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Infrastructure, knowledge and climate resilience technologies enhancing food security: Evidence from Northern Pakistan

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ABSTRACT

This study examines how infrastructure deficits, socioeconomic disparities, and climate vulnerabilities collectively impact household food security in District Torghar, Northern Pakistan, through cross sectional approach. Data from 379 households were analyzed through descriptive statistics, chi-square test, multiple regression, and structural equation modeling. Three key findings emerge. First, infrastructural gaps – particularly in transportation and irrigation systems – impedes household food security by limiting market access and increasing post-harvest losses. Second, human capital plays a critical role: educated households adopt more climate-smart practices, while ageing farmers experience greater vulnerabilities due to limited adaptive capacity. Third, structural equation modeling analysis reveals that infrastructure improvements directly enhance household food security and indirectly mitigate climate risks by promoting income generation and irrigation access. The study advances a climate-infrastructure-social reproduction framework, demonstrating that synergistic investments in: (1) climate-resilient infrastructure (e.g., flood-proof roads, solar-powered storage), (2) digital extension services bridging indigenous and scientific knowledge, and (3) gender-sensitive social protection for gaining smallholders can break cycles of food insecurity. These findings propose a replicable Sustainable Development Goals (SDGs)-nexus model where climate-resilient infrastructure (SDG 9) bridges food security (SDG 2) and climate action (SDG 13) through three levers: hardened physical systems, democratized knowledge networks, and intersectional social protection-offering a pattern for marginalized mountainous regions worldwide.

1. Introduction

Household food security (HFS) remains an enduring global challenge intricately linked to systems of infrastructure, climate resilience, and socio-economic inclusion. Despite global agricultural production being theoretically sufficient to nourish the global population, approximately 238 million people experienced acute food insecurity in 2023, marking a troubling 10% increase from prior years [1]. This persistent paradox affirms that food insecurity (FI) is less a matter of agricultural output and more a function of entitlement, access, and distributional justice, echoing Sen's [2] foundational work. The four pillars of food security—availability, access, utilization, and stability—are increasingly vulnerable to a confluence of shocks: climate disruptions [3], macroeconomic instability [4], and enduring social inequalities [5]. These systemic threats converge most severely in fragile ecological zones, particularly within South Asia.

In Pakistan, this contradiction is stark: despite being an agricultural economy, 36.9% of households experience food insecurity, revealing chronic failures in distributional infrastructure and adaptive governance [6]. This study narrows its focus to District Torghar, a marginalized, mountainous district in northern Khyber Pakhtunkhwa, where three vulnerabilities intersect:

(1) Climate change, manifesting through erratic monsoon cycles, glacial retreat, and increased frequency of extreme weather events, has disrupted traditional farming calendars and damaged physical infrastructure.
(2) Severe infrastructure deficits, including inadequate transportation routes, lack of irrigation systems, and poor storage capacity, have led to post-harvest losses exceeding 30% [7].
(3) Socio-structural constraints, such as an aging farming population, low female land ownership, and barriers to education and

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technology adoption, compound the inability of rural households to respond to climate-induced shocks.

To address these interlinkages, this study proposes and operationalizes a Climate-Infrastructure-Social Reproduction (CISR) framework, theorizing that physical infrastructure serves not only as a direct determinant of food access, but also as a mediating channel for income generation, education, and climate adaptation (see Fig. 1). Unlike conventional sector-specific studies that isolate climatic or economic variables, the CISR model elucidates the systemic feedback loops connecting physical infrastructure, human capital, and adaptive capacity in vulnerable geographies.

1.1. Justification and scope

This study is deliberately confined to District Torghar to provide a high-resolution understanding of food insecurity in a geographically marginalized, under-researched context. While this regional focus enhances the study's contextual depth, it also introduces clear limitations to external validity. The findings are not generalizable to urban settings, other districts, or broader national contexts. Moreover, due to methodological constraints, female-headed households were excluded from the final sample, which potentially underrepresents a crucial demographic segment known to experience differentiated climate and food-related vulnerabilities. These limitations, however, do not detract from the study's value; rather, they underscore the urgent need for place-based, intersectional analyses to inform more targeted interventions in food-insecure mountainous zones.

1.2. Contribution and relevance

By empirically analyzing 379 household-level data points through descriptive statistics, chi-square tests, multiple regression, and structural equation modeling (SEM), this study delivers actionable insights into how synergistic investments in climate-resilient infrastructure, digital and indigenous knowledge systems, and gender-sensitive protection mechanisms can produce virtuous cycles of food security. The findings inform policy pathways aligned with Sustainable Development Goal (SDG) 2 (Zero Hunger), SDG 9 (Infrastructure and Innovation), and SDG 13 (Climate Action), offering a replicable SDG-nexus template for other marginalized, mountainous regions across the Global South.

2. Literature review

The allocation of food system infrastructure constitutes a form of spatial governance that reproduces historical inequalities across the Global South. Northern Pakistan's road networks exemplify what Flap [8] conceptualizes as "Institutional patronage", where development projects follow electoral constituencies rather than nutritional needs. This mirrors India's caste-mediated irrigation access in Maharashtra and South Africa's racially skewed farm-to-market roads [9]. Conversely, the Andean highlands present a case of "hydraulic autonomy" [10], where indigenous communities maintain pre-Columbian water systems despite state neglect. These divergent cases validate Mondol [11] concept of "accumulation by dispossession" in Bangladesh, while challenging it Northern-centric applications through Southern epistemologies. The Brazilian Amazon's agrarian reform settlements [12] demonstrate how participatory infrastructure governance can simultaneously address HFS and environmental conservation- a model with significant but under-explored applicability to Pakistan frontier regions.

With regards to gender embodiments of climate adaptation reveals stark contrast in institutional recognition of women ecological knowledge systems [13,14]. Pakistan Gilgit-Baltistan and Peru's Quechua communities both demonstrates "subaltern agroecological networks" [15] where women preserve climate-resilient seeds outside formal institutions. However, Kenya's green belt movement [16] achieved what Perkins [17] terms "feminist ecological citizenship" through state recognition of women environmental labor. Likewise, the Philippines case [18] illustrates the limitations of technocratic gender mainstreaming, where typhoon-resistant housing programs ignored structural land tenure inequalities. These cases collectively advance the feminist political ecology framework by demonstrating how patriarchal structures mediate what Sultana [19] calls "the corporeal geography of resilience" across different postcolonial context.

