scientific reports

Check for updates

OPEN

Gender dynamics and remittances in the adoption of sustainable agricultural practices in Nepal

Giri Prasad Kandel[1]✉, Mustapha Yakubu Madaki[2], Tereza Pilarova[2], Ayat Ullah[2], Prajal Pradhan[3,4], Ioannis Manikas[1] & Miroslava Bavorova[2]

Agricultural systems in rural Nepal face significant transformation due to climate change and shifting household labour dynamics. Male out-migration, a key but underexplored driver of this change, disrupts traditional gendered labor divisions and reshapes agricultural decision-making. In smallholder farms, traditionally, men are more responsible for tasks like ploughing and harvesting, whereas women take on planting, weeding, and winnowing roles. In the context of male out-migration, women must take primary responsibility for managing farms and households. However, persistent social and structural inequalities continue to constrain their decision-making authority. The feminisation of agriculture has important implications for adopting sustainable agricultural practices (SAPs). Using survey data from 400 households and Poisson regression analysis, this study examines the effects of migration, remittances, and female-managed farms on SAP adoption. Our results highlight that household farms having migrated member(s), receiving remittance and female-managed farms are more likely to adopt SAPs. In contrast, a higher number of out-migrating females negatively affects adoption, reflecting women's critical role in sustainable farming adoption. Their participation in women's groups, which provide training and financial resources and their management of tasks such as seed selection, winnowing, and organic pest control, are essential to SAP implementation. As such, our study provides a deeper understanding of the positive role of females in SAP adoption. We advocate for policies that recognising intersectional vulnerabilities, supporting women's groups, lead to increased adoption of sustainable agricultural practices.

Keywords Feminization of agriculture, Gender dynamics, Male out-migration, Climate change, Remittances, Sustainable agricultural practices

Agricultural sector is increasingly vulnerable to the growing impacts of climate change, which pose serious threats to productivity, food security, and rural livelihoods. Climate-driven weather extremes and seasonal shifts such as erratic rainfall, shifting monsoon cycles, prolonged droughts, and more frequent floods and landslides have disrupted traditional farming calendars and reduced crop yields across many regions[1]. These climatic shocks are further compounded by rising temperatures, which accelerate soil degradation, increase pest and disease outbreaks, and reduce water availability for irrigation[2,3]. In response to these escalating challenges, sustainable agricultural practices (SAPs) such as organic farming, conservation tillage, changing crops and planting dates, agroforestry, and integrated pest management have gained increasing attention for their potential to enhance ecological resilience and mitigate climate risks. Nevertheless, adoption of these practices is not merely a technical matter: it is deeply embedded in socio-economic and gendered labor dynamics and shifting household structures, particularly in the context of rural out-migration[4].

International labor migration has emerged as a defining livelihood strategy for rural households grappling with limited employment opportunities and climatic shocks[5–7]. Although agriculture remains the backbone of Nepal's rural economy[7,8], labor within the sector has traditionally been highly gendered. Men performed tasks such as ploughing, terrace bund preparation, and harvesting, while women were confined to less physically intensive and economically undervalued activities like planting, weeding, and winnowing[9–11].

[1]Faculty of Agrobiology, Food, and Natural Resources, Czech University of Life Sciences Prague, Kamycka 129, Prague, Suchdol 16500, Czech Republic. [2]Faculty of Tropical AgriSciences, Czech University of Life Sciences Prague, Kamycka 129, Prague, Suchdol 16500, Czech Republic. [3]Energy and Sustainability Research Institute Groningen (ESRIG), University of Groningen, Groningen 9747 AG, Netherlands. [4]Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, P.O. Box 60 12 03, Potsdam D-14412, Germany. ✉email: kandelg@af.czu.cz; carlous.girish49@gmail.com

In Nepal, our study region, as of 2023, approximately 3.5 million people were working abroad, primarily in Gulf countries[7]. Remittances from migrants account for approximately a quarter of the country's GDP[7,12]. Due to a growing trend of male out-migration in several countries including rural Nepal[7], it significantly reshaped traditional gender roles, with women assuming greater responsibilities in farm management and household decision-making, contributing to the ongoing "feminization of agriculture"[10,13–17]. While this shift offers pathways to women's economic and social empowerment, it also increases their labor burden and imposes emotional and psychological stress due absence of male members in the household[18–25]. Despite women's expanded roles, structural barriers such as land ownership, credit, training, extension services, markets, and male-dominated institutions may constrain their capacity to implement innovative agricultural practices[1,11,15,26].

These social structure, labor and environmental shifts are occurring alongside increased financial inflows from remittances, which bring opportunities and constraints. Adopting SAPs, which often requires technical knowledge, upfront investment, and long-term planning, is intricately linked to intra-household power relations and gendered control of resources[5]. The transformative potential of remittances is similarly uneven. While remittances can reduce liquidity constraints and enable investments in agriculture, their impact depends on who controls and allocates these resources. In many households, men influence spending decisions remotely, often prioritizing immediate consumption or construction over long-term agricultural improvements[1,27]. Even when women gain financial control, social norms and fear of reputational risks can limit their autonomy in deploying funds toward innovation. As a result, the benefits of sustainable agricultural practice from migration-driven financial inflows remain contingent on shifting gender roles, household bargaining, and social structures.

Male out-migration has been shown to significantly affect agricultural labor availability, decision-making, and farm productivity in Nepal[13,14,22,28,29]. Research by[14,28], and[29], highlighted that male migration leads to feminization of agriculture however such household often face economic vulnerability. At the same time, women in these household exercise greater autonomy in household and agricultural decision-making. Even though migration reshaped gender roles, it intensifies food insecurity due to labor shortages for agricultural production[22,30]. This highlights household composition and its critical role in shaping women's empowerment. Women in nuclear households are more likely to act as primary decision-makers, with greater control over agricultural inputs, improved access to credit, and higher levels of participation in farmer groups, all of which are key to successful SAP adoption[10,31]. In contrast, women in extended households often remain subject to hierarchical control, particularly from mothers-in-law, which limits their agency in deploying remittances, accessing resources, or experimenting with new farming techniques[1,11]. Women's empowerment in areas such as asset control, legal rights, and Information and Communication Technologies (ICT) access significantly enhances women's decision-making power and SAP adoption[32–34]. Interventions such as training[35] and literacy programs[36] further catalyze adoption and even reduce migration pressure. Yet, due to structural gaps adoption rates among women is lower for yield-enhancing techniques, such as agroforestry initiatives[37,38]. In Nepal, households where women are involved early in agricultural decisions are 19% more likely to engage with environmental conservation agriculture[26].

This highlights that prior studies have examined migration's economic impacts[13,14,22,28,29] and feminization of agriculture[10,13–17], none have empirically tested how intra-household control of remittances mediates women's ability to adopt SAPs. This gap is critical because remittance usage (e.g., housing vs. farm investment) may reinforce or offset gender disparities in SAP adoption, a dimension overlooked in existing literature. Thus, our study seeks to fill this gap by examining how migration and remittances influence the adoption of SAPs in Nepal, with a particular focus on gender dynamics. Specifically, our study is guided by the following research questions:

1. Does male out-migration influence the adoption of sustainable agricultural practices (SAPs)?
2. What gender-specific challenges or opportunities do women face in adopting SAPs within the context of migration-affected households?
3. Do remittances affect adoption of SAPs?

By linking migration, remittance use, and gendered decision-making, this research offers an integrated analysis of the structural and socio-economic forces shaping sustainable agriculture. It uniquely bridges three often-siloed domains: gender, migration/remittances, and SAPs contributing to more inclusive and resilient agricultural development strategies.

