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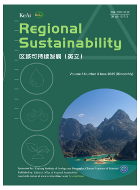

Full Length Article

How climate change adaptation strategies and climate migration interact to control food insecurity?

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ABSTRACT

As the impact of climate change intensifies, climate migration (climate change-induced migration) has become a pressing global issue that requires effective adaptation strategies to lessen its effects. Therefore, this study delved into the complex relationship between climate change adaptation strategies and climate migration with food insecurity serving as a mediating factor. We collected sample data through face-to-face interviews in Khorramabad City, Iran from February to May in 2023. Using the Structural Equation Modeling (SEM), we explored how food insecurity influences the relationship between climate change adaptation strategies and climate migration. The findings showed that while climate change adaptation strategies can boost community resilience, their success is closely tied to levels of food insecurity. About 78.72% of the surveyed households experienced certain levels of food insecurity, increasing the risk of displacement due to climate-related disasters. Climate change adaptation strategies including economic strategies, irrigation management strategies, organic-oriented strategies, sustainable development-oriented strategies, and crop variety management strategies played a significant role in reducing climate migration. Moreover, we found that climate change adaptation strategies not only impact food security, but also shape migration decisions. This research underscores the importance of an integrated approach that links climate change adaptation strategies, climate migration, and food insecurity. This study emphasizes the importance of food security for formulating sustainable adaptation strategies.

1. Introduction

Individuals or communities are forced to relocate due to sudden or gradual climate change, including extreme precipitation, prolonged droughts, desertification, environmental degradation, and rising sea levels (Abbass et al., 2022; Szaboova et al., 2023; Kalantari et al., 2024). Climate migration (climate change-induced migration) is a complex and widespread response to these changes, presenting both opportunities and challenges for both the

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regions where people leave and those where they move in (Adger et al., 2020).

In light of these challenges, climate change adaptation strategies are essential for mitigating the impact of climate change and reducing the need of climate migration (Urban et al., 2021; Rashidi et al., 2024b). These strategies focus on enhancing community resilience through improved infrastructure, sustainable practices, and early warning systems to tackle the challenges posed by climate change (Rashidi et al., 2024a). However, the effectiveness of these adaptation strategies is closely linked to food security, which is a vital aspect of human well-being (Sahraei et al., 2022). Access to reliable and nutritious food plays a crucial role in a community's ability to withstand climate change shocks (Raj et al., 2022). When the food system is disrupted, the risk of displacement increases, thus creating a complex relationship between climate change adaptation strategies and climate migration patterns (McMichael, 2014).

While there has been significant research on climate change, climate migration, and food security individually, gaps remain, particularly at their intersections (McGregor, 1994; Luginaah et al., 2009; McMichael, 2014; Nawrotzki et al., 2016; Mugambiwa and Makhubele, 2023; Tuholske et al., 2024). Furthermore, there is a lack of empirical evidence examining how food insecurity mediates the relationship between climate change adaptation strategies and climate migration, especially in developing countries where the impact of climate change is severe and food insecurity is a pressing issue (Rashidi et al., 2024b).

This paper aims to address these critical gaps by providing a comprehensive analysis of how climate change adaptation strategies can influence climate migration, with a specific focus on the mediating role of food insecurity. By proposing a holistic framework that connects three factors (climate change adaptation strategies, climate migration, and food insecurity), this study seeks to establish a solid theoretical foundation to guide future research and policy-making. The originality of this research lies in its integrative approach, which draws insights from climate science, migration studies, and food insecurity. This study will deepen our understanding of local contexts and identify specific adaptation strategies that can effectively enhance food security and reduce migration pressures. Additionally, this study will provide actionable recommendations for policy-makers, highlighting the importance of integrated approaches that consider food insecurity as a mediating factor.

2. Literature review

As the impact of climate change intensifies, especially in vulnerable regions, the connections among climate change adaptation strategies, climate migration, and food insecurity have gained a significant attention in academic discussion. Climate migration is often influenced by specific regional factors that shape both the drivers and outcomes of migration. For instance, Vinke et al. (2022) found that environmental degradation and food insecurity are key driving factors for climate migration, pushing communities to seek more stable living environment. Research has also highlighted the importance of local knowledge and community involvement in implementing effective climate change adaptation strategies (Jat et al., 2016; Nor Diana et al., 2022; Sarker et al., 2024). Furthermore, adopting sustainable agricultural practices such as crop diversification and integrated pest management, has been shown to enhance food security and reduce the vulnerability of farmers to climate change (Jat et al., 2016; Nurjati and Adityawati, 2024; Rashidi et al., 2024a, b). Nawrotzki et al. (2016) and Carney (2024) revealed that food insecurity is closely linked to climate migration patterns, and regions with a high food insecurity often face increased migration pressures. Food insecurity can exacerbate the decision to migrate, as households look for better opportunities to secure their livelihoods (Crush and Ramachandran, 2024; Daoust and Selby, 2024; Fan et al., 2024; Rashidi et al., 2024b). Despite this interconnectedness, many existing studies treat climate change adaptation strategies and their effects on climate migration as separate issues (Bettini, 2014; Nishimura, 2015; Brzoska and Fröhlich, 2016; Gemenne and Blocher, 2017; Wiederkehr et al., 2018; McLeman, 2019; Maharjan et al., 2020; Vinke et al., 2022; Mukherjee and Fransen, 2024), overlooking the mediating role of food insecurity. McMichael (2014) emphasized that the impact of climate change on migration and food security occurs through complex pathways. Most research tends to focus on socio-economic factors of climate migration or the effectiveness of climate change adaptation strategies without adequately addressing how food insecurity influences climate migration (Warner et al., 2010; Black et al., 2011; Sharmin, 2023; Fernandes-Jesus et al., 2025). Indeed, climate migration can be driven by food insecurity (Carney, 2017), but the impact of climate change on food security varies significantly by scale. Recent studies, particularly in the context of frequent floods, underscore this relationship (Reed et al., 2022). Hermans and Garbe (2019) and Sam et al. (2019) also indicated that income loss often coincides with food shortages, leading to the increased food insecurity and highlighting the interrelationship between agricultural conditions and food access. Households that adopt both on-farm and off-farm adaptation strategies tend to experience lower rates of food insecurity. Effective adaptation capabilities and livelihood strategies can help mitigate the adverse impact of drought on food security (Hermans and Garbe, 2019; Sam et al., 2019). Kaczan and Orgill-Meyer (2020) noted that climate migration patterns vary based on household capabilities, vulnerabilities, and the nature of climate shocks. Madaki et al. (2024) demonstrated that implementing climate change adaptation strategies significantly benefits the food security of farming households, increasing dietary diversity and reducing reliance on coping mechanisms. Mukherjee and Fransen (2024) argued that farming households employing effective climate change adaptation strategies are more likely to maintain stability and reduce their migration needs, as these strategies boost food security and income resilience. Conversely, those households facing barriers to adaptation—like limited access to credit or information—are more vulnerable to climate change, which can increase their likelihood of migrating.