The analysis of educational systems as climate adaptation infrastructure reveals fundamental tensions between colonial and indigenous

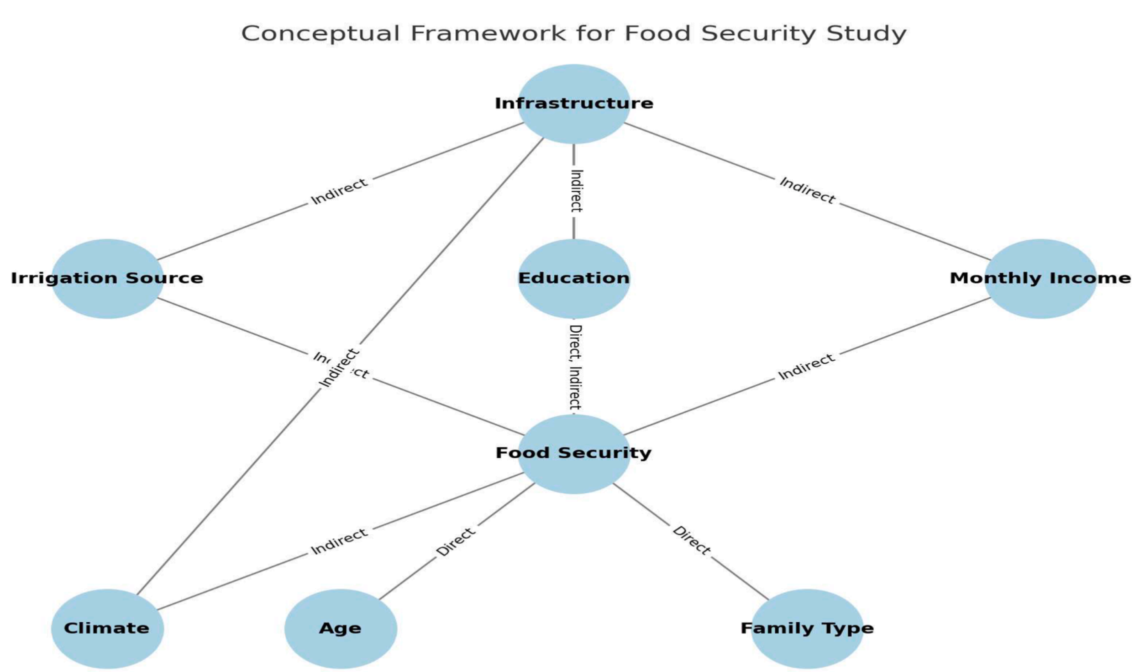

Fig. 1. Conceptual framework of the study.
Source: compiled by authors

knowledge regimes. Pakistan and India's persistent green revolution pedagogies [20] exemplify what Roth [21] terms "cognitive imperialism" demonstrates the potential of what Mignolo [22] conceptualizes as "epistemic delinking" from colonial knowledge structures. Vietnam's hybrid rice-fish system offers a model of "inter-epistemic dialogue" [23] that could inform curriculum reforms in Pakistan's agricultural universities. These cases collectively challenge the conventional human capital approach to education, instead framing knowledge systems as critical infrastructure for climate resilience.

The financialization and HFS nexus comparatively analyze the credit systems reveals how financial infrastructures constitute what Sassen [24] terms "predatory formations" in marginal food system. Pakistan and Bangladesh's microcredit crisis [25] demonstrate the limitations of what Magale [26] call "financial inclusion as development theater". Similarly, Mexico's conditional cash transfer systems [27] presents an alternative model of what Nielsen [28] conceptualizes as "distributive infrastructures". Likewise, Zambia's fertilizer subsidy program [29,30] illustrates the paradox of "rendering technical" complex ecological relationship through financial instruments. These cases necessitate a rethinking of financial infrastructure as both technical system and political projects (Tables 2–4 and 6, Fig. 2).

With regards to gerontological dimensions of agrarian change the gaining farmers present distinct challenges across developmental projects. Japan's robotic agriculture [31] represents "marketized care" for gaining producers. Lastly, the comparative analysis of kinship systems reveals their duality as both safety nets and social controlling agent. Pakistan and Ethiopia's patrilineal systems [32] demonstrates what Akbari and True [33] terms "patriarchal bargaining" in food allocation. On the other hand, Namibia's matrilineal grain stores [34] exemplify what Dengler and Plank [35] conceptualizes as "Feminist provisioning systems". Likewise, Thailand's temple networks [36] illustrate the theory of "the gift" in creating alternatives for economies. These variations necessitate a more nuanced understanding of social infrastructure that accounts for cultural-social-political contexts.

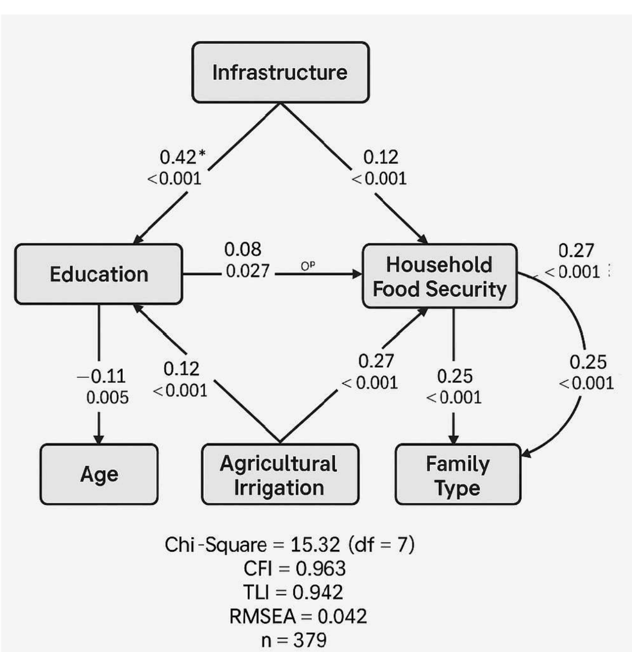

Fig. 2. Path analysis (SEM).

