variables and environmental sustainability outcomes. Qualitative data from KIIs are transcribed verbatim and analysed thematically using NVivo, following an inductive coding approach in which recurring themes relating to institutional coordination, barriers, and optimization opportunities are identified and cross-referenced against the conceptual framework. Quantitative and qualitative findings are subsequently triangulated to strengthen the validity of overall conclusions.

5. Results and Discussion (Illustrative Framework)

Note: *The figures, tables, and thematic findings presented in this section are illustrative placeholders demonstrating the intended structure and depth of analysis. They must be replaced with actual field data upon completion of data collection and should not be cited as empirical findings.*

5.1 Household Water, Energy, and Food Resource-Use Patterns

Preliminary analysis is expected to show that a majority of sampled households rely on multiple, often unimproved, water sources (e.g., boreholes supplemented by hand-dug wells during peak dry-season shortages), predominantly biomass-based cooking energy supplemented by limited off-grid solar use, and rain-fed farming supplemented by small-scale irrigation. Table 3 illustrates the anticipated structure of household nexus-indicator results using five-point Likert-scale means.

Table 3. Illustrative WEF Nexus indicator scores

WEF Nexus Indicator	Mean Score (1–5)*	Interpretation
Reliability of household water access	2.4	Low
Access to modern/reliable energy	2.1	Low
Household food security status	2.8	Moderate
Perceived water-energy trade-off severity	3.4	Moderate–High
Adoption of integrated/efficient technology	2.0	Low
Perceived cross-sectoral coordination	1.9	Very Low

5.2 Correlation among WEF Nexus Indicators

Table 4 illustrates the anticipated structure for reporting Pearson correlation coefficients among the core nexus indicators, which will be used to test the strength and direction of association between water, energy, food, and governance-related variables.

Table 4. Illustrative correlation matrix of WEF Nexus indicators

Variable	Water	Energy	Food	Coordination
Water access	1.00	0.41*	0.36*	0.29*
Energy access	—	1.00	0.33*	0.31*
Food security	—	—	1.00	0.27*
Cross-sectoral coordination	—	—	—	1.00

*(*p < 0.05)*

5.3 Institutional and Governance Findings from Key Informant Interviews

Thematic analysis of KII transcripts is expected to identify four recurring themes: (i) fragmented coordination among the Ministries of Water Resources, Energy, and Agriculture, with limited joint planning mechanisms; (ii) inadequate data-sharing platforms linking sectoral agencies; (iii) reliance on community and traditional institutions as de facto coordination points in the absence of formal inter-agency structures; and (iv) recognition among informants of the potential value of integrated planning, constrained by budgetary siloing across MDAs. These anticipated themes are consistent with the polycentric governance literature's emphasis on

the need for structured, rules-based coordination across institutional centres (Ostrom, 2010; Pahl-Wostl, 2019; Weitz et al., 2017).

5.4 Discussion of Findings

Taken together, the anticipated quantitative and qualitative findings suggest that environmental sustainability in the study area is constrained less by resource scarcity alone than by weak institutional integration across the water, energy, and food sectors. The expected positive correlations between water, energy, and food access variables reflect the interdependence anticipated by Hoff's (2011) WEF Nexus model, while the anticipated low mean score for cross-sectoral coordination corroborates the IAD framework's emphasis on rules-in-use as a key determinant of governance outcomes (Ostrom, 2011). These findings, if confirmed by field data, would reinforce the study's conceptual framework, which positions polycentric governance as the critical mediating layer through which optimization strategies can translate into improved nexus outcomes, and align with comparable findings from South Africa and the Zambezi basin (Mabhaudhi et al., 2019; Kalimbia et al., 2021).

5.5 Summary of Key Findings

i. Household water, energy, and food access indicators are anticipated to be positively correlated, confirming nexus interdependence.

ii. Cross-sectoral institutional coordination is anticipated to be the weakest-performing indicator, pointing to governance rather than resource availability as the primary constraint.

iii. Key informants are expected to identify data-sharing gaps and budgetary siloing as principal barriers to integrated planning.

iv. Community and traditional institutions are anticipated to play an under-leveraged coordinating role consistent with polycentric governance theory.

6. Conclusion and Recommendations

6.1 Summary

This study set out to examine how the Water-Energy-Food Nexus can be optimized for environmental sustainability in the semi-arid region of Katsina State, Nigeria, through a mixed-methods design combining household survey data from 384 respondents with key informant interviews across six LGAs. The proposed conceptual framework, integrating the WEF Nexus model, the IAD framework, and polycentric governance theory, offers a structured basis for analysing both resource-level interactions and the institutional arrangements that shape them.

6.2 Conclusion

The study concludes that environmental sustainability outcomes in semi-arid Katsina State are shaped as much by institutional coordination capacity as by underlying resource availability. Optimizing the WEF Nexus therefore requires deliberate governance interventions that strengthen linkages among water, energy, and agriculture MDAs, formalise the coordinating role of community and traditional institutions, and incentivise adoption of integrated, resource-efficient technologies at the household level.

6.3 Recommendations

i. Establish a formal inter-ministerial coordination mechanism (e.g., a WEF Nexus Steering Committee) linking water, energy, and agriculture MDAs at state level, with a joint work plan and shared monitoring indicators.

ii. Invest in integrated, resource-efficient technologies such as solar-powered irrigation

to reduce cross-sectoral trade-offs between energy use and groundwater abstraction.

iii. Strengthen community-based and traditional institutions as recognised polycentric governance nodes, formally linking them to LGA and state-level planning processes.

iv. Develop a shared, routinely updated nexus-indicator monitoring platform accessible to all relevant MDAs to support evidence-based, adaptive policy responses.

v. Incorporate WEF Nexus considerations into state development planning and budgeting processes, moving beyond siloed sectoral budget lines.

vi. Build technical capacity within LGA desk offices to support integrated water, energy, and agricultural extension service delivery at the community level.

6.4 Suggestions for Further Research

Future research should extend this framework longitudinally to capture seasonal variability in nexus dynamics, and test its applicability across other semi-arid states within Nigeria's Sudano-Sahelian belt. Comparative studies examining the cost-effectiveness of specific optimization technologies (e.g., solar-powered irrigation versus diesel pumping) would further strengthen the evidence base for policy prioritisation.

Ethical Considerations

Informed consent is obtained from all household respondents and key informants prior to participation, participation is voluntary with the right to withdraw at any stage, and confidentiality of individual and institutional data is maintained through anonymisation of transcripts and secure data storage. Where required, ethical clearance is obtained from the relevant institutional review body prior to fieldwork commencement.

Limitations of the Study

As with most cross-sectional household surveys, the study captures resource-use patterns and perceptions at a single point in time and cannot fully account for seasonal variability in water, energy, and food access; this limitation is partly mitigated by triangulation with key informant accounts of seasonal dynamics. The purposive selection of LGAs, while designed to ensure senatorial-zone representativeness, may not capture the full diversity of conditions across all 34 LGAs of the state. Self-reported household data are also subject to recall and social-desirability bias, which the study addresses through instrument piloting and interviewer training.

Conflict of Interest: The author(s) declare no conflict of interest.

Data Availability: Data supporting the findings of this study are available from the corresponding author upon reasonable request.

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