Overall, this study uniquely investigates the mediating role of food insecurity in the relationship between climate change adaptation strategies and climate migration. It highlights how the effectiveness of these strategies is critically dependent on food security, particularly in vulnerable regions like Khorramabad City, Iran. This research offers valuable and context-specific insights for enhancing community resilience to climate change.

3. Theoretical and conceptual framework

This study is guided by a comprehensive theoretical framework that combines elements from the Sustainable Livelihoods Framework (SLF), Human Security Framework (HSF), Vulnerability Framework (VF), and Push-Pull-Mooring (PPM) theory. The SLF emphasizes the significance of different types of capital including natural, social, human, physical, and financial capital in shaping people's livelihoods, and how capital can be utilized to build adaptive capacity in the face of climate change, ultimately affecting food security and migration decisions (Scoones, 1998). The HSF focuses on the connections among environmental security, food security, and human rights. It underscores how threats to food security driven by climate change can push people to migrate as a coping strategy (United Nations, 1994). On the other hand, the VF emphasizes how adaptation strategies can reduce the vulnerability of farming households to climate change, influencing both food security and migration patterns (Turner et al., 2003). Finally, the PPM theory provides a comprehensive framework for understanding the factors that influence farming households' decisions to migrate in response to climate change (de Haas, 2010; Wang et al., 2020). This conceptual framework indicates that effective climate change adaptation strategies can enhance food security, which in turn affects farming households' migration choices. Climate change adaptation strategies include various aspects, such as economic strategies (focusing on investments in sustainable agricultural practices), irrigation management strategies, organic-oriented strategies, sustainable development-oriented strategies, and crop variety management strategies (Sahraei et al., 2022; Rashidi et al., 2024b). Irrigation management strategies aim to improve irrigation efficiency, thus increasing crop productivity and improving the adaptability of crops to climate change (Madaki et al., 2024). Organic-oriented strategies involve adopting ecological farming methods that strengthen the resilience and sustainability of soil (Malhi et al., 2021). Crop variety management strategies refer to using drought-resistant and early-maturing species to mitigate the impact of climate change on food production (Sam et al., 2019). Food security is defined as having access to food that reliably meets dietary needs (Pérez-Escamilla et al., 2017) and can be categorized into different levels: food security, mild food insecurity, moderate food insecurity, and severe food insecurity (Rashidi et al., 2024a). Climate migration encompasses migration intentions, which are decisions to move based on perceived climate risks and food insecurity (Carney, 2024; Mukherjee and Fransen, 2024). Ultimately, food insecurity may serve as a mediating factor between climate change adaptation strategies and climate migration. Improved food security could reduce the likelihood of migration, while food insecurity may increase the tendency to migrate (Nawrotzki et al., 2016).

This study gathered data from the respondents about the variables of interest and employed the Structural Equation Modeling (SEM) to explore the relationship among climate change adaptation strategies, climate migration, and food security. In this framework, climate change adaptation strategies are treated as the independent variable, climate migration as the dependent variable, and food insecurity as the mediating factor. Using the SEM is particularly advantageous, as it can be applied to examine both direct and indirect relationship between variables, while controlling potential confounding factors.

4. Materials and methods

4.1. Study area

This study was conducted in Khorramabad City (33°27′28″–33°30′00″N, 48°17′42″–48°19′12″E), the largest city in Lorestan Province of Iran, with an average altitude of 1147.8 m a.s.l. According to the latest census by the Iran Statistics Center in 2020, Khorramabad City had a population of 373,416 persons (Rashidi et al., 2024b). Lorestan Province is famous for its abundant water resources and is the third province in Iran with the richest water resources, accounting for approximately 12.00% of the country's total water supply. Despite its abundant water resources, the province is facing significant challenges due to climate change: increased dust, rising temperatures, variable precipitation patterns, and uneven precipitation distribution. These changes have intensified drought conditions, causing considerable harm to farmers in Khorramabad City. Given these urgent issues and their impacts on agricultural livelihoods, Khorramabad City serves as an ideal region for the current research objectives.

Fig. 1. Overview of the study area.

4.2. Data collection

4.2.1. Questionnaire process

In this study, we focused on farmers living in the rural areas of Khorramabad City. The sampling process was carried out in two stages. In the first stage, six villages (Soheyl Beygi, Tappeh Goji, Dowlatabad, Istgah-e Bisheh, Cham Sangar, and Tang-e Haft) were selected in Khorramabad City. In the second stage, the respondents were randomly chosen from these villages. To determine the appropriate sample size, we utilized Cochran's method, which resulted in the selection of 596 respondents. We used G^*Power software v 3.1.9.2 developed by Faul et al. (2007) to calculate the required sample size, incorporating several key statistical assumptions. Specifically, we set the desired power level for detecting significant effect at 0.80 and the significance level of 0.05 based on the previous literature (Sadat et al., 2023). We selected one respondent from each household. Finally, 173, 107, 101, 77, 74, and 64 respondents were collected from Soheyl Beygi, Tappeh Goji, Dowlatabad, Istgah-e Bisheh, Cham Sangar, and Tang-e Haft villages, respectively. Sample data were collected by face-to-face interviews with the respondents. The questionnaire used in these interviews was organized into three sections: climate change adaptation strategies, climate migration, and food insecurity. Questionnaire was designed to gather relevant data on the respondents' backgrounds, evaluate their food insecurity status, investigate the various adaptation strategies they employed, and assess their intentions to response to climate change (Sahraei et al., 2022; Rashidi et al., 2024a). Before administering the questionnaires, five students specializing in agricultural economics, agricultural promotion and education, and rural development received training. This training was designed to familiarize them with the questionnaire process and enhance their communication skills in interacting with the respondents. Data were collected from February to May in 2023.