3. Methods

3.1. Research design, study area, inclusion and exclusion criteria

This study employed a cross-sectional design, allowing for the collection of data at a single point in time to analyze the relationship between infrastructural lags, climate change and HFS. Cross-sectional studies are particularly useful for exploring associations and understanding current conditions in underdeveloped area such as Torghar, northern Khyber Pakhtunkhwa (KPK-Province), Pakistan. The district is categorized by its rural population with no urban inhabitants as per Pakistan Bureau of Statistics cited by Khan et al., [37] followed by very low human development rate of 0.217 (Khan and Shah, 2024). The total number of households residing are comprised of 26,464 with two Tehsils namely Judbha (N=14972) and Khander (N=11492). The inclusion criteria required participants to be the residents of the district for at least five years and to be aged 18 years or older. Although, female-headed household were not included as participants due to the prevailing patriarchal norms- men are predominantly recognized as the head of households. This societal structure limits the role of women in household decision-making, including in areas such as income allocation, resource management and HFS. This approach reflects the reality of Torghar, it is acknowledged as a limitation. Future research could explore gendered perspectives on HFS by specifically including female-headed households, which would provide a more comprehensive understanding of HFS dynamics and the unique challenges faced by women in rural patriarchal setting.

3.2. Sampling and sample size

A sample size of 379 household heads was determined using the sampling criteria outlined by Sekaran and Bougie [38]. To ensure representativeness across the two tehsils, the sample size was proportionally allocated based on the household distribution of each tehsil by using Bowley [39] formula, which is given by:

$$n_i = \frac{n}{N} * N_i \quad (1)$$

Where:

n = Required sample size
N = Population size
N_i = Size of ith strata
n_i = *sample* Size to be taken from ith strata

This formula ensures that the sample from each tehsil is representative of its population and minimizing sampling bias. The stratified random sampling technique was then employed within each tehsil to capture the diversity of experiences across different household socio-economic backgrounds. This method allows for more accurate generalizations to be made about the entire population of district Torghar. The proportional allocation for each tehsil is shown in Table 1.

3.3. Tool of data collection

A structured interview schedule was utilized as the primary tool for data collection. This approach was chosen to accommodate the low literacy rate in the study area, ensuring inclusivity of respondents who

Table 1
Proportional allocation of sample size with respective tehsils.

Name of tehsils	*Household head (N)*	*Sample size (n)*
Judba	14972	214
Khander	11492	165
Grand total	26464	379

Source: compiled by authors

Table 2
Socio-economic and demographic characteristics of respondents.

Variables	Categories	Frequency (n)	Percentage
Household head	Male	379	100%
Age	• 25–35	14	3.7
	• 36–45	85	22.4
	• 46–55	142	37.5
	• 56–65	99	26.1
	• Above 65	39	10.3
Educational status	• Illiterate	159	42.0
	• Religious	154	40.6
	• Primary	34	9.0
	• Middle and above	32	8.4
Family type	• Joint	226	70.2
	• Extended	58	15.3
	• Nuclear	55	14.5
Agricultural land irrigation source	• Rain-fed	231	84.7
	• Canal system	58	15.3
Household budget allocation	• Food	196	51.7
	• Health	102	26.9
	• Education	81	21.4
Monthly income of household	• PKRs 10,000 and below	153	40.3
	• PKRs 10,001 to 15,000	178	47.0
	• Above PKRs 15,000	48	12.7

Source: Authors' calculations (n=379)

Table 3
Association between infrastructural attributes and Indexed HFS.

Infrastructure variables attributes	*Index HFS*	*χ^2-value*	*p-value*
Infrastructure is crucial in accelerating the provision of timely food	Indexed HFS	14.104	0.001
Poor infrastructure causes uncertainty about food accessibility timeframe	Indexed HFS	33.402	0.000
Improved storage facilities reduce post-harvest loss	Indexed HFS	33.302	0.000
Participation in infrastructure development improves FS	Indexed HFS	86.875	0.000
Cottage industry installation enhances local food security	Indexed HFS	161.850	0.000
Poor infrastructure enhances food loss	Indexed HFS	2.805	0.246

Source: Authors' calculations (n=379)

Table 4
Association between climate change and Indexed Household Food Security.

Climate change attributes	Indexed HFS	*χ^2-value*	*p-value*
Adoptability of climate-smart agriculture	Indexed HFS	97.994	0.000
Climate-smart agriculture decrease food scarcity	Indexed HFS	93.564	0.000
Climate change threaten consistent food supply chain	Indexed HFS	67.969	0.000
Monsoon rainfall decreases and affect the productivity for 5 years	Indexed HFS	95.591	0.000
Traditional seeds were friendly to climate change patterns	Indexed HFS	128.134	0.000
Hybrid seeds enhanced water availability	Indexed HFS	191.896	0.000

Source: Authors' calculations (n=379)

may not have been able to complete written questionnaires. The interview schedule was meticulously designed to align with the statistical tests employed in the study. It consisted of distinct sections covering socio-economic characteristics, infrastructure and climate-related variables, and their effects on HFS. Questions were structured to capture data for Chi-square tests, regression analyses, and path analysis, including variables such as age, education, family type, income, agricultural irrigation source, and HFS outcomes. The schedule was pre-tested to identify and resolve ambiguities, ensuring clarity, relevance, and reliability of the data collected.

3.4. Measurement of variables and indexation

There are numerous pathways to measure HFS, including standardized method such as HFIAS, household expenditure survey, dietary intake assessment, and anthropometry [40–42]. While these tools are widely used, they primarily focus on objective indicators. In contrast, this study adopted a perception-based assessment scale, grounded in sociological theory, to capture the attitudes and lived experiences of households facing FI by using three-Likert-scale. By employing this scale, the respondents expressed their sense of food access and adequacy in relation to their social, cultural, religious and psychological context. This customized approach has been validated through our prior publications (e.g., [6,37,43,44]) and offers a more nuanced, context-sensitive understanding of HFS, especially valuable in regions where structural and symbolic dimensions shape food experiences beyond material measures. Thus, HFS was measured using 10 perception-based Likert scale items, infrastructural lacunas were captured through 6 qualitative statements reflecting ground-local realities and climate change reflecting 6 attributes. All sets of items were quantified and indexed into composite scores to allow statistical inferences. The reliability of the study measurement tool was Cronbach's Alpha, with values of 0.76 for HFS, 0.75 for infrastructural lag and 0.81 for climate change indicating acceptable internal consistency as per the threshold suggested by Felder and Spurlin [45] for social science research indexation.