Theoretical framework

We employed combined framework drawing from the Sustainable Livelihoods Framework (SLF)[39–41] with Intersectionality Theory[42–46] to examine how gender dynamics, remittance flows and the feminisation of agriculture influence the adoption of sustainable agricultural practices (SAPs) in rural Nepal (Fig. 1). The SLF posits that household livelihoods are shaped by access to and interaction among five key forms of capital: human, natural, financial, social, and physical[40]. These capitals jointly determine a household's ability to cope with and adapt to socio-environmental challenges. In rural Nepal, male out-migration interrupts this balance by reducing household labour (human capital) while augmenting financial capital through remittances[47]. Remittances may offer financial relief, but they often have unintended consequences. It raises managerial and physical burdens on women left behind, who often lack adequate institutional support and access to agricultural resources[13,48].

The feminisation of agriculture understood as a growing involvement of women in farm management in the absence of male household members[1]. It emerges not just as a demographic trend but as a deeper structural shift in rural livelihoods[48]. As women increasingly take charge of agricultural decisions and labour, their ability to adopt SAPs becomes pivotal at the household level. However, this capacity is shaped by different livelihood capitals and a set of demographic characteristics (age, education, and household size), farm attributes (farming systems, land tenure, and income levels), and institutional factors (access to credit or participation in farmer

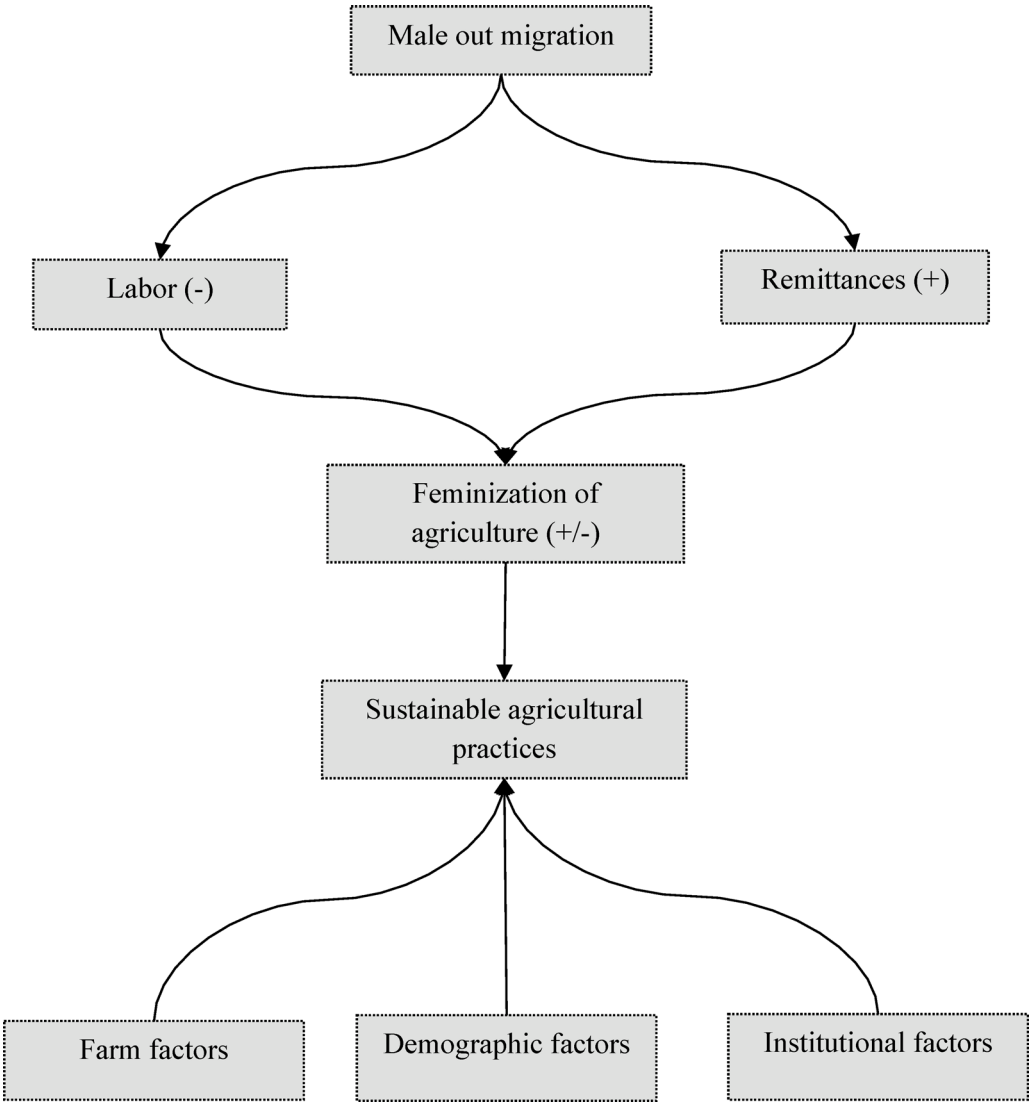

Fig. 1. Framework illustrating the intersection of male out-migration, gender dynamics, and the adoption of SAPs.Source: Authors own construction based on the SLF[39,40] and concept of the feminisation of agriculture.

groups). Additionally, migration-specific variables such as the volume and stability of remittances, the gender composition of migrants, and household involvement in off-farm income-generating activities can either strengthen or constrain women's role in agricultural decision-making[13,48,49].

By combining SLF with intersectionality, our study does not treat rural women as a homogenous category. Instead, it recognises that women's capacity to adopt SAPs is shaped by the intersection of gender with other social identities such as caste, class, ethnicity and marital status. These overlapping identities influence their access to livelihood capitals and their position within intra-household and community-level power structures[50]. For instance, a female-headed household in a nuclear family may exercise greater decision-making autonomy than a woman in a multi-generational household where patriarchal norms, even if both receive remittances[10,31]. Moreover, looking at the intra-household perspectives, women are often responsible for domestic labour and caregiving, which limits their time, mobility, and participation in decision-making and income-generating activities. Such intersecting inequalities limit women's bargaining power in agricultural markets and influence their ability to engage effectively in purchasing and selling agricultural goods. These dynamics affect women's access to and control of key livelihood capitals (human, social, financial, natural, and physical), ultimately shaping their ability to adopt and sustain SAPs.

Within this framework, adopting SAPs is not solely determined by access to resources or awareness, but is deeply embedded in gendered power relations and evolving livelihood strategies. By situating male out-migration within the broader context of the SLF and applying an intersectional lens, our study highlights how shifts in household composition reshape women's roles in agriculture.

Materials and methods

Study zones and environmental features

Our research was conducted in Nepal, a country in the broader Hindu Kush Himalayan (HKH) region, known for its sharp ecological gradients and diverse farming systems[51]. To capture this variation, we adopted a zonal framework based on elevation: the lowland Terai zone (67–610 m), the mid-hill zone (610–2,500 m), and the high mountain zone (2,500–8,848 m above sea level).

Our data were collected from three districts representing each zone: Chitwan (Terai), Baglung (mid-hills), and Mustang (mountains) as shown in Fig. 2. These sites were selected to reflect variations in altitude, climate stress, migration patterns and farming practices. Each zone faces unique opportunities and constraints. The Terai offers fertile land and irrigation access, supporting cash crop production and livestock farming, but it is increasingly affected by floods, erratic rainfall, and labour shortages driven by migration[52]. Meanwhile, the mid-hills zone relies on terrace farming to manage sloped terrain, yet they suffer from landslides, limited access to credit, and declining labour availability[5]. The high mountain zone features short growing seasons, limited rainfall, and harsh winters, where households often depend on remittances, migration, and off-farm activities to maintain their livelihood[5,52].