4.2.2. Questionnaire items

The survey was divided into several sections. The first section focuses on climate change adaptation strategies, featuring questions that assess the implementation of specific strategies across various categories: economic strategies (six items), irrigation management strategies (five items), organic-oriented strategies (four items), sustainable development-oriented strategies (seven items), and crop variety management strategies (four items). All items were derived from previous studies and reworded to fit the local context (Ahmmadi et al., 2021; Sahraei et al., 2022; Rashidi et al., 2024a, b). The second section focuses on food insecurity, utilizing the Household Food Insecurity Access Scale (HFIAS) to measure the access to food within households. It provides a standardized method for assessing the frequency and severity of food insecurity experienced by individuals and households over the past 30 d (Pérez-Escamilla and Nutrição, 2008; Salarkia et al., 2011). The HFIAS includes nine core questions covering various aspects of food insecurity, such as worrying about food availability, preferred food, limited variety of food, unwanted food, smaller meals, fewer meals, food shortage, hunger at bedtime, and whole-day without any food (Rashidi-Chegini et al., 2021). Each question assesses how frequently these experiences happen, with response options ranging from “never” to “often”. We scored these answers according to their frequency of occurrence, which allows us to calculate an overall HFIAS score for each household (Rashidi-Chegini et al., 2021). Households were then classified into four levels of food insecurity: food security, mild food insecurity, moderate food insecurity, and severe food insecurity (Pérez-Escamilla et al., 2017). The third section focuses on climate migration, employing several Likert items to evaluate the respondents’ intentions to migrate due to climate change. These items were adapted from previous studies (Kalantari et al., 2024) and rephrased to align with the local context, comprising three items specifically designed to assess households’ migration intentions.

4.3. Statistical methods

Descriptive statistics were used to summarize the demographic characteristics of the respondents. Additionally, the SEM was conducted to investigate whether food insecurity acted as mediators in the relationship between climate change adaptation strategies and climate migration (Pearl, 2012). SEM is a type of statistical model used to examine whether the relationship between an independent variable (X) and a dependent variable (Y) is influenced (partially or fully) by a third variable called the mediating factor (Z). The model can be expressed through the following equations:

$$X=\beta_0+\varepsilon_1, \tag{1}$$

$$Z=\delta_0+\gamma X+\varepsilon_{2,} \tag{2}$$

$$Y=\eta_0+\beta X+\varphi Z+\varepsilon_3, \tag{3}$$

where X represents the climate change adaptation strategy; Z represents the food security; Y represents the climate migration; β_0, δ_0, and η_0 represent the regression intercepts; γ, β, and φ are the estimated coefficients; and ε_1, ε_2, and ε_3 are the uncorrelated error terms with a mean of zero. We computed the conditional expectation to assess the total effect, yielding the conditional expectation $E(\{Y\,|\,x, \mathrm{Z}\}=\eta_0+\beta x+\varphi Z)$. In fact, it ($E$) was used to evaluate the overall causal impact of changing the independent variable (X) from one baseline value (x) to new value (x') on the dependent variable (Y), while accounting for both direct and indirect effects influenced by the mediating factor (Z). This compares outcomes when X changes from a baseline value (x) to a new value (x'). From this, we derived the indirect effect as follows:

$$\mathrm{IE}_{(x,x')}=\sum_{Z}((\eta_0+\beta x+\varphi Z)[P(Z\,|\,x')-P(Z\,|\,x)])=\varphi[E(Z\,|\,x')-E(Z\,|\,x)]\,, \tag{4}$$

where IE is the indirect effect; and P is the pre-transition distribution. Equation 4 can be simplified as follows:

$$\mathrm{IE}_{(x,x')}=\gamma\varphi(x'-x)=(x'-x)(\tau-\beta)\,, \tag{5}$$

where τ represents the slope of the total effect, which can be calculated as follows:

$$\tau=\frac{E(Y\,|\,x')-E(Y\,|\,x)}{x'-x}=\beta+\gamma\varphi\,. \tag{6}$$

We derived standard expressions for indirect effects within linear systems, which can be estimated as the difference $\tau-\beta$ or as the product $\gamma\phi$ (Pearl, 2012). Before using the SEM, we first evaluated the Cronbach’s Alpha and Dillon-Goldstein’s Rho of all items to evaluate their internal consistency (Maleknia, 2024). Next, we examined the factor loadings to identify the main factors related to climate change adaptation strategies, and analyzed the Variance Inflation Factor (VIF) to check multicollinearity among the variables (Maleknia and Salehi, 2024). Factor loadings are Pearson correlation coefficients that represent the relationship between items. To evaluate the quality of the estimated model, we applied the coefficient of determination (R^2) derived from the final model (Sadat et al., 2023). We utilized the Composite Reliability (CR) and Average Variance Extracted (AVE) to assess the reliability and validity of factors, respectively (Maleknia et al., 2024). Additionally, we examined discriminant validity using the Fornell-Larcker criterion and the Heterotrait-Monotrait Ratio (HTMT). According to the Fornell-Larcker criterion, we established discriminant validity if the square root of the AVE for each factor is greater than the correlation between this factor and all other factors in the model. A low HTMT value indicates that factor is adequately distinct, while a high HTMT value shows potential overlap. To assess the fitting effect of the SEM, we considered several indices, including the Standardized Root Mean Square Residual (SRMR), Squared Euclidean Distance, Geodesic Distance, Chi-Square, Normed Fit Index (NFI), and Root Mean Square (RMS). Table S1 lists the equations and descriptions of all statistics. Data analysis was conducted using the SmartPLS software v 3.2.8 (SmartPLS GmbH, Hamburg, Germany), which facilitates the implementation of the SEM and provides comprehensive outputs for interpretation.