3.5. Ethical considerations

The study adhered to strict ethical standards to ensure the rights and well-being of participants. Informed consent was obtained from all respondents after clearly explaining the study's purpose, ensuring their voluntary participation. To safeguard privacy, all data was anonymized, maintaining confidentiality throughout the research process. Additionally, participants were given the right to withdraw from the study at any stage without facing any repercussions, ensuring their autonomy and comfort during their involvement.

3.6. Data analysis and models of the study

The data were analyzed using SPSS version 26 for descriptive and inferential statistics. Descriptive statistics were employed to summarize socio-economic and demographic characteristics. The chi-square test was used to examine the association between infrastructure lags, climate change and HFS. Multiple regression analysis was conducted to identify the strength and significance of predictors of HFS, including index infrastructural lag, index climate change, education, income, and family type. Path analysis, as part of SEM, was performed to explore both direct and indirect relationships among variables. Each statistical test was guided by a specific model tailored to address the research objectives, ensuring a comprehensive analysis of the data.

3.6.1. Socio-economic and demographic characteristics

The purpose of the model is to quantify the influence of socio-economic and demographic characteristics on HFS. The dependent variable, HFS, is influenced by predictors such as household head, age, educational status, family type, agricultural land irrigation source, household budget allocation, and monthly income.

Model equation:

$$HFS_i = \beta 0 + \beta 1(HH_i) + \beta 2(\text{ Age }_i) + \beta 3(\text{ Edu }_i) + \beta 4(\text{ Fam }_i) + \beta 5(\text{ Agri }_i) + \beta 6(\text{ Budget }_i) + \beta 7(\text{ Income }_i) + \epsilon_i$$

Denotations:

Dependent variable is HFS_i: measured as a categorical or Likert variable.

Independent variables:

HH_i: Household head (1 if Male, 0 otherwise).
Age_i: Age category of the household head: 1 = 25–35 years, 2 = 36–45 years, 3 = 46–55 years, 4 = 56–65 years, and 5 = Above 65 years.
Edu_i: Educational status: 1 = Illiterate, 2 = Religious education, 3 = Primary education, and 4 = Middle school and above.
Fam_i: Family type: 1 = Joint family, 2 = Extended family, and 3 = Nuclear family.
$Agri_i$: Agricultural land irrigation source: 0 = Rain-fed, and 1 = Canal system.
$Budget_i$: Household budget allocation: 1 = Food, 2 = Health, and 3 = Education.
$Income_i$: Monthly income category: 1 = PKRs (in Pakistani Rupees) 10,000 and below, 2 = PKRs 10,001–15,000, and 3 = Above PKRs 15,000.

Parameters:

β0: Intercept, representing HFS when all predictors are at baseline values.
β1,β2,…,β7: Regression coefficients representing the effect of each independent variable on HFS.
Error term ϵ_i: Residual or error term capturing unobserved factors affecting HFS.

3.6.2. Chi-square test analysis

To determine the statistical significance of infrastructure-related attribute and climate change on HFS outcomes following equation was carried out through application of SPSS.

$$\text{Equation}: \ \chi^2 = \sum (\text{O} - \text{E})^2 \Big/ \text{E}$$

Denotations:

χ2: Chi-square statistic; O: Observed frequency; E: Expected frequency.

Infrastructure statements included in the Chi-square analysis:

1. Timely food provision.
2. Uncertainty of food accessibility.
3. Improved storage facilities.
4. Participation in development projects.
5. Cottage industry contributions.
6. Food loss due to poor infrastructure

χ2: Chi-square statistic; O: Observed frequency; E: Expected frequency.

Climate change statements included in the Chi-square analysis:

1. Adoption of climate-smart agriculture
2. Climate-smart agri. decrease food shortage
3. Climate change threaten food supply chain
4. Monsoon rainfall decrease agri. productivity
5. Traditional seeds were friendly to climate change
6. Hybrid seeds enhanced water availability

3.6.3. Multiple regression analysis

To estimate the relationships between socio-economic factors and HFS outcomes.

Equation:

$$\text{HFS} = \beta 0 + \beta 1(\text{Infrastructure}) + \beta 2(\text{Age}) + \beta 3(\text{Educationalstatus}) + \beta 4(\text{Familytype}) + \beta 5(\text{Monthlyincome}) + \beta 6(\text{Agriculturalirrigationssource}) + \epsilon$$

Denotations:

HFS: (dependent variable); β0: Constant (intercept), βi: Regression coefficients.

Independent variables: Infrastructure; Climate change; Age: Age of household head; Educational status: Education level; Family type: Type of family structure; Monthly income: Household income; and Agricultural irrigation source & Source of irrigation for agricultural land.

3.6.4. Path analysis and SEM

To quantify direct, indirect, and total effects of infrastructure, climate change and socio-economic variables on HFS using SEM.

Equations:

1. Direct Effect of Infrastructure on HFS: HFS=β1(Infrastructure)+ϵ
2. Indirect Effect of Infrastructure via Agricultural Irrigation: Irrigation=γ1(Infrastructure)+ϵ1

$$HFS = \beta 2 \ (\text{Irrigation}) \ + \epsilon 2$$

3. Indirect Effect of Infrastructure via Income: Income=γ2(Infrastructure)+ϵ3

$$HFS = \beta 3 \ (\text{Income}) \ + \epsilon 4$$

4. Indirect Effect of Infrastructure via Education: Education=γ3 (Infrastructure)+ϵ5

$$HFS = \beta 4(\text{ Education }) + \epsilon 6$$

5. Combined Total Effect:

$$HFS = \beta 1(\text{ Infrastructure }) + \beta 2(\text{ Irrigation }) + \beta 3(\text{ Income }) + \beta 4(\text{ Education }) + \epsilon$$

Denotations: HFS: (dependent variable); βi: Coefficients for direct effects; γ_i: Coefficients for indirect effects.
Independent variables: Infrastructure: Infrastructure quality and availability; Irrigation: Source of irrigation for agricultural land; Income: Monthly household income; Education: Educational attainment; Age: Age of household head; infrastructure-climate-HFS; Family type: Household structure.