Sampling technique and data collection

Our study adopted a multistage, purposive sampling strategy across three agro-ecological zones: lowland (Terai), mid-hill, and high mountain regions. We selected one representative district from each zone – e.g. Chitwan (lowland), Baglung (mid-hill), and Mustang (high mountain). One rural municipality, Nepal's smallest administrative unit was purposively chosen from each district based on farming communities. Within these municipalities, we selected specific villages as primary data collection sites. Lanku, Ratnanagar, and Sharadpur villages were selected from the Chitwan district, whereas Bhuskat, Hila, and Tara were chosen from the Baglung district. Meanwhile, we selected Thasang, Gharapojung, and Baragaun Muktikshetra from the Mustang district. A snowball sampling method was employed within purposively selected villages to identify smallholder farmers. This approach was appropriate for reaching dispersed farming households in remote areas where no comprehensive household lists were available. A total of 400 farmers were surveyed: 70 from Chitwan, 150 from Baglung, and 180 from Mustang districts. The sample distribution reflects the relative prevalence of smallholder farming across these regions. Because both site selection and farmer identification followed non-probability procedures, the sample should not be interpreted as statistically representative of all farming households in Nepal. Nonetheless, we conducted post-stratification checks using district-level data from the 2021 National Population and Housing Census of Nepal to evaluate the comparability of key demographic characteristics (Appendix 1, Table A1). For demographic variables such as age, household size, caste, and formal education, the sample broadly aligns with district averages. Data on farm income, remittances, credit access, and farmer group

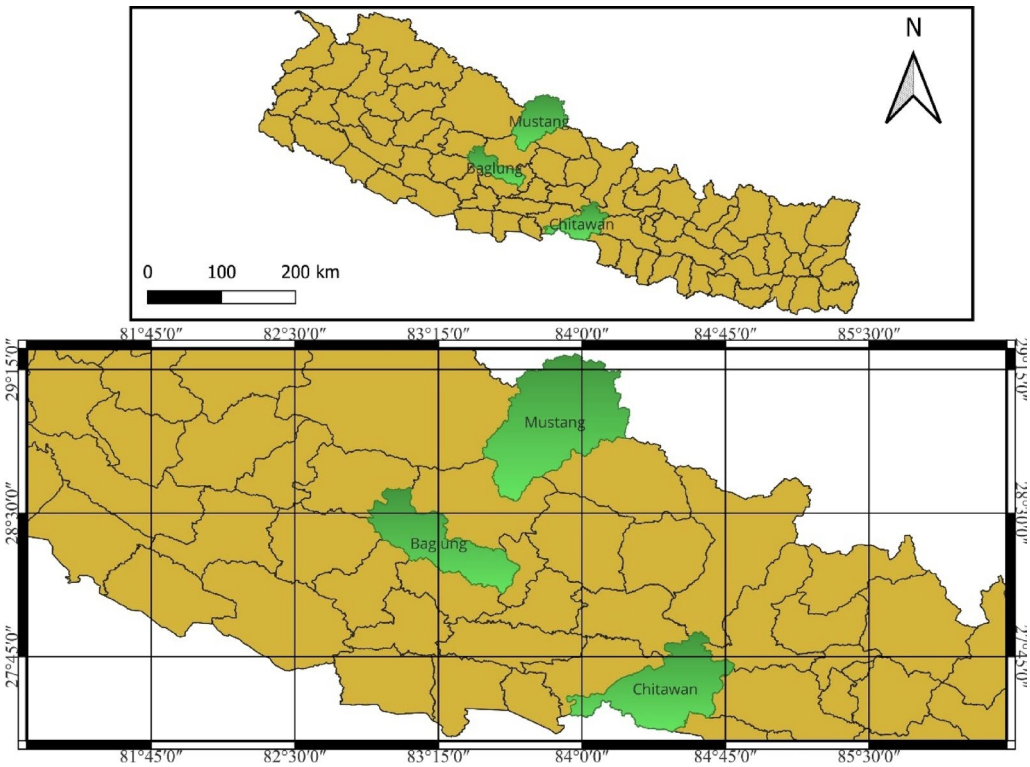

Fig. 2. Map of study zones.Source: Authors own construction using QGIS.

membership were unavailable at the district level. Perception-based variables (e.g., labor shortages, rainfall variability) are inherently context-specific and not directly comparable to census data.

Data collection relied on a semi-structured questionnaire based on the study's conceptual framework and existing literature[1,22,53–55]. Moreover, inputs from focus group discussions with local and local key informants helped to refine the questionnaires. We also conducted a pilot survey with 28 participants across the three zones: six in Terai, 10 in mid-hills, and 12 in mountainous to ratify the questionnaires.

The survey was conducted during March and July 2021 by a team of 15 well-trained enumerators (five per zone). We conducted face-to-face interviews using printed questionnaires translated from English into Nepali language to ensure clear communication with rural farmers. To avoid any misconception, we obtained formal permissions from the municipality mayor or secretary before data collection. The initial entry points for the snowball sampling were identified through the secretary of the wards, local agricultural extension officers and farmer group leaders, who helped connect enumerators with the first respondents in each research site. In some scenarios, the initial contact with households was facilitated through village representatives. While this approach facilitated access to otherwise hard-to-reach households, it also posed challenges such as reliance on social networks, which may have limited diversity among referred participants. Our survey data covered various topics, including socio-demographics, farming, institutions, migration, and remittance information.

According to national regulations in Nepal at the time of data collection, formal ethical approval was not required for social survey-based studies of this nature. Nevertheless, the study was conducted in line with internationally recognized ethical principles, including the Declaration of Helsinki. Prior to each interview, we informed participants about the objectives of the study, and their right to withdraw at any stage without consequence. Informed consent was obtained verbally, as many participants had limited literacy levels, making written consent less practical. All participants provided explicit verbal consent before participation. No minors were interviewed for this study.

Data analysis

Poisson regression model

This study used Poisson regression to analyze the effect of migration, remittances and gender dynamics on the adoption of sustainable agricultural practices, since the dependent variable is counting data. Specifically, the outcome variable represents the number of sustainable agricultural practices adopted by each household make the Poisson regression most appropriate for the analysis[56,57]. Let Y_i represent the count of practices adopted by households i. The Poisson regression model assumes:

$$Y_i \sim Poisson\ (\lambda_i) \tag{1}$$

$$Pr\ (Y_i = yi) = \varepsilon^{-\lambda_i} \lambda_i^{yi}/yi! \tag{2}$$

where λ_i is the expected count, expressed as a log-linear function of a vector of covariates X_i:

$$log\ (\lambda_i) = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \ldots \quad + \beta_k X_{ki} + \varepsilon \tag{3}$$

$$\lambda_i = \exp\left(\beta_0 + \sum_{k=1}^{k} \beta_k X_{ki}\right) \tag{4}$$

The model was estimated using Maximum Likelihood Estimation (MLE), and the results are presented in terms of coefficients, incident rate ratios (IRRs), and marginal effects for robustness checks.

Selection of variables

Our study incorporates three categories of variables: outcome, variable of interest and control (see Table 1). The outcome variable is the adoption of SAPs, measured through a range of strategies such as crop diversification, changes in planting time or crop type, early maturing and drought-resistant varieties, irrigation, rainwater harvesting, reduced tillage, mulching, agroforestry, use of organic fertilizers, and integrated pest management system. We considered as SAP adoption if one of these strategies was implemented by households in the last 10–15 years. The variables of interest include female-managed farms, household migration status, remittances, and the number of female migrants to capture household labour dynamics and gendered decision-making. Control variables account for demographic, farming, environmental, and institutional factors. These include age, caste, education, marital status, household size, off-farm work, farm income, land size, farming type, labour availability, erratic rainfall, access to credit, and farmer groups membership. Variable selection is informed by the study's conceptual framework and supported by prior research on migration, gender, and sustainable agricultural practices[1,22,53–55].