5. Results

5.1. Food security characteristics of the respondents

Table 1 provides an overview of the food security status of the surveyed households based on the HFIAS. Approximately 21.28% of households reported food security, while 78.72% of households experienced different levels of food insecurity. Specifically, 10.47% of households experienced mild food insecurity, 21.95% of households were in moderate food insecurity, and 46.28% of households were in severe food insecurity. Interestingly, 38.21% of households indicated that they are never worried about food availability. In contrast, 14.49% of households expressed that they often worry about food availability. Regarding limited variety of food, 43.21% of households reported no limitations, while 10.49% of households often faced limited variety of food. In terms of unwanted food, 42.93% of households never had to eat foods that they really did not want to eat, but 7.06% of households often had to eat unwanted food. Most households maintained regular meal sizes, although 7.18% of households often had smaller meals. While 65.21% of households never experienced food shortage, 4.70% of households did so often. Additionally, 70.33% of households reported never going to bed hungry at night, highlighting that the rest of the households faced considerable challenges. Overall, the data illustrated significant issues faced by many households.

Table 1
Descriptive results of the Household Food Insecurity Access Scale (HFIAS).

Category	Question	Never (%)	Rarely (%)	Sometime (%)	Often (%)
Worrying about food availability	Q1: worrying about food availability	38.21	30.11	17.19	14.49
Preferred food	Q2: unable to eat preferred food	41.62	29.41	21.57	7.40
Limited variety of food	Q3: eating a limited variety of food	43.21	26.02	20.28	10.49
Unwanted food	Q4: eating foods that you have to eat unappealing food	42.93	26.01	24.00	7.06
Smaller meals	Q5: eating a smaller meal	45.93	27.02	19.87	7.18
Fewer meals	Q6: eating fewer meals in a day	57.48	20.88	16.92	4.72
Food shortage	Q7: no food to eat at home	65.21	18.58	11.51	4.70
Hunger at bedtime	Q8: going to bed hungry at night	70.33	16.51	9.06	4.10
Whole-day without any food	Q9: not eating for a whole day and night	68.57	15.18	10.13	6.12

5.2. Structural Equation Modeling (SEM) processes and results

5.2.1. Pre-estimation analysis of the SEM

The results presented in Table 2 shows the consistency and reliability of climate change adaptation strategies, climate migration, and food insecurity. The sample mean values of many climate change adaptation strategies showed strong positive relationship with climate migration. Significant *t*-statistic and low *P*-value further confirmed that these factor loadings were reliable and statistically significant. The variability in standard deviation (SD) values highlighted differing perceptions among the respondents regarding these adaptation strategies. The coefficient of variation (CV) indicated notable differences in how the respondents perceive the effectiveness of these strategies, which may be influenced by their personal experiences with food insecurity and climate migration. Items with large SD and CV values indicated greater disagreement among the respondents, increasing potential misfit. Table 2 reveals that economic strategies such as reducing household expenses (SD=0.143, CV=0.080) and non-agricultural

Table 2
Descriptive statistics of climate migration, food insecurity, and climate change adaptation strategies.

Factor		Item	Factor loading					Descriptive statistic			VIF
			Original sample	Sample mean	SD	*t*-statistics	*P*-value	Mean	Average	CV	
Climate migration		I am willing to move to another region	0.867	0.868	0.027	32.148	0.001	1.661	1.738	0.016	2.282
		I feel prepared to migrate if necessary	0.872	0.868	0.031	28.000	0.001	1.731		0.018	2.254
		I would be willing to leave my community	0.937	0.937	0.009	104.111	0.001	1.823		0.005	3.326
Food insecurity		Worrying about food availability	0.588	0.590	0.087	6.782	0.001	1.194	0.804	0.073	1.337
		Preferred food	0.832	0.825	0.027	30.556	0.001	0.961		0.023	2.371
		Limited variety of food	0.811	0.807	0.030	26.900	0.001	0.990		0.030	2.650
		Unwanted food	0.846	0.841	0.028	30.036	0.001	0.951		0.029	3.504
		Smaller meals	0.830	0.826	0.026	31.769	0.001	0.884		0.029	3.321
		Fewer meals	0.764	0.764	0.033	23.152	0.001	0.693		0.048	2.215
		Food shortage	0.701	0.704	0.052	13.538	0.001	0.561		0.093	2.387
		Going to bed hungry	0.643	0.645	0.061	10.574	0.001	0.470		0.130	2.645
		Full day without eating	0.462	0.465	0.078	5.962	0.001	0.540		0.144	1.724
Climate change adaptation strategies	Economic strategies	Non-agricultural activity outside the farm	0.946	0.929	0.133	6.985	0.001	1.772	1.763	0.075	3.586
		Non-agricultural employment (labor, sales, etc.)	0.916	0.902	0.118	7.644	0.001	1.852		0.064	3.771
		Getting a loan	0.915	0.899	0.123	7.309	0.001	1.871		0.066	3.323
		Using personal savings	0.917	0.902	0.119	7.580	0.001	1.724		0.069	3.130
		Reducing household expenses	0.944	0.924	0.143	6.462	0.001	1.671		0.086	3.681
		Livestock sale	0.850	0.831	0.127	6.543	0.001	1.692		0.075	2.823
	Irrigation management strategies	Changing the irrigation system	0.814	0.812	0.030	27.067	0.001	1.750	1.705	0.017	1.742
		Improving the coverage of water transmission channels	0.787	0.781	0.034	22.971	0.001	1.700		0.020	1.692
		Use of alternative water sources (rainwater, sewage, etc.)	0.538	0.532	0.076	7.000	0.001	1.651		0.046	1.200
		Management of irrigation intervals	0.712	0.712	0.052	13.692	0.001	1.832		0.028	1.414
		Watershed management activities (dam, gabion, trust, etc.)	0.513	0.512	0.074	6.919	0.001	1.594		0.046	1.151
	Organic-oriented strategies	Weed management	0.745	0.740	0.047	15.745	0.001	2.131	1.778	0.022	1.565
		Use of organic fertilizer	0.774	0.772	0.036	21.444	0.001	1.630		0.022	1.556
		Organic farming	0.794	0.794	0.026	30.538	0.001	1.640		0.016	1.632
		Diversifying crops	0.864	0.863	0.024	35.958	0.001	1.711		0.014	2.283
	Sustainable development -oriented strategies	Changing the crop cultivation deadline	0.719	0.716	0.046	15.565	0.001	1.583	1.597	0.029	1.592
		Conservation tillage	0.729	0.724	0.044	16.455	0.001	1.684		0.026	1.780
		Agricultural land leveling	0.739	0.734	0.047	15.617	0.001	1.910		0.025	1.777
		Changing the time of crop harvest	0.546	0.540	0.063	8.571	0.001	1.590		0.040	1.301
		Multi-cropping	0.813	0.811	0.025	32.440	0.001	1.570		0.016	2.012
		Compliance with crop rotation	0.747	0.743	0.042	17.690	0.001	1.114		0.038	1.701
		Reducing the distance between crop rows	0.656	0.653	0.052	12.558	0.001	1.732		0.030	1.604
	Crop variety management strategies	High-yielding varieties	0.682	0.686	0.045	15.244	0.001	1.651	1.624	0.027	1.235
		Using cold-resistant and pest-resistant varieties	0.809	0.806	0.033	24.424	0.001	1.692		0.020	1.757
		Using varieties resistant to drought	0.778	0.772	0.040	19.300	0.001	1.612		0.025	1.702
		Using varieties resistant to salt	0.819	0.816	0.026	31.385	0.001	1.544		0.017	1.721