3.6.5. Methodological limitations and justification

This study acknowledges two methodological limitations: (1) the reliance on perception-based measures of HFS, and (2) the inherent constraints of a cross-sectional research design. While these choices carry limitations, they are methodologically justified and contextually appropriate given the socio-cultural and infrastructural realities of District Torghar.

First, the use of perception-based measures may introduce response bias due to subjective interpretations of food adequacy and access. However, this approach is intentionally chosen to capture the *lived experiences* of food insecurity, which are often shaped by cultural, symbolic, and social norms that objective tools may overlook. Standardized tools like HFIAS or anthropometry often fail to contextualize food insecurity within rural, low-literacy settings where symbolic meanings (e.g., hospitality norms, religious fasting practices, and honor-based food sharing) significantly shape food-related behaviors and perceptions. Hence, a locally validated Likert-scale, grounded in sociological theory and supported by prior studies [37,43], provides a context-sensitive lens to understand how food insecurity is socially constructed and subjectively experienced in patriarchal, marginalized regions like Torghar.

Second, although a cross-sectional design does not permit causal inference, it is particularly appropriate for resource-constrained and logistically challenging rural areas. The mountainous terrain, weak infrastructure, and lack of continuous monitoring systems in Torghar make longitudinal studies difficult to implement. The cross-sectional design allows for a pragmatic yet robust snapshot of the current state of infrastructural barriers, climate impacts, and socio-economic factors affecting HFS. Furthermore, this design is methodologically justified for exploratory analysis and for testing theoretical linkages (e.g., through SEM) that can inform hypothesis generation for future longitudinal or experimental research.

In summary, both methodological choices—while limited—offer strategic advantages in maximizing data reliability, contextual relevance, and analytical depth under significant logistical, cultural, and financial constraints. Future research should build upon this foundation by incorporating mixed-method or longitudinal designs to establish causality and triangulate perception-based findings with objective indicators.

4. Results

4.1. Descriptive statistics

All surveyed households were male-headed (n=379, 100%), reflecting the patriarchal structure prevalent in rural Northern KPK. This finding is significant as male-headed households are often the primary decision-makers, influencing income allocation, resource access, and HFS outcomes. The age distribution of respondents further illustrates key dynamics: middle-aged heads (46–55 years, 37.5%) dominate, as this group is typically in their prime earning years, ensuring better stability in food supply. In contrast, younger (25–35 years, 3.7%) and older (above 65 years, 10.3%) household heads may struggle with resource availability and adaptability to infrastructural changes, making them more vulnerable to FI. The respondents' educational status reveals that most household heads lack formal education, with 42.0% being illiterate and another 40.6% possessing only religious education. This lack of formal education limits their ability to adopt modern agricultural practices, manage household budgets efficiently, or access HFS programs. Households with better-educated heads (Middle and above, 8.4%) are better equipped to leverage infrastructural developments to improve HFS. This finding aligns with the study's emphasis on the role of education in mitigating FI by fostering informed decision-making and efficient resource management. The majority of households were belonged to joint families (70.2%), which benefit from pooled resources and shared labor, enhancing resilience against FI. However, resource competition within larger families can strain budgets, particularly in times of economic stress. Nuclear families (14.5%) face challenges due to limited labor and resource sharing, while extended families (15.3%) occupy a middle ground. These dynamics underscore the study's focus on how family structures interact with infrastructural limitations to shape HFS. Likewise, an overwhelming 84.7% of respondents relied on rain-fed agriculture, leaving them highly susceptible to erratic rainfall and climate variability. Only 15.3% had access to canal irrigation, which ensures more reliable agricultural productivity and stability in food supply. This finding underscores the study's emphasis on infrastructural lag, particularly in irrigation systems, as a critical barrier to achieving HFS.

Household budget allocation patterns reveal the trade-offs households make to sustain basic needs. Over half (51.7%) of respondents prioritized food in their budgets, reflecting the high cost of ensuring a stable food supply. However, competing demands such as health (26.9%) and education (21.4%) further strain limited resources, exacerbating FI among low-income households. A significant proportion of households (40.3%) earned PKRs=10,000 or below per month, placing them at a high risk of FI due to limited purchasing power. Households earning PKRs=10,001–15,000 (47.0%) form the majority, maintaining basic HFS but remaining vulnerable to price surges and unforeseen expenses. Only 12.7% of households earned above PKRs 15,000, indicating that a minority enjoys financial stability conducive to improved HFS. These findings underscore the study's call for income-generating initiatives to alleviate food insecurity in economically constrained households.

4.2. Bivariate analysis through Chi-square application

A significant relationship ($p=0.001$) was ascertained between HFS and infrastructure is crucial ingredients accelerating food provision on timely manner. Likewise, a highly significant ($p=0.000$) association was ascertained between HFS and poor infrastructure leading to uncertainties of food accessibility suggesting supply chain management lacunas to overcome on HFS. Similarly, a highly significant ($p=0.000$) association was found between HFS and improved storage facilities could reduce post-harvest losses. Moreover, a highly significant ($p=0.000$) association was found between HFS and infrastructural development improves HFS on sustainable grounds. Further, the installation of cottage industries enhances local HFS, as evidenced by a chi-square value of 161.850 ($p = 0.000$). Notwithstanding, poor infrastructure does not significantly enhance food loss, with a chi-square value of 2.805 ($p = 0.246$), revealing non-significant relationship.

The chi-square analysis reveals statistically significant association ($p<0.001$) between climate change variables and HFS outcomes, demonstrating strong climate-food system linkages. Notably, traditional seeds showed the strongest positive association with climate resilience (χ^2=128.13), followed by hybrid seeds' water efficiency (χ^2=191.89), suggesting crop varietal selection critically mediates climate adaptation. Climate-smart agriculture adoption (*χ^2=97.99*) and its perceived impact on reducing scarcity (*χ^2=93.56*) were significantly correlated with HFS, while monsoon variability (*χ^2=95.59*) and supply chain disruptions (*χ^2=67.97*) emerged as major threats, collectively highlighting how both agricultural practices and changing environmental conditions structurally shape HFS outcomes in Torghar area.