Model robustness checks and diagnostics summary

Several diagnostic tests were performed to validate the model and ensure the reliability of the coefficient estimates and other parameters. The overdispersion test (goodness-of-fit chi² = 252.75, p = 1.000) indicates no significant overdispersion issue, supporting the appropriateness of the Poisson model for the count data (Appendix 2, Table A2). Although a Negative Binomial regression was not strictly required since the overdispersion test indicated no significant overdispersion, we estimated it as an additional robustness check. The results were consistent with the Poisson model in terms of coefficient signs and significance, confirming the robustness of our main findings (Appendix 5 Table A5). The Variance Inflation Factor (VIF) was used to assess multicollinearity among the

Variables	Definitions	Mean	Std. Dev.
Dependent variable			
Sustainable agricultural practices	Number of sustainable agricultural practices adopted by household (total SAP = 10)	5.79	2.21
Independent variables			
Migration and remittances (variables of interest)			
Female managed farm	1 if farm is managed by female, 0 otherwise	0.28	0.45
Migration	1 if household has migrated members, 0 otherwise	0.35	0.47
Remittances	1 if the household receives remittances from migrated members, 0 otherwise	0.29	0.45
Female migrants	Total number of female migrants from the households	1.07	2.01
Demographic characteristics			
Age	Years of household head	50.31	13.99
Higher caste	1 if household belongs to ethnic groups "so-called" higher caste, 0 otherwise	0.24	0.42
Formal education	1 if household head has formal education, 0 otherwise	0.65	0.47
Household size	Total number household members	5.80	2.88
Marital status	1 if household head is married, 0 otherwise	0.85	0.35
Off-farm activities	1 if any members of the household are involved in the off-farm activities, 0 otherwise	0.57	0.49
Farm characteristics			
Farming practices	1 if household practices mix farming system, 0 otherwise	0.88	0.31
Cash crops	Total percentage of cultivated land for cash crops such as potato production	31.27	22.24
Livestock	Total number of livestock such as cattle of the household as major livestock	1.40	2.15
Farm income	Scale (1–5), total household earnings from farms, 1 being earning less than 50,000 NPR1 annually to 5 being earning more than 200,000 NPR[1]	1.76	0.99
Cultivated land	Total size of cultivated land (*Ropani*[2])	9.88	15.54
Land size	Total land size owned by household in *Ropani*	13.16	17.86
Lack of labor	1 if households perceive lack of labor for agricultural work, 0 otherwise	0.79	0.40
Erratic rainfall	1 if farmers perceived negative impact of erratic rainfall on their farm over the past 10–15 years, 0 otherwise	0.86	0.34
Institutional characteristics			
Access to formal credit	1 if household has access to formal credit sources such as bank, 0 otherwise	0.03	0.19
Farmer groups	1 if household is member of farmer groups, 0 otherwise	0.67	0.47

Table 1. Definition of variables ($n = 400$). Note: [1]NPR= Nepalese rupee (Currency of Nepal), 1$ = 120 NPR as of May 2021. [2]Ropani = A unit of the area measured in Nepal, 1 *Ropani* = 0.051 hectare.

independent variables. The VIF values for all the covariates were below 10 (Appendix 3, Table A3), indicating that multicollinearity is not a concern in the model[58,59]. This confirms that the explanatory variables are not linearly dependent and that the regression coefficients are stable. To evaluate potential model misspecification due to omitted variables or incorrect functional form, the link test for model specification was employed (Appendix 4, Table A4). The test regresses the dependent variable on the predicted value (_hat) and its square (_hatsq). In a correctly specified model, _hat should be significant while _hatsq should not. Results showed that the _hatsq term was not statistically significant at $p > 0.05$. This indicates that the model is well-specified, with no strong evidence of misspecification or omitted variable bias[60,61]. Although the link test indicates correct model specification, we acknowledge that potential endogeneity due to unobserved factors beyond the observed controls such as farmer groups membership and access to formal credit may still be present and is recognized as a limitation of the study. Furthermore, a zero-inflated Poisson (ZIP) model was estimated as a robustness check. The ZIP model shows a slightly higher log pseudolikelihood (−833.09) than the standard Poisson model (−836.29), indicating only a marginal improvement in fit (Appendix 6, Table A6). However, given that the dataset contained only one zero count and the overdispersion test did not indicate significant dispersion issues. As so zero-inflated or hurdle models were deemed unnecessary.

Sample description

On average, the farmers adopt approximately six practices at a time, with a standard deviation of 2.22, this indicates moderate but varied uptake of SAPs across the sample (Table 1). Migration and remittances are central to this study, about 28% of farms are managed by women, often due to male out-migration. These gender-specific roles and constraints may influence the choice and extent of SAPs adoption. Additionally, 35% of households have at least one migrated member, which may impact labor supply and alter household decision-making regarding farm management and innovation. About one-third of the households receive remittances (29%), these financial inflows can support SAP adoption by easing liquidity constraints or substitute agricultural engagement entirely. Households report an average of one female migrant, with a standard deviation of 2.02. This reflects gendered patterns in migration and potential shifts in household farm labor dynamics.

Regarding the demographic characteristics of the sample, the average age of household heads is 50 years, with a standard deviation of 14 years, indicating a mature farming population that may be experienced and risk-averse when adopting new practices. About one-fourth of respondents belong to higher caste groups, which could influence access to resources and networks that facilitate SAPs adoption. Two-thirds of the household head have formal education, a factor that demonstrates greater openness to and understanding of sustainable practices. Households have an average of six members, with a standard deviation of three, which could reflect labor availability for farm work. The majority (85%) of household heads are married, which may indicate responsibility in household decision-making. More than half (57.8%) of households have at least one member engaged in non-agricultural employment, which could influence farm investment and resource allocation.

In terms of farm characteristics, a large proportion (88.5%) of households practice mixed farming systems, which could improve the integration of various SAPs. On average, 31% of cultivated land is used for cash crops such as potatoes, suggesting a market orientation that could affect input choices and land use decisions. Households keep an average of one livestock animal, which may contribute to nutrient cycling and influence practices such as the use of organic manure. On a scale of 1 (earning below 50,000 NPR annually) to 5 (earning above 250,000 NPR annually), the average farm income score is 1.76, suggesting relatively low-income levels from farming activities. The average cultivated land area is 9.89 *Ropani* (approximately 0.5 hectares), and the average total land ownership is 13.16 *Ropani* (approximately 0.67 hectares), indicating generally small-scale farming. Notably, 79% reported a lack of labor as a constraint in agricultural work, likely due to out-migration or youth disengagement, and 86% perceive that erratic rainfall has negatively affected their farms over the past 10–15 years. This indicates strong climate vulnerability and may motivate the adoption of resilient practices. Only 3.7% of households have access to formal credit sources, such as banks, revealing major financial constraints that could hinder SAPs adoption. Two-third (67%) of households belong to farmer groups, which may enhance information dissemination and peer learning, supporting broader SAPs implementation.

Results

We implemented several statistical measures such as Pseudo R^2, chi^2 statistics, the Akaike Information Criterion (AIC), the probability associated with the chi-square test, and the Bayesian Information Criterion (BIC) to evaluate the overall performance of the regression model (Table 2). The model's chi^2 statistic was 181.515, with an associated probability value ($prob > chi^2$) of 0.000. This indicates that the model is statistically significant and confirms that the set of explanatory variables included in the model significantly improve fit compared to an intercept-only model. Whereas the Poisson regression results offer important insights into how migration dynamics, farm characteristics, and institutional factors influence the adoption of SAPs in Nepal.