Note: SD, standard deviation; CV, coefficient of variation; VIF, Variance Inflation Factor.

non-agricultural activity outside the farm (SD=0.133, CV=0.075) exhibited the highest response variability among all adaptation strategies, indicating different perceptions or behaviors among respondents. The divergent perceptions among respondents were particularly evident in food insecurity, especially for going to bed hungry (SD=0.061, CV=0.130) and a full day without eating (SD=0.078, CV=0.144), which showed the highest variability in responses. Additionally, the VIF was used to evaluate potential multicollinearity among items. Table 2 indicates that there were no multicollinearity issues with any of the suggested items. Overall, these findings highlighted the importance of ensuring the reliability and consistency of terms to better understand the relationship between climate change adaptation strategies and their impacts on food security and climate migration.

5.2.2. SEM fitting test results

Table 3 summarizes the criteria for the saturated and estimated models, providing a comprehensive evaluation of its fitting. The SRMR value was 0.068, suggesting a good fitting, as values below 0.080 are generally accepted as indicative of a well-fitting model. This indicated that the predictions made by the estimated model align closely with the observed data. The Squared Euclidean distance value measured the discrepancy between the observed and predicted covariance matrices, with a lower value of 3.427, indicating a better fitting. In this study, this value suggested that the model is reasonably well-fitted with the data. The Geodesic Distance value was 1.082, indicating a low distance between the covariance matrices, further confirming that the model aligns well with the data. The NFI value was 0.961, which is closer to 1.000, suggesting that the model explains a substantial portion of the variance in the data. An NFI value above 0.900 is generally regarded as an indication of a good model fitting. Additionally, the RMS value was 0.122, providing an insight into the average discrepancy between the observed and predicted values. A lower RMS value indicates a better fitting, and in this case, the value of 0.122 suggested that the model does a reasonable job of predicting the outcomes. Overall, the estimated model criteria collectively indicated that the model fits well with the data. The SRMR, Squared Euclidean distance, Geodesic Distance, and NFI values highlighted strong relationships among climate change adaptation strategies, climate migration, and food insecurity, while the Chi-Square and RMS values further supported the model's predictive capability. These criteria affirmed the validity of the factors and demonstrated the model's applicability in understanding the relationships among climate change adaptation strategies, climate migration, and food insecurity.

From Table 4 we can see that climate migration has a Cronbach's Alpha value of 0.872, indicating high internal consistency, which is supported by a Dillon-Goldstein's Rho value of 0.880. Moreover, the CR and AVE values of climate migration were 0.922 and 0.797, respectively, showing robust reliability and strong convergent validity. Economic strategies performed exceptionally well, with a Cronbach's Alpha value of 0.961 and a CR value of 0.969, indicating high internal consistency and robust reliability, and an AVE value of 0.837 further supported its validity. In contrast, food insecurity had a Cronbach's Alpha value of 0.882 and a Dillon-Goldstein's Rho value of 0.940, indicating high internal consistency and robust reliability, although its AVE value was 0.522, suggesting room for improvement. Irrigation management strategies showed an adequate internal consistency with a Cronbach's Alpha value of 0.706, and its AVE value was 0.568, indicating a convergent validity. Organic-oriented strategies had a Cronbach's Alpha value of 0.805 and an AVE value of 0.633, suggesting high internal consistency and strong convergent validity. The Cronbach's Alpha and AVE values of sustainable development-oriented strategies were 0.834 and 0.506, respectively, indicating high internal consistency but marginal convergent validity. Crop variety management strategies, with a Cronbach's Alpha value of 0.775 and an AVE value of 0.599, showed an adequate internal consistency. Overall, these metrics highlighted the factors' effectiveness while identifying areas for improvement, essential for ensuring accurate measurement in climate migration and related fields.

Table 3
Fitting results of the saturated and estimated models.

Criterion	Saturated model	Estimated model
SRMR	0.068	0.068
Squared Euclidean distance	3.427	3.427
Geodesic Distance	1.082	1.082
Chi-Square	1749.170	1749.170
NFI	0.961	0.961
RMS	-	0.122

Note: -, no value. SRMR, Standardized Root Mean Square Residual; NFI, Normed Fit Index; RMS, Root Mean Square.

Table 4
Reliability and validity of climate migration, food insecurity, and climate change adaptation strategies.

Factor		Cronbach's Alpha	Dillon-Goldstein's Rho	CR	AVE
Climate migration		0.872	0.880	0.922	0.797
Food insecurity		0.882	0.940	0.904	0.522
Climate change adaptation strategies	Economic strategies	0.961	1.002	0.969	0.837
	Irrigation management strategies	0.706	0.742	0.810	0.568
	Organic-oriented strategies	0.805	0.807	0.873	0.633
	Sustainable development-oriented strategies	0.834	0.846	0.876	0.506
	Crop variety management strategies	0.775	0.779	0.856	0.599

Note: CR, Composite Reliability; AVE, Average Variance Extracted.

The values of the Fornell-Larcker criterion in Table S2 indicated that the factors maintain adequate discriminant validity, as the square roots of the AVE for each factor exceed their correlations with other factors. This finding suggested that each factor measures distinct concepts, confirming that they are not merely reflections of one another. Additionally, the HTMT values in Table S3 demonstrated that the factors are sufficiently distinct from one another. Overall, these metrics provided a nuanced understanding of the interrelationships among factors, ensuring that they captured unique dimensions relevant to this study.