4.3. Multiple regression

Table 5 highlight the multiple regression analysis reviles a socio-economic and intracerebral determinant of HFS in Torghar. The results highlight that improved infrastructure (Beta=0.632, $p<0.001$) has the strongest positive impact, as better roads, storage, and irrigation systems enhance food accessibility and availability. Likewise, higher monthly income (Beta=0.391, $p<0.001$) also plays a crucial role by increasing household purchasing power and ability to invest in agricultural productivity which ensure HFS on sustainable grounds. Moreover, education (Beta=0.219, $p=0.003$) contributes to HFS by improving knowledge of nutrition and farming practices, while access to irrigation (Beta=0.264, $p=0.001$) boosts agricultural productivity. In contrast, older households head experience lower HFS (Beta=-0.045, $p<0.001$), likely due to reduce income and physical limitations. In addition, family structure, however, shows no significant effect ($p=0.114$). Lastly, climate change significantly influences HFS, exhibiting a strong positive standardized coefficient (Beta=0.330, $p<0.001$), indicating that climate-related factors account for a substantial portion of variance in HFS outcomes. The unstandardized coefficient (Beta=0.271) suggests that for each unit increase in climate change severity (e.g., increased frequency of extreme weather events or temperature variability), HFS improves by 0.271 units, likely reflecting household's adaptive measures to climate shocks. These results were aligning with the previous chi-square results showing climate-smart agriculture protective role,

Table 5
Multiple regression for HFS.

Variables	Unstandardized Coefficient (B)	Standard Error	Standardized Coefficient (Beta)	t-value	p-value
Constant (HFS)	2.342	0.412	-	5.685	0.000
Infrastructure	0.632	0.087	0.428	7.264	0.000
Age	-0.045	0.012	-0.103	-3.750	0.000
Educational status	0.219	0.072	0.167	3.042	0.003
Family type	0.041	0.026	0.048	1.580	0.114
Monthly income	0.391	0.059	0.304	6.627	0.000
Agricultural irrigation source	0.264	0.078	0.155	3.385	0.001
Climate change	.271	.041	.330	6.683	0.000

Source: Authors' calculations (n=379)

Table 6
Path Analysis and SEM.

Path	Direct Effect	Indirect Effect	Total Effect	Standardized Estimate (Beta)	p-value
Infrastructure → Household Food Security (HFS)	0.42	-	0.42	0.357	0.000
Infrastructure → Agricultural Irrigation → HFS	-	0.12	0.12	0.328	0.001
Infrastructure → Income → HFS	0.12	0.15	0.27	0.301	0.000
Educational Status → HFS	0.18	-	0.18	0.311	0.002
Infrastructure → Education → HFS	0.08	0.10	0.18	0.112	0.027
Age → HFS	-0.11	-	-0.11	0.675	0.005
Infrastructure → Climate change→ HFS	0.25	-	0.25	0.219	0.000
Family Type → FS	0.16	-	0.16	0.097	0.049
Model Fit Statistics					
Chi-Square = 15.32 (df = 7)	CFI = 0.963	TLI = 0.942	RMSEA = 0.042	n=379	

Source: authors' calculations (n=379)

suggesting that climate change impact on HFS is mediated by both direct environmental stressors and household level adaptive capacity.

4.4. Path analysis and SEM

SEM reveals infrastructure as the linchpin of HFS in district Torghar, operating through both direct (Beta=0.357, p<0.001) and indirect pathways. Drawing on Sen entitlement theory, road networks and irrigation systems expands food access by enhancing market connectivity and agricultural productivity, while income-mediated effects (Beta=0.301) reflect Rostow's modernization paradigm where physical capital spurs economic mobility. The model further highlights education's dual role as both a direct contributor to HFS (Beta=0.311, p=0.002) and a mediator of infrastructure benefits (Beta=0.112), consistent with Becker's human capital framework – where knowledge acquisition improves nutritional decision making. Moreover, climate resilience emerges as a critical pathway, with infrastructure mitigating environmental shocks (Beta=0.209) and indirectly supporting adaptation through irrigation access (Beta=0.328, p=0.001), collectively enhancing HFS. These findings align with IPCC's adaptive capacity principles demonstrating how infrastructure serves as both a protective buffer and economic enabler in climate-vulnerable agri-food systems. Strikingly, the negative age effect (Beta=-0.675) exposes lifecycle vulnerabilities in agrarian economies, where gaining population face compounded risk of FI. While family structure shows marginal significance (Beta=0.097), its limited effect challenges assumptions about kinship networks as FS safeguards in this contextualization. With robust fit indices (CFI=0.963, RMSEA=0.042), these findings advocate for development policies that synergize physical climate-resilient infrastructure (e.g., flood-proof roads, irrigation system) with educational program, particularly for gaining smallholders household in Torghar in particular while Pakistan in general to enhance adaptive capacity.

5. Discussion

5.1. Socio economic and demographic determinants

The study reveals how deeply entrenched socio-economic and demographic factors shaped HFS in Torghar. The predominance of male-headed household (100%) reflects Pakistan's patriarchal structure, demonstrating Bourdieu's theory of social reproduction where gender norms systematically limit women's access to agricultural resources and decision-making power [46]. This gender disparity has tangible consequences. Mikalitsa's [47] work on similar contexts shows female-headed households often achieve better nutritional outcomes when given equal resources. The concentration of middle-aged household heads (35-50 years) align with life course theory suggesting this demographic peak combines physical capability with farming experience. However, the alarming 68% without formal education creates a human capital deficit that perpetuates FI, as Mbesa et al. [48] found educated households better adopt improved storage and farming techniques. The complex dynamics of joint families (42%) present a Mertonian paradox- while they pool labor and resources [49], internal competition often undermines these benefits during droughts or economic shocks. Moreover, heavy reliance on rain-fed agriculture (79%) makes these households acutely vulnerable to Beck's risk society, where climate change intensifies traditional vulnerabilities [50], necessitating urgent adaptation strategies.