Effect of migration, remittances, and gender dynamics on the adoption of SAPs

Table 2 display the Poisson regression result of effect of male out-migration on the adoption of SAPs, with regards to the variable of interest. Our results shows that female-managed farm has a positive and statistically significant effect on SAPs adoption. The marginal effect (0.425) implies that when a household is managed by a female, the number of SAPs adopted increases by approximately 0.43 practices, holding other variables constant. Migration status also positively affects SAPs adoption of the household, with a marginal effect of 0.609. Households with at least one migrant member adopt around 0.61 more practices compared to households without migrant members. Remittances exhibit a strong positive and significant effect with SAPs adoption. The marginal effect of 1.25 indicates that households receiving remittances adopt, on average, 1.26 more SAPs. To further explore the nature of remittance flows, Fig. 3 categorizes them into four types: money, farm inputs, household items, and food items. Respondents rated the frequency of receiving each type on a five-point Likert scale: never, rarely, sometimes, often, and very often. The results indicate that the majority of households often receive money, making it the most common form of remittance. The direct farm input, by contrast, were largely never received. Household items such as clothing and electronics were sometimes received, while food items were generally received rarely or not at all.

To complement the analysis of remittance types, we further examined their perceived importance across various household expenditure categories. Figure 4 presents how respondents rated the importance of remittances for different uses, using a five-point Likert range ranging from not at all important to extremely important. The results indicate that house construction is considered the most important use of remittances, with the highest proportion of respondents rating it as extremely important. This is closely followed by migration costs and repayment of debts, both of which were also widely perceived as very to extremely important. Spending on health and education is also ranked high, with a significant share of respondents identifying them as very or extremely important. In contrast, agricultural investments such as seeds, pesticides, and agricultural tools were generally viewed as less important. A substantial proportion of respondents rated these categories as neutral or slightly important, indicating a relatively lower priority. Food fell in the mid-range, with more varied responses, reflecting mixed levels of perceived importance.

Another important variable of interest in our study was number of female migrant members in the household. This is negatively and significantly associated with SAPs adoption. More specifically, a unit increase in the number of female migrants leads to a reduction of 0.40 SAPs adoption.

Regarding demographic characteristics, household size positively and significantly affects SAPs adoption. Each additional member contributes to the adoption of 0.14 more practices. Off-farm activities are positive and significantly associated with adoption of SAPs. The marginal effect is 0.58, implying households involved in non-farm work adopt 0.58 more practices.

In terms of farm characteristics, mixed farming practices significantly enhance SAP adoption. More specifically there was a high marginal effect of 1.29. This indicates that households practicing mixed-farming adopted 1.29 more SAPs. Cash crop cultivation shows a small but significant positive impact, with each

Variables	Coefficient	Standard error	Incident rate ratio	Standard error	Marginal effect	Standard error
Migration and remittances (variables of interest)						
Female managed farm	0.073	0.038*	1.076	0.041*	0.425	0.220*
Migration	0.105	0.058*	1.111	0.06*	0.609	0.338*
Remittances	0.217	0.085**	1.242	0.106**	1.255	0.496**
Female migrants	−0.069	0.022***	0.933	0.02***	−0.401	0.128***
Demographic characteristics						
Age	0.000	0.001	1.000	0.001	0.001	0.019
Higher caste	0.051	0.037	1.052	0.039	0.295	0.001
Formal education	0.038	0.041	1.038	0.043	0.218	0.001
Household size	0.024	0.011**	1.024	0.011**	0.136	0.019**
Marital status	0.026	0.044	1.027	0.079	0.152	0.001
Off-farm activities	0.100	0.037***	1.105	0.041***	0.579	0.211***
Farm characteristics						
Farming practices	0.223	0.063***	1.250	0.079***	1.291	0.365***
Cash crops	0.003	0.001***	1.003	0.001***	0.017	0.004***
Livestock	−0.027	0.009***	0.974	0.009***	−0.155	0.054***
Farm income	0.040	0.018**	1.041	0.019**	0.234	0.104***
Cultivated land	0.004	0.001***	1.004	0.001***	0.020	0.007***
Land size	0.001	0.001	1.001	0.001	0.004	0.004
Lack of labor	−0.021	0.043	0.979	0.042	−0.122	0.249
Erratic rainfall	0.128	0.055**	1.136	0.062**	0.740	0.316**
Institutional characteristics						
Access to formal credit	0.038	0.069	1.038	0.072	0.219	0.402
Farmer groups	0.072	0.038*	1.074	0.04*	0.415	0.219*
Constant	0.913	0.143***	2.491	0.357***	-	-
Pseudo R^2	0.052		0.052			
Chi-square	181.515		181.515			
Akaike criteria (AIC)	1714.576		1714.576			
Prob > chi^2	0.000		0.000			
Bayesian criteria (BIC)	1798.396		1798.396			

Table 2. Effect of migration and remittances on sustainable agricultural practices ($n = 400$). Note: ***, **, and * represent significance at 1%, 5%, and 10% probability levels, respectively.

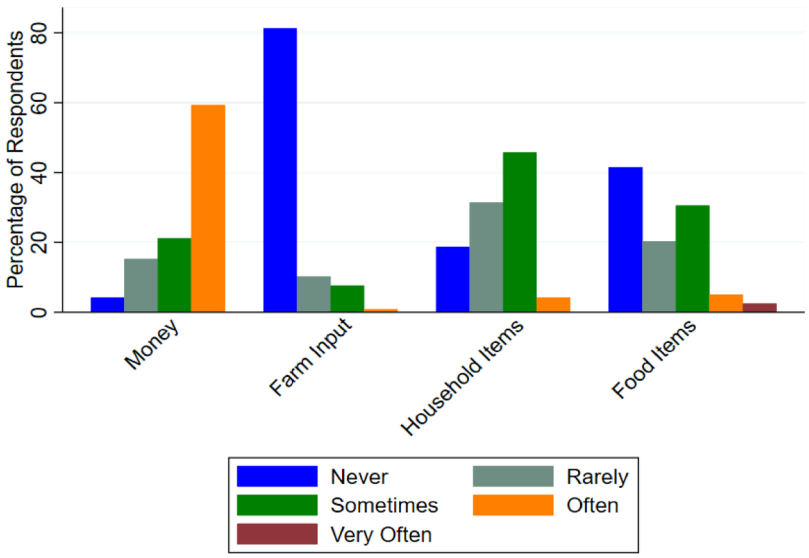

Fig. 3. Frequency of distribution of remittances by types.