5.2.3. SEM results

The mediation analysis conducted in this study examined the relationships among climate change adaptation strategies, climate migration, and food insecurity. Table 5 indicates significant direct and indirect effects of various climate change adaptation strategies on climate migration and food insecurity. The direct effect of economic strategies on climate migration was significant ($\beta = -0.046$, $P<0.001$), suggesting that economic strategies influence climate migration. The indirect effect was also significant ($\beta = -0.008$, $P<0.001$), indicating that economic strategies influence climate migration through food insecurity. The total effect of economic strategies on climate migration was significant ($\beta = -0.054$, $P<0.001$). Similarly, the analysis revealed a direct effect of economic strategies on food insecurity ($\beta = -0.060$, $P<0.001$), indicating that enhanced economic strategies were associated with reduced food insecurity.

Furthermore, irrigation management strategies had a significant negative direct effect ($\beta = -0.201$, $P=0.011$) and a significant negative indirect effect ($\beta = -0.026$, $P<0.001$) on climate migration. The total effect of irrigation management strategies on climate migration was significant ($\beta = -0.227$, $P=0.006$), which suggested that effective irrigation management strategies could significantly reduce climate migration. Similarly, irrigation management strategies had a direct effect ($\beta = -0.192$, $P=0.023$) on food insecurity, indicating that better irrigation management strategies are correlated with lower food insecurity.

In contrast, organic-oriented strategies had a significant negative direct effect ($\beta = -0.051$, $P<0.001$) and a significant negative indirect effect ($\beta = -0.024$, $P<0.001$) on climate migration. The total effect of organic-oriented strategies on climate migration was significant ($\beta = -0.075$, $P<0.001$), suggesting that organic-oriented strategies effectively mitigate climate migration. The direct effect of irrigation management strategies on food insecurity was also significant ($\beta = -0.177$, $P<0.001$), indicating a significant relationship between organic-oriented strategies and food insecurity.

The results for sustainable development-oriented strategies showed a direct effect ($\beta = -0.061$, $P<0.001$) on climate migration, while the indirect effect was not significant ($\beta=0.004$, $P=0.731$). The total effect of sustainable development-oriented strategies on climate migration was also not significant ($\beta = -0.057$, $P=0.389$), suggesting that although there is a direct negative relationship, the overall impact might not be substantial. However, sustainable development-oriented strategies had a direct effect ($\beta = -0.031$, $P<0.001$) on food insecurity, indicating a meaningful relationship.

Lastly, crop variety management strategies demonstrated a significant negative direct effect ($\beta = -0.287$, $P<0.001$) on climate migration, while the indirect effect was not significant ($\beta = -0.008$, $P=0.505$). However, the total effect was significant ($\beta = -0.295$, $P<0.001$), indicating that crop variety management strategies significantly reduced climate migration. The direct effect of crop variety management strategies on food insecurity was not significant ($\beta = -0.062$, $P=0.469$). Moreover, food insecurity had a direct effect ($\beta=0.134$, $P=0.023$) on climate migration, suggesting that higher level of food insecurity was associated with increased climate migration. Overall, these findings highlighted the complex relationship among climate change adaptation strategies, climate migration, and food insecurity, underscoring the importance of targeted interventions in these areas.

Table 5
Results of the Structural Equation Modeling (SEM).

Factor		Effect pathway	Original sample	Sample mean	SD	*t*-statistic	*P*-value
Economic strategies	Climate migration	Direct effect	–0.046	–0.048	0.009	4.721	0.000
		Indirect effect	–0.008	–0.008	0.001	4.709	0.000
		Total effect	–0.054	–0.040	0.008	4.580	0.000
	Food insecurity	Direct effect	–0.060	–0.064	0.012	4.818	0.000
Irrigation management strategies	Climate migration	Direct effect	–0.201	–0.209	0.079	2.542	0.011
		Indirect effect	–0.026	–0.027	0.007	3.515	0.000
		Total effect	–0.227	–0.236	0.082	2.770	0.006
	Food insecurity	Direct effect	–0.192	–0.200	0.084	2.277	0.023
Organic-oriented strategies	Climate migration	Direct effect	–0.051	–0.045	0.013	3.790	0.000
		Indirect effect	–0.024	–0.024	0.006	3.559	0.000
		Total effect	–0.075	–0.073	0.022	3.225	0.000
	Food insecurity	Direct effect	–0.177	–0.179	0.049	3.554	0.000
Sustainable development-oriented strategies	Climate migration	Direct effect	–0.061	–0.069	0.015	3.946	0.000
		Indirect effect	–0.004	–0.004	0.012	0.345	0.731
		Total effect	–0.057	0.064	0.066	0.862	0.389
	Food insecurity	Direct effect	–0.031	–0.032	0.009	3.396	0.000
Varity management strategies	Climate migration	Direct effect	–0.287	–0.276	0.068	4.241	0.000
		Indirect effect	–0.008	–0.009	0.012	0.668	0.505
		Total effect	–0.295	0.267	0.070	3.948	0.000
	Food insecurity	Direct effect	–0.062	–0.064	0.085	0.725	0.469
Food insecurity	Climate migration	Direct effect	0.134	0.131	0.059	2.282	0.023

6. Discussion

As climate change accelerates, it is increasingly obvious that how climate change adaptation strategies, climate migration, and food insecurity are intertwined. This study emphasized that climate change adaptation strategies play an essential role in reducing the negative impact of climate change on vulnerable communities, particularly in areas like Khorramabad City, Iran. This study indicated that these climate change adaptation strategies significantly improve food security, which in turn affects people's decisions about whether to migrate.

Climate change adaptation strategies have been recognized as essential tools for communities facing climate-related challenges (Lawler et al., 2013; Rashidi et al., 2024b). In Khorramabad City, where agricultural livelihoods are threatened by climate change, implementing climate change adaptation strategies such as improved irrigation management and organic farming can significantly bolster food security (Sahraei et al., 2022). Begashaw et al. (2024) and Tchonkouang et al. (2024) emphasized that well-designed adaptation strategies can reduce vulnerability and enhance food availability. Evidence suggests that adaptation measures must be tailored to specific socio-economic conditions (Chenani et al., 2021). This necessitates a participatory approach that empowers local stakeholders, ensuring that adaptation strategies are not only technically feasible but also culturally appropriate (Kalantari et al., 2024).