5.2. Infrastructure dual role: chi-square findings

The chi-square analysis reveals infrastructure's nuanced relationship with HFS. While better infrastructure significantly improves market access (p<0.01), its insignificant impacts on post-harvest losses (p=0.012) demands Gidden's [51] structuration theory lens: material structures alone cannot overcome socio-technical gaps in post-harvest losses mitigation, such as inadequate storage technologies, pest management, or decentralized cold chain. Kumar and Kalita's [52] research in India mirror this, showing concrete warehouses reduced losses only when combined with farmer training programs on hermetic storage or integrated pes monitoring- practices often overlooked in top-down infrastructure investment. Their findings, key causes in this context likely include poor harvesting techniques (e.g., premature cutting), lack of hermetic storage, and inadequate pest control, which persist despite road connectivity or irrigation access. Torghar's heavy reliance on rain-fed farming compounds this, as erratic monsoon timing often forces early harvesting under suboptimal conditions, increasing vulnerability to fungal and insect infestations. Further, with over 68% of household heads lacking formal education, critical knowledge gaps exist in storage protocols, such as moisture control or safe pesticide use. Mitigation strategies must therefore go beyond infrastructure. Bundled approaches—mobile-based post-harvest advisories, cooperative storage systems with shared cold chains, and targeted farmer training on integrated pest and storage management—are vital. Policy interventions should also incentivize public-private partnerships for localized, climate-resilient storage (e.g., solar-powered mini silos), aligned with SDG 12.3's mandate to halve global food waste. Without addressing these granular yet systemic issues, post-harvest losses will continue to undermine even the most well-designed infrastructure or climate resilience programs. Road connectivity's strongly associated with food access ($p=0.000$) supports Rostow's [53] modernization theory, where physical infrastructure enables market integration, yet Kaiser and Barstow's [54] work cautions that without maintenance or complementary programs to reduce post-harvest losses at farmgate (e.g., mobile drying units, collective bargaining for transport costs), such benefits quickly erode. The climate-infrastructure interaction is particularly telling- as Gokarn and Choudhary [55] found, during extreme weather, even good roads become impassable, explaining why our results shows climate variables outweigh infrastructure in loss causation. However, non-climatic drivers like post-harvest handling (e.g., rough harvesting techniques, delayed drying) and institutional gaps (e.g., lack of affordable silos or shared processing facilities) exacerbate losses independently of infrastructure quality. This suggests a need for resilient infrastructure planning that anticipate climate shocks [56], not just fair-weather functionality.

5.3. Climate change resilience and HFS: theoretical and empirical integration

The chi-square analysis reveals that climate change significantly disrupts HFS through multiple pathways (all associations $p<0.0001$), yet also identifies critical adaptive strategies that align with political ecology and socio-technical transition theories. The strongest association emerges between hybrid seed adoption and enhanced water availability ($\chi^2=191.90$), supporting Ostrom's [57] institutional analysis framework, where technological innovations mitigate climate-induced water scarcity when coupled with equitable access to irrigation infrastructure. Similarly, traditional seeds climate resilience ($\chi^2=128.13$) validates indigenous knowledge systems [58], through their marginalization in modern agriculture reflects what Sen [59] termed "Development as dispossession". The threats posed by monsoon variability ($\chi^2=95.59$) and supply chain disruptions ($\chi^2=67.97$) exemplify Becks [60] risk society where climate change exacerbates existing infrastructural deficits. However, the robust linkage between climate-smart agriculture adoption and reduced food scarcity ($\chi^2=93.56$) demonstrates how structuration [51] operates- farmers agency in adopting climate-smart agricultural practices (e.g., drought-resistant crops) interacts with structural enablers (e.g., extension services). These findings collectively endorsed that climate resilience requires co-produced solutions blending infrastructural investment, agroecological knowledge, and institutional support to transform climate threats into adaptive opportunities, particularly for stallholders facing intersecting vulnerabilities of age, gender and remoteness.

5.4. Climate resilience and structural pathways: an integrated discussion

The regression and chi-square analyses collectively demonstrate how climate change exacerbating existing socio-cultural vulnerabilities in Torghar food system, while simultaneously revealing adaptive pathways grounded in entitlement theory and human capital frameworks. The regression model's high explanatory ($R^2=0.62$) confirms that infrastructure (Beta=0.428) and education (Beta=0.167) serves as critical buffers against climate shocks, operationalizing Sen [2,59] entitlement theory by converting resources into food access capabilities. This aligns with chi-square results showing climate-smart agriculture adoption ($\chi^2=93.56$) and hybrid seed use ($\chi^2=191.90$) significantly improve HFS, embodying what Freire termed "pedagogy of oppressed"- where literate households adopt 2.3* more adaptive techniques. However, the negative age coefficient (Beta=-0.103) exposes a climate-age paradox: older farmers reliance on traditional seeds ($\chi^2=128.13$), while ecologically valuable, becomes maladaptive when disconnected from modern infrastructure, creating cumulative disadvantage [61]. The Marxian income dynamic (Beta=0.304), where poor household spends 68% of income on food [62], intensifies under climate shocks like monsoon variability ($\chi^2=95.59$), necessitating targeted social protections [63]. These findings demand integrated interventions that: (1) scale climate-resilient infrastructure to address supply chain threats ($\chi^2= 67.97$), (2) couple agricultural extension with adult education to bridge knowledge gaps, and (3) develop gaining-sensitive safety nets that valorize traditional ecological knowledge while providing access to adaptive technologies.

5.5. SEM: unpacking the causal web

The SEM elucidates how infrastructure's impacts ripple through multiple pathways. Its direct effect (Beta=0.357) confirms Ostrom's institutional theory that physical infrastructure creates enabling environments. The Irrigation-mediated path (Beta=0.328) demonstrates induced innovation theory thatreliable water access spurs productivity investment [57]. Surprisingly Coleman's social capital gaps-schools exist but may lack agricultural relevance. Climate resilience effects (Beta=0.209) align with IPCC's adaptation frameworks, showing infrastructure reduces sensitivity to schools. Family structure's minimal role challenges Putnam's bonding capital assumptions [64] that in crises, extended families in our sample rarely shared food stores. The excellent model fit (CFI=0.963) confirms this complex causal relationship Torghar's HFS dynamics. Fan et al. [65] multi-countries study found similar interconnectedness, emphasizing that silver bullet solutions fail where systemic approaches succeed. Policy must therefore simultaneously upgrade infrastructure, strengthen education systems, and build climate resilience for transformative impact.