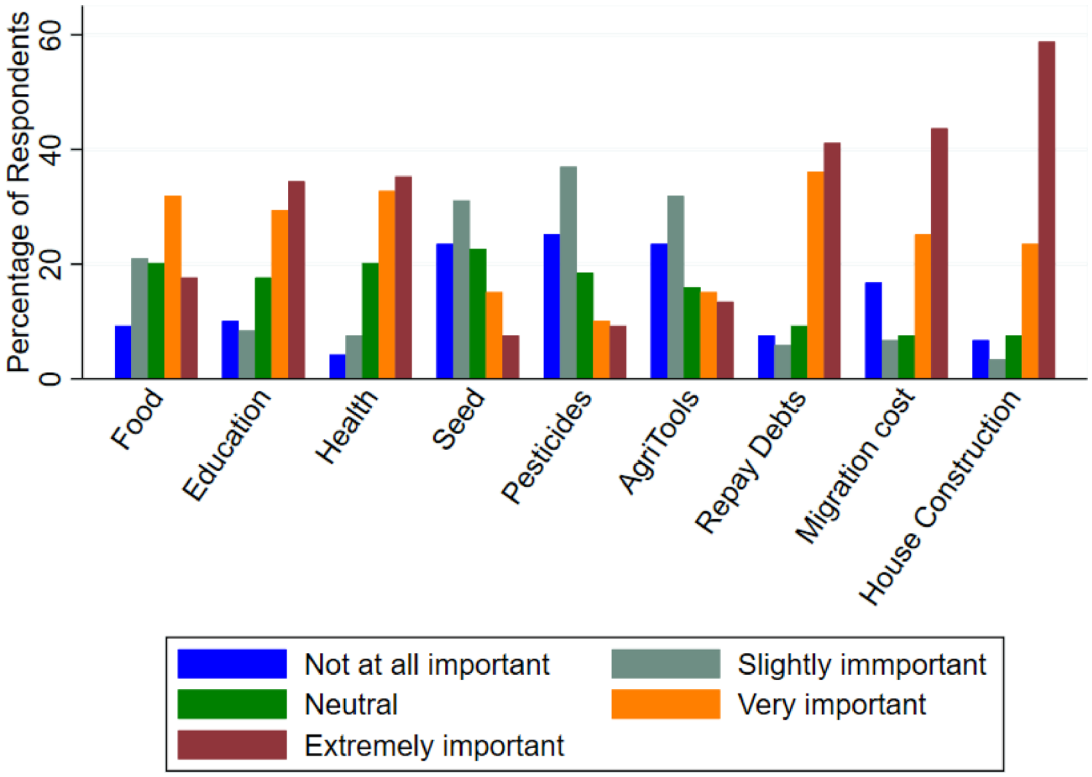

Fig. 4. Perceived importance of remittance across various household expenditure categories.

additional percentage of land under cash crops increasing SAPs by 0.02. The households with livestock holdings have a significant negative association, reducing SAPs adoption by 0.15 practices per unit increase in livestock such as cattle and buffalo. Farm income, cultivated land, and erratic rainfall perception are all positively and significantly associated with SAPs by 0.23, 0.02 and 0.74 respectively. Farmer groups membership has a positive and marginally significant effect, increasing SAP adoption by 0.41.

Discussion

Female-managed farms and adoption of SAPs

Our study results indicate that female-managed farms are positively and significantly associated with the adoption of SAPs. Specifically, households where women are identified as the primary farm managers adopt more SAPs. This finding underscores the crucial role women play in promoting environmentally sustainable farming in rural Nepal. In the study area, female farmers, especially in smallholder contexts, often manage diverse and multifunctional farms. Their decision-making tends to prioritize household food security, soil conservation, and long-term productivity over short-term yield maximization. Several studies in South Asia and Sub-Saharan Africa have shown that women are more inclined than men to adopt sustainable practices such as intercropping, organic inputs, and crop diversification[34,62–64].

Additionally, female farm managers may be more likely to adopt SAPs out of necessity, particularly in households facing male out-migration or limited access to credit or mechanization[65]. The practices like composting, mulching, and crop rotation are often low-cost, labor-based strategies that align well with women-managed plots together with their household activates[66]. In this context, SAPs are not just environmentally sound they are also economically rational for women operating under resource constraints[67]. Another plausible reason is female farmers often participate actively in female originated and other informal community networks (e.g., mothers' group, seed exchanges, local cooperatives, savings groups), which serve as key channels for disseminating sustainable agricultural practices[68]. Although formal extension services may underserve women, these peer-based systems often compensate for institutional gaps and encourage mutual learning[69].

Despite their positive impact, female-managed farms may still face systemic constraints. Access to land, extension services, training, and inputs tends to be lower for women compared to men, even when they are de facto or de jure household heads[70,71]. Thus, the observed positive association may be even stronger in contexts where these institutional inequalities are reduced. Moreover, in Nepal, the increasing feminization of agriculture due to male migration is often not accompanied by a matching shift in institutional recognition or support for female farmers. While many women are assuming managerial roles on the farm, their legal and social recognition as "farmers" remains weak[72,73]. This disconnect can limit their access to subsidies, training, or credit programs intended to support sustainable agriculture.

Rural out-migration and adoption of SAPs

In terms of rural out-migration, households with at least one migrant member tend to adopt more SAPs compared to their counterparts. This implies that the benefits of migration extend beyond economic contributions through remittances. Migration can facilitate behavioral change and strategic innovation within rural households. Specifically, migration can reshape household decision-making processes by increasing access to different knowledge systems, changing risk perceptions, and encouraging forward-looking investment behavior. Given that most Nepali migrants are employed in Gulf countries or any other countries, often within the agriculture or food sectors, there is potential for the transfer of agricultural knowledge, skills, or exposure to new practices to their households back home. This transnational flow of knowledge, though often informal, may influence the adoption of sustainable agricultural practices, especially when returning migrants or their family members integrate these ideas into local farming systems. Moreover, migrants are often exposed to new technologies, environmental management approaches, and socio-economic norms in their destination areas[19,74,75]. Through regular communication or return visits, migrants can share these new insights and aspirations with their communities of origin. This "social remittance" effect can influence how households view agriculture, risk, and long-term sustainability[76,77]. For example, exposure to more mechanized or conservation-oriented farming systems in urban or international contexts may cause migrants to adopt similar methods at home. Furthermore, migration can serve as an informal risk mitigation strategy. The knowledge that a household member can provide support during agricultural shocks, such as crop failure or market fluctuations, may lower the perceived risk of experimenting with new, potentially costly, sustainable practices[78,79]. This dynamic highlights how migration can indirectly foster adaptive capacity in the face of environmental and economic uncertainty. In Nepal, rural male out-migration reshapes intra-household roles and supports the adoption of SAPs. In Terai region such as Chitwan district, migrant-member households adopt labor-saving innovations like integrated crop–livestock systems, influenced by knowledge shared through migrant networks[80]. In mid hills region such as Baglung district, the absence of male labor has increased women's decision-making authority, leading to the uptake of soil conservation and agroforestry practices[81]. In the mountain district of Mustang, households sustain apple and herb farming by reorganizing labor or hiring workers, demonstrating adaptive strategies under shifting gender and labor dynamics[82,83].

Remittances and adoption of SAPs

The results further reveal that remittances exert a strong, positive, and statistically significant influence on the adoption of SAPs. Households that receive remittances tend to adopt more such practices, suggesting that these financial inflows play a pivotal role in supporting environmentally conscious farming decisions. Due to Nepal's diverse geography from the fertile Terai plains to the Mid-Hills and mountainous regions farmers encounter varying agro-ecological constraints, making financial support through remittances vital for adopting region-specific sustainable farming methods that enhance productivity, resilience, and environmental conservation[16]. Remittance income may facilitate by funding improved irrigation systems, the adoption of drought-resistant crop varieties, diversification into higher-value crops, and the application of integrated pest management techniques. This finding aligns with a growing body of empirical research emphasizing the importance of remittances as a critical source of liquidity for rural households, particularly in regions where access to credit and financial services is limited[84,85]. Remittances can alleviate liquidity constraints that often prevent households from investing in sustainable but capital-intensive farming inputs, such as organic fertilizers, improved seeds, irrigation infrastructure, or conservation tools[22,55]. In many rural settings, these inputs are considered risky or unaffordable, especially for resource-constrained smallholders. However, with remittance income, households are better positioned to take on these investments, thereby facilitating the transition toward more resilient and sustainable agricultural systems[86]. Beyond merely increasing purchasing power, remittances may also influence risk preferences and planning horizons. Households with stable external income sources may be more willing to experiment with long-term sustainability measures that do not yield immediate returns but contribute to environmental and livelihood resilience over time[87]. Additionally, remittance-receiving households might allocate labor more flexibly, hiring additional help or reducing dependence on family labor, thus allowing time and resources to be directed toward the management of more complex, sustainable farming systems[88].