Economic strategies play a significant role in adapting to climate change and controlling climate migration. Many communities, particularly in developing countries, lack the financial resources necessary to invest in effective adaptation strategies. These financial limitations can lead to the perception that migration is a more viable option for survival when faced with the impact of climate change, such as droughts or floods (Kalantari et al., 2024). On the other hand, although organic-oriented strategies and sustainable development-oriented strategies are beneficial in many contexts, they may also contribute to migration trends. Farmers relying on organic development-oriented strategies and sustainable farming strategies may experience less predictable yields, particularly under changing climatic conditions. This unpredictability can lead to food insecurity, prompting people to migrate as a way of survival.

Additionally, crop variety management strategies present further challenges. If the crop varieties be inclined to climate change, agricultural productivity may decline, leading farmers to abandon their lands. Knowledge gaps regarding the selection and utilization of resilient varieties can further exacerbate this issue, pushing communities toward migration as they seek better opportunities elsewhere. The lack of access to information and resources can leave farmers feeling helpless and are more inclined to leave their homes (Grigorieva et al., 2023).

This study highlighted food security as a crucial mediating factor between climate change adaptation strategies and climate migration. Access to reliable and nutritious food is essential for household stability, especially in regions where food systems are often disrupted by climate shocks (Nawrotzki et al., 2016; Tuholske et al., 2024). These findings suggested that when food security is compromised, the likelihood of climate migration increases, confirming the complex relationship between these factors (Sadiddin et al., 2019; Smith and Floro, 2020; Carney, 2024). Moreover, food insecurity can intensify socio-economic pressures, prompting households to migrate in search of better opportunities. Therefore, enhancing food security through targeted adaptation strategies can be an effective way to curb climate migration (Raj et al., 2022). This perspective aligns with the holistic framework proposed by this study, which integrates insights from climate science, migration studies, and food security (Rashidi et al., 2024b). To reduce the potential bias of self-reported data, we trained data collectors to provide clear guidance to minimize respondents' misunderstandings and recall bias of the questionnaire survey. While we employed the SEM to explore relationships among climate change adaptation strategies, climate migration, and food security, we acknowledged the difficulty in establishing causation. To strengthen our findings, we discussed related factors such as political, economic, and cultural factors, and suggested that these variables could be incorporated into future research fields.

7. Conclusions and limitations

This study explored the complex relationships among climate change adaptation strategies, climate migration, and food insecurity in Khorramabad City, Iran by using the SEM from February to May in 2023. The findings highlighted the urgent need for targeted policy responses that integrate these factors. Policy-makers should focus on investing in sustainable agricultural practices and improving infrastructure to boost food security, especially in vulnerable regions. By encouraging local ownership of adaptation initiatives, communities are more likely to adopt and maintain these practices, thus enhancing food security and reducing migration pressures.

Additionally, this study emphasized the importance of gathering empirical evidence to guide the development of climate change adaptation strategies. It advocates for multidisciplinary investigations that bring together insights from climate science, migration studies, and food security. In conclusion, strengthening climate change adaptation strategies is vital for improving food security and addressing climate migration. A comprehensive approach that includes sustainable agricultural practices, effective irrigation management, and resilient varieties is essential.

Policy-makers should give priority to investing in resources and infrastructure to enable local communities to adapt to changing conditions. Furthermore, fostering collaboration among stakeholders across disciplines will help ensure that strategies are well-informed and context-specific. By tackling the underlying economic, social, and environmental factors driving migration, we can build resilient systems that improve food security, promote livelihood stability, and lessen the need for communities to relocate. It is important to recognize that farmers' attitudes toward climate change adaptation strategies and climate migration can greatly influence individual decisions.

This study also has some limitations. Firstly, it focuses on Khorramabad City, which may limit the applicability of the findings to other regions with different socio-economic and environmental contexts. To address this, we conducted thorough literature reviews and incorporated findings from similar studies in various geographical regions to provide a broader context. Secondly, the time range for this study is limited, which may not fully reflect the changing dynamics of climate change impact, migration patterns, and food security. We think the need for longitudinal studies in future research to track these changes over time.

Authorship contribution statement

Mohammad Reza PAKRAVAN-CHARVADEH: formal analysis, investigation, project administration, supervision, validation, and writing - original draft; Jeyran CHAMCHAM: data curation, resources, software, writing - original draft, and writing - reviewing & editing; and Rahim MALEKNIA: conceptualization, methodology, resources, and writing - reviewing & editing. All authors approved the manuscript.

Ethics statement

Ethics approval was obtained from the Ethics Committee of Lorestan University of Medical Science. In addition, the respondents provided their informed consent to participate in this study.

Declaration of conflict of 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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Appendix

Table S1
The description of all statistics for assessing the reliability and validity of the Structural Equation Modeling (SEM).