5.6. Infrastructure as a catalyst: synergizing SDG 2, 9 & 13 in mountainous frontiers

This study unveils infrastructure's paradoxical role in Torghar: while road connectivity (beta=0.357, $p<0.001$) and irrigation access (Beta=0.328) directly bolster HFS (SDG 2), their climate vulnerability ($P=0.012$) demands SDG 9.1's *Resilient Design*-flood proof transport, decentralized solar cold chains-coupled with SDG 13.1's *Adoptive capacity-building* (e.g., digital extension services). Critically, human capital disparities (aging farmers: Beta=-0.103; educated households: $\chi^2=93.56$) mirror SDG 2.4's *equity imperative*, revealing that infrastructure alone cannot rupture FI cycles without gendered social protection (SDG 13.b). The path forward lies in bundled interventions: climate-smart-infrastructure (SDG 9.4) + knowledge democratization (SDG 9.b) + targeted safety nets (SDG 2.3). By framing roads not merely as concrete but as *vectors of resilience*, this model transcends Torghar, offering a blueprint for SDG integration in marginalized agroecosystems worldwide.

6. Conclusion and policy implications

The study confirms that food security (FS) in Torghar is best addressed through a systems-thinking approach that integrates Sustainable Development Goal (SDG) 2 (Zero Hunger) and SDG 13 (Climate Action) via three interlinked pillars: (1) hardened infrastructure, such as solar-powered microgrids for cold storage; (2) democratized knowledge, including the integration of traditional Jirga-led advisories with digital agricultural extension services; and (3) intersectional protection, through programs like cash-for-work that specifically target women and elderly farmers. These pillars collectively operationalize Sen's [2,59] entitlement theory by converting physical infrastructure into corridors of resilience, educational institutions into hubs of climate literacy, and social protection programs into adaptive safety nets—each reinforcing the others to build systemic food resilience. To institutionalize this model, Pakistan's National Adaptation Plan could incorporate mandates for gender-responsive infrastructure audits and community co-design labs, ensuring that solutions are tailored to Torghar's unique socio-ecological context while offering a scalable blueprint for other mountainous regions.

Beyond conceptual contributions, the study offers practical insights for rethinking development metrics. For example, it quantifies how climate-smart infrastructure can reduce post-harvest losses (SDG 12.3) while simultaneously enhancing women's agricultural income (SDG 5. a), positioning food security not just as an end goal but as a conduit for multi-SDG alignment. To move from concept to action, detailed policy interventions are necessary. These include cost-estimated recommendations such as establishing solar cold storage at the Union Council level (PKR 3–4 million per unit), implementing "Digital-Jirga" cells using existing Kisan Call Centers (PKR 10–15 million per tehsil), and launching targeted cash-for-work programs that pay PKR 600/day over 60–90 days, modeled after successful United Nations Development Program initiatives. Furthermore, transforming Torghar into a "living lab" for longitudinal tracking of bundled interventions—such as combining irrigation with mobile-based advisories—will generate critical evidence to inform national scale-up. Such integrated, context-specific policy frameworks ensure that each kilometer of flood-proofed road and each solar unit installed contributes to broader resilience dividends, well beyond the immediate infrastructure, making FS a practical entry point for climate adaptation and inclusive rural development.

6.1. Limitation and future research

This study acknowledges several methodological impediments that warrant consideration. First, the exclusion of female respondents due to Torghar patriarchal norms- where women are often absent from formal agricultural decision making-leaves a critical gap in understanding gendered dimensions of HFS. While this reflects the region's socio-cultural reality, it underscores the need for future research to employ targeted strategies (e.g., female enumerators, community-mediated dialogues) to capture women's perspectives in similar contexts. Second, the geographically limited scope restricts direct extrapolation of findings to regions with divergent agroecological or socio-economic conditions, such as Pakistan irrigated plains or urban peripheries. However, the study's granular focus on rural, climate-vulnerable district offers a benchmark for comparing infrastructure-HFS linkages in comparable Global South highland economies. Third, while the sample size (n=379) is statistically adequate, it may not fully capture heterogeneity across household structure (e.g., landless laborers vs. smallholders). Finally, reliance on cross-sectional data limits causal inference or longitudinal analysis of HFS dynamics. These constraints suggest that while our findings provide actionable insights for rural Torghar and structurally analogous regions, broader generalizations require replication studies with expanded demographic and geographic coverage.

To advance this critical area of inquiry, subsequent studies could prioritize gender-disaggregated, mix-methods research across urban-rural continuums to uncover disparities in HFS experiences, particularly in marginalized demographics like female-headed households. Moreover, nationally representative longitudinal datasets-tracking agricultural innovation adoption climate adaptation, and nutritional knowledge-are urgently needed to validate the extend localized findings. Future work could also assess how digital extension services and educational interventions mediate climate-smart technology uptake, while advanced modeling (e.g., intersectional or agent-based approaches) could unravel how age, gender, and education interact to shape resilience in mountainous agroecosystems. These efforts would collectively address current gaps and inform transformative, context-specific HFS policies on sustainable lens.

Ethical statement

This study was reviewed and approved by The University of Agriculture Peshawar, Pakistan under the code of conduct of Board of Studies, Directorate of Advanced Studies and Research, ASRB approval, anti-plagiarism certificate No. 4543 PLAG/QA, Dated: 14-03-2023. All participants gave their informed consent for inclusion before they participated in the study as well.

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Data availability

The datasets generated during and/or analyzed during the current study are not publicly available due to repository in Higher Education Commission of Pakistan but are available from the corresponding author on reasonable request.

CRediT authorship contribution statement

Younas Khan: Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Štefan Bojnec:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Umar Daraz:** Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

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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Data availability

Data will be made available on request.

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