Women migrant-sending households and adoption of SAPs

Our results show a negative association with female migrants and adoption of SAPs in the study areas. This implies that when women migrate, households may face labor or knowledge gaps, especially given the central role women play in subsistence agriculture in South Asia[70]. The negative association may be explained by several mechanisms. First, loss of skilled labor, for example women typically manage essential tasks related to input selection, weeding, harvesting, and seed management[89]. Their migration can result in a substantial loss of labor and knowledge. Dependency on less skilled labor, households may compensate for female migration by hiring external labor or relying on remaining members with less experience or motivation to implement sustainable practices. This finding aligns with studies that emphasize the gendered dimensions of migration and caution against assuming that all remittance-receiving households benefit equally[90,91]. The result suggests that when female migration occurs without adequate institutional or community support, it can undermine sustainability goals in agriculture. This finding resonates with studies that highlight the "feminization of agriculture" without adequate empowerment or resource access for remaining members[90]. While the analysis assumes that female migrants may send remittances, the study does not measure how these remittances are used; therefore, the mechanisms described should be viewed as plausible pathways rather than directly observed effects.

Second, in rural Nepal, particularly in districts like Mustang, Baglung, and Chitwan, the lower adoption of SAPs in women migrant-sending households can be explained by how remittances are allocated. Money sent by female migrants is often not invested directly in farming; in unmarried or single women migrants,

families frequently deposit the funds in bank accounts for the woman's future use upon return, or spend it on high-value, non-productive assets such as gold jewellery. This economic diversion, which diverts away from farm inputs and infrastructure, reduces the likelihood of adopting improved irrigation, new crop varieties, crop diversification, or integrated pest management[92]. Third, female migrants move abroad for educational purposes, which requires households to send money to support tuition fees and living costs rather than investing in agricultural improvements, which could not be the case for male migrants. Combined with reduced on-farm labour availability and limited engagement with agricultural extension services, these financial choices contribute to the observed lower uptake of SAPs.

Socio-demographic, farm, institutional characteristics and adoption of SAPs

In terms of demographic factors, larger households are more likely to adopt SAPs, likely due to better labor availability, which aligns with findings from studies in Nigeria and Malawi[93,94]. Involvement in off-farm activities suggests that income diversification can facilitate sustainable farming, possibly by providing cash flow for inputs or equipment[95]. With regards to farm characteristics, mixed farming systems show a strong positive association, reflecting the complementary use of crop-livestock systems and integrated nutrient management, as promoted in conservation agriculture literature[96]. The negative relationship with livestock holdings may be due to competition for land, labor, or even preference for more traditional practices incompatible with SAPs[97]. The positive impact of cash cropping may reflect better market access or the need to maintain soil quality for commercial yields[98]. Additionally, perception of erratic rainfall is positively associated with SAPs adoption, implying that farmers use these practices as climate adaptation strategies[34].

The institutional support reveals that membership in farmer groups enhances adoption, consistent with evidence that social networks facilitate information sharing, risk reduction, and peer support[99]. However, the low significance of access to formal credit reflects a systemic barrier in rural Nepal, where informal borrowing is more prevalent and formal finance is underutilized[63]. Similar patterns were observed in studies conducted in Nigeria, Ethiopia and Pakistan, suggesting a possible universal trend of limited access to formal credit among women farmers[95,100,101].

Limitations of the study

The study has some limitations to acknowledge. Firstly, the utilisation of cross-sectional data impedes our capacity to discern temporal changes and to ascertain causal relationships. Secondly, while the categorization of remittances as tangible types (e.g., money, goods, and agricultural inputs) was employed, this approach may overlook informal or non-monetary contributions, such as knowledge exchange, decision-making support, or labor assistance, that also shape farm-level practices. Future research endeavors may benefit from the adoption of mixed-method designs, which have been shown to enhance the capture of informal support systems and the nuanced gender dynamics that are frequently overlooked in quantitative analyses. Thirdly, despite the implementation of controls for salient factors, including membership in farmer groups and access to formal credit, the potential for endogeneity resulting from unobserved variables cannot be entirely excluded. Finally, while the present analysis accounts for male migration, the potential bi-directional relationship between male out-migration and female farm management may complicate causal interpretation. Further exploration of this relationship is recommended, ideally through the use of longitudinal or panel studies.

Conclusion

This study uses data from 400 households across three agro-ecological zones in Nepal, which provide empirical insights into how migration, remittances, and gender dynamics impact the adoption of sustainable agricultural practices. Moreover, it highlights women's capability on farms to adopt more sustainable and resilient farming practices while facing systemic vulnerabilities within society. Our findings emphasise that financial flows from migration, particularly remittances, are key drivers enabling households to invest in sustainable agricultural practices. However, increased migration of women appears to constrain adoption, likely due to labour shortages and the diversion of funds toward savings, education, or household consumption rather than direct agricultural investment. Beyond gender, migration and remittance-related factors, farming systems, cash crop production, and cultivated land size significantly support implementing sustainable agricultural practices in the study area. Conversely, reliance on livestock limits such adoption, possibly reflecting competing demands on household resources. Moreover, engagement in local farmer groups increases adoption of sustainable agricultural practices. It emphasises the importance of social networks for knowledge exchange and community support in advancing sustainable agricultural transitions.

Considering the positive link between female farm management and the adoption of sustainable agricultural practices, policymakers and development agencies should prioritise gender-responsive agricultural interventions. These programs must focus on empowering women, especially in migrant-sending communities where women increasingly manage farms. Empowerment can be achieved by gender-targeted agricultural training, easy access to credit, tailored extension services, and strengthening local women's groups. Moreover, remittance utilisation strategies need better alignment with agricultural development goals. Since remittances were often spent on household consumption rather than farming, creating innovative schemes and providing subsidies such as matched savings schemes, agricultural input vouchers, and community investment funds can encourage households to invest remittances into sustainable technologies and practices.

Finally, the adverse effects of the sequence of female household members' migration on implementing SAPs highlight the necessity of addressing labour and knowledge deficits resulting from their absence. Community labour-sharing networks, public-private partnerships for mechanisation, and subsidised agricultural services can help mitigate these challenges. By integrating gender empowerment, strategic remittance use, and community-

driven support systems, climate resilience can be enhanced, and sustainable agriculture can be effectively fostered.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request. Due to ethical considerations and to protect participants' privacy, the raw survey data cannot be made openly accessible.

Received: 29 August 2025; Accepted: 5 December 2025
Published online: 15 December 2025