Statistic	Description	Equation	Explanation
λ	It describes the correlation between an observed variable and underlying latent variable.	$\lambda = \frac{\mathrm{Cov}(X,Y)}{\sqrt{\mathrm{Var}(X)\times\mathrm{Var}(Y)}}$	λ is the factor loading (Pearson correlation coefficient); Cov(X, Y) is the covariance between observed variable (X) and latent variable (Y); Var(X) is the variance of X; and Var(Y) is the variance of Y. The range of λ is between –1.000 and 1.000. λ value above 0.500 is considered acceptable relationship; λ value ranging from 0.400 to 0.500 is generally considered to reflect moderate relationship; while λ value below 0.400 may indicate weak relationship.
SRMR	It is calculated by the square root of the difference between the observed and predicted covariance matrices.	$\mathrm{SRMR} = \sqrt{\frac{\sum_{i=1}^{n}(O_{ii}-P_{ii})^2}{n}}$	SRMR is the Standardized Root Mean Square Residual; i is the observation value; n is the total number of observations; O_{ii} is the observed covariance matrix; and P_{ii} is the predicted covariance matrix. The range of SRMR is between 0.000 and 1.000, and SRMR value less than 0.080 is generally considered a good fitting.
$\mathrm{d_{ULS}}$	It is the sum of squared differences between the observed and predicted covariance matrices.	$\mathrm{d_{ULS}} = \sum_{i=1}^{n}\sum_{j=1}^{m}(O_{ij}-P_{ij})^2$	$\mathrm{d_{ULS}}$ is the Squared Euclidean distance; m is the total number of variables; O_{ij} is the observed matrix for the observation i^{th} and variable j^{th}; and P_{ij} is the predicted matrix for the observation i^{th} and variable j^{th}. There is no fixed range for $\mathrm{d_{ULS}}$, but lower value indicates a better fitting.
$\mathrm{d_G}$	It is similar to $\mathrm{d_{ULS}}$, but it takes into account the degrees of freedom.	$\mathrm{d_G} = \sum_{i=1}^{n}\sum_{j=1}^{m}\frac{(O_{ij}-P_{ij})^2}{\delta_{ij}^2}$	$\mathrm{d_G}$ is the Geodesic Distance; and δ_{ij}^2 is the variance associated with the observed matrix O_{ij}. Like $\mathrm{d_{ULS}}$, lower values indicate a better fitting, with no specific upper limit.
χ^2	It is a statistical test used to determine if there is a significant association between categorical variables.	$\chi^2 = \sum_{l=1}^{L}\frac{(O_l-E_l)^2}{E_l}$	χ^2 is the Chi-Square; L is the total number of categories; O_l is the observed frequency (count) for the l^{th} category; and E_l is the expected frequency (count) for the l^{th} category. The range of χ^2 is between 0.000 to infinity. Compared with the critical value based on the degrees of freedom, a lower value indicates a better fitting.
NFI	It compares the fitting of a proposed model to a baseline model, which usually represents a model of independence (i.e., no relationship between the variables).	$\mathrm{NFI} = \frac{\chi_{\mathrm{null}}^2-\chi_{\mathrm{model}}^2}{\chi_{\mathrm{null}}^2}$	NFI is the Normed Fit Index; χ_{nul}^2 is the Chi-Square for the null model; and χ_{model}^2 is the Chi-Square for the specified model. The range of NFI is from 0.000 to 1.000. NFI value above 0.900 is typically considered indicative of a good fitting.
VIF	It quantifies how much the variance of an estimated regression coefficient increases when predictors are correlated. Moreover, it assesses multicollinearity in regression analysis.	$\mathrm{VIF} = \frac{1}{1-R_j^2}$	VIF is the Variance Inflation Factor; and R_j^2 is the coefficient of determination obtained by regressing the j^{th} independent variable against all other variables. VIF=1.000 means no correlation; 5.000<VIF<10.000 means moderate correlation; 1.000≤VIF≤5.000 means high correlation; and VIF>10.000 means very high correlation.
CV	It measures the relative variability of a dataset compared to its mean.	$\mathrm{CV} = \frac{\sigma}{\mu}$	CV is the coefficient of variation; σ is the standard deviation (SD); and μ is the mean of the dataset. A higher CV indicates greater variability relative to the mean.
RMS	It measures the average of the squared differences (residuals) between the observed and predicted covariance matrices.	$\mathrm{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i-P_i)^2}$	Where RMS is the Root Mean Square; O_i is the observed value for the i^{th} observation; and P_i is the predicted value for the i^{th} observation. A value of RMS closer to 0.000 suggests that the model adequately captures the relationships in the data.
α	It measures the internal consistency and assesses how closely related a set of items are as a group.	$\alpha = \frac{k}{k-1}(1-\frac{\sum_{g=1}^{k}\delta_{Y_g}^2}{\delta_Y^2})$	α is the Cronbach's Alpha; k is the number of items; δ_{Yg}^2 is the variance of the gth item; and δ_Y^2 is the variance of the total score. The range of α is between 0.000 and 1.000, with values above 0.700 generally being considered acceptable.
ρ_{A}	It is another measure of internal consistency and is often preferred over Cronbach's Alpha, because it does not assume equal item loadings.	$\rho_A = \frac{\sum\lambda_g^2}{\sum{\lambda_g}^2+\sum\lambda\sigma_{\varepsilon_g}^2}$	ρ_{A} is the Dillon-Goldstein's Rho; λ_g is the factor loading of item; and $\sigma_{\varepsilon_g}^2$ is the error variance of item. Similar to Cronbach's Alpha, values of ρ_{A} above 0.700 are considered acceptable.
CR	It reflects the factors' reliability based on the factor loadings and error variances.	$\mathrm{CR} = \frac{\left(\sum\lambda_g\right)^2}{\left(\sum\lambda_g\right)^2+\sum\sigma_{\varepsilon_g}^2}$	CR is the Composite Reliability. CR value above 0.700 is considered acceptable.
AVE	It indicates how much of the variance in the observed variables (factors) is accounted for by the latent variables.	$\mathrm{AVE} = \frac{\sum_{g=1}^{k}\lambda_g^2}{k}$	AVE is the Average Variance Extracted. AVE≥0.500 indicates good convergent validity and AVE<0.500 indicates concerns about the factor's validity.

Table S2
Discriminant validity results of the Fornell-Larcker criterion.

Factor	Climate migration	Economic strategies	Food insecurity	Irrigation management strategies	Organic-oriented strategies	Sustainable development-oriented strategies	Crop variety management strategies
Climate migration	0.893						
Economic strategies	–0.090	0.915					
Food insecurity	0.237	–0.119	0.722				
Irrigation management strategies	–0.465	0.248	–0.238	0.753			
Organic-oriented strategies	–0.330	0.180	–0.244	0.503	0.795		
Sustainable development -oriented strategies	0.316	–0.429	0.144	–0.560	–0.386	0.711	
Crop variety management strategies	0.478	–0.122	0.136	–0.643	–0.457	0.432	0.774

Table S3
Discriminant validity results of the Heterotrait-Monotrait Ratio (HTMT).

Factor	Climate migration	Economic strategies	Food insecurity	Irrigation management strategies	Organic-oriented strategies	Sustainable development-oriented strategies	Crop variety management strategies
Economic strategies	0.095						
Food insecurity	0.251	0.117					
Irrigation management strategies	0.581	0.278	0.274				
Organic-oriented strategies	0.392	0.201	0.261	0.671			
Sustainable-oriented strategies	0.368	0.465	0.161	0.704	0.472		
Crop management strategies	0.572	0.146	0.143	0.844	0.565	0.524	