References

1. Leder, S. Beyond the 'Feminization of agriculture': rural out-migration, shifting gender relations and emerging spaces in natural resource management. *J. Rural Stud.* **91**, 157–169. https://doi.org/10.1016/j.jrurstud.2022.02.009 (2022).
2. Sunam, R., Sugden, F., Kharel, A., Sunuwar, T. R. & Ito, T. Unpacking youth engagement in agriculture: Land, labour mobility and youth livelihoods in rural Nepal. *J. Agrarian Change*. **25** (1), e12611. https://doi.org/10.1111/joac.12611 (2025).
3. Rayamajhee, V., Guo, W. & Bohara, A. K. The impact of climate change on rice production in Nepal. *Econ. Disasters Clim. Change*. **5**, 111–134. https://doi.org/10.1007/s41885-020-00079-8 (2021).
4. CIAT; World Bank Climate-Smart agriculture in Nepal. CSA country profiles for Asia series. In *International Centerfor Tropical Agriculture (CIAT); the World Bank; CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS); Local Initiatives for Biodiversity Research and Development* 26 (LI-BIRD), 2017).
5. Kandel, G. P., Bavorova, M., Ullah, A., Kaechele, H. & Pradhan, P. Building resilience to climate change: examining the impact of agro-ecological zones and social groups on sustainable development. *Sustain. Dev.* **31** (5), 3796–3810 (2023).
6. Gomis, R., Kapsos, S. & Kuhn, S. World employment and social outlook: trends 2020. *ILO: Geneva Switzerland*, **127**. (2020).
7. The World Bank. Employment in agriculture (% of total employment). (2025). https://data.worldbank.org/indicator/SL.AGR.EMPL.ZS?locations=NP
8. World Bank. Unlocking Nepal's Growth Potential: Nepal Country Economic Memorandum 2025. (2025b). Retrieved from https://www.worldbank.org/en/country/nepal/publication/unlocking-nepal-s-growth-potential
9. Jaquet, S., Shrestha, G., Kohler, T. & Schwilch, G. The effects of migration on livelihoods, land management, and vulnerability to natural disasters in the Harpan watershed in Western Nepal. *Mt. Res. Dev.* **36** (4), 494–505. https://doi.org/10.1659/MRD-JOURNAL-D-16-00034.1 (2016).
10. Bhawana, K. C. & Race, D. Women's approach to farming in the context of feminization of agriculture: A case study from the middle hills of Nepal. *World Dev. Perspect.* **20**, 100260. https://doi.org/10.1016/j.wdp.2020.100260 (2020).
11. Adhikari, J. & Hobley, M. Everyone is leaving. Who will Sow our fields? The livelihood effects on women of male migration from Khotang and Udaypur districts, Nepal, to the Gulf countries and Malaysia. *Himalaya* **35** (1), 11–23 (2015).
12. National Statistics Office (NSO). *National Population and Housing Census 2021: National Report* (NSO, 2022).
13. Maharjan, A., Bauer, S. & Knerr, B. Do rural women who stay behind benefit from male out-migration? A case study in the hills of Nepal. *Gend. Technol. Dev.* **16** (1), 95–123. https://doi.org/10.1177/097185241101600105 (2012).
14. Maharjan, A., Bauer, S. & Knerr, B. International migration, remittances and subsistence farming: evidence from Nepal. *Int. Migration*. **51**, e249–e263. https://doi.org/10.1111/j.1468-2435.2012.00767.x (2013).
15. Upreti, B. R., Ghale, Y., Shivakoti, S. & Acharya, S. Feminization of agriculture in the Eastern hills of nepal: A study of women in cardamom and ginger farming. *SAGE Open.* **8** (4), 2158244018817124. https://doi.org/10.1177/2158244018817124 (2018).
16. Koirala, S. & Bashyal, S. The land left behind: a systematic review of transnational migration-induced change and its implication for rural sustainability in Nepal. *Humanit. Social Sci. Commun.* **12** (1), 1–12. https://doi.org/10.1057/s41599-024-04180-1 (2025).
17. Atreya, K. & Gartaula, H. Changing gender role declines maize yield, but remittances offset: findings from migrant households in the central Himalayas. *Nepal. Outlook Agric.* **51** (2), 247–259. https://doi.org/10.1177/00307270221097984 (2022).
18. Koirala, S. Empowering absence? Assessing the impact of transnational male Out-Migration on left behind wives. *Social Sci.* **12** (2), 80. https://doi.org/10.3390/socsci12020080 (2023).
19. Leder, S., Upadhyaya, R., van der Geest, K., Adhikari, Y. & Büttner, M. Rural out-migration and water governance: gender and social relations mediate and sustain irrigation systems in Nepal. *World Dev.* **177**, 106544. https://doi.org/10.1016/j.worlddev.2024.106544 (2024).
20. Buisson, M. C., Clement, F. & Leder, S. Women's empowerment and the will to change: evidence from Nepal. *J. Rural Stud.* **94**, 128–139. https://doi.org/10.1016/j.jrurstud.2022.06.005 (2022).
21. Pandey, R. Farmers' perception on agro-ecological implications of climate change in the Middle-Mountains of nepal: a case of Lumle village. *Kaski Environ. Dev. Sustain.* **21** (1), 221–247. https://doi.org/10.1007/s10668-017-0031-9 (2019).
22. Pandey, R. Male out-migration from the himalaya: implications in gender roles and household food (in) security in the Kaligandaki Basin, Nepal. *Migration Dev.* **10** (3), 313–341. https://doi.org/10.1080/21632324.2019.1634 (2021).
23. Kellogg, N. J., Andersen, A. B., Biraschi, R. & Puri, S. Beyond the (dis) empowerment binary: inevitability and the feminization of agriculture in Chitwan, Nepal. *HIMALAYA-The J. Association Nepal. Himal. Stud.* **40** (2), 108–118 (2021).
24. Yokying, P., Saksena, S. & Fox, J. Impacts of migration on time allocation of those who remain at home in rural Nepal. *J. Int. Dev.* **35** (7), 2067–2106. https://doi.org/10.1002/jid.3765 (2023).
25. Maharjan, A., Kochhar, I., Chitale, V. S., Hussain, A. & Gioli, G. Understanding rural outmigration and agricultural land use change in the Gandaki basin. *Nepal. Appl. Geogr.* **124**, 102278. https://doi.org/10.1016/j.apgeog.2020.102278 (2020).
26. Maharjan, K. L. & Gonzalvo, C. M. Examining farmers' willingness to learn environmental conservation agriculture: implications for women farmer empowerment in Bagmati Province. *Nepal. Agric.* **15** (7), 726. https://doi.org/10.3390/agriculture15070726 (2025).
27. Sugden, F. et al. Agrarian stress and climate change in the Eastern gangetic plains: gendered vulnerability in a stratified social formation. *Glob. Environ. Change.* **29**, 258–269. https://doi.org/10.1016/j.gloenvcha.2014.10.008 (2014).
28. Gartaula, H. N., Niehof, A. & Visser, L. Feminisation of agriculture as an effect of male Out-migration: unexpected outcomes from Jhapa District, Eastern Nepal. *Int. J. Interdisciplinary Social Sci.* **5** (2). https://doi.org/10.18848/1833-1882/CGP/v05i02/51588 (2010).
29. Kaspar, H. *I Am the Household Head Now! Gender Aspects of Out-migration for Labour in Nepal* (Nepal Institute of Development Studies, 2005).
30. Kim, J. J., Stites, E., Webb, P., Constas, M. A. & Maxwell, D. The effects of male out-migration on household food security in rural Nepal. *Food Secur.* **11**, 719–732. https://doi.org/10.1007/s12571-019-00919-w (2019).
31. Doss, C. R., Meinzen-Dick, R., Pereira, A. & Pradhan, R. Women's empowerment, extended families and male migration in nepal: insights from mixed methods analysis. *J. Rural Stud.* **90**, 13–25. https://doi.org/10.1016/j.jrurstud.2022.01.003 (2022).

32. Nadeem, M., Wang, Z., Shahbaz, P., Haq, S. U. & Boz, I. The nexus of women's empowerment and sustainable agricultural practices in developing countries: a case of Pakistani women farmers. *J. Environ. Planning Manage.* **68** (4), 820–842. https://doi.org/10.1080/09640568.2023.2273198 (2025).
33. Shahbaz, P. et al. Adoption of climate smart agricultural practices through women involvement in decision making process: exploring the role of empowerment and innovativeness. *Agriculture* **12** (8), 1161. https://doi.org/10.3390/agriculture12081161 (2022).
34. Aryal, J. P. et al. Does women's participation in agricultural technology adoption decisions affect the adoption of climate-smart agriculture? Insights from Indo-Gangetic plains of India. *Rev. Dev. Econ.* **24** (3), 973–990. https://doi.org/10.1111/rode.12670 (2020).
35. Dar, M. H. et al. Gender focused training and knowledge enhances the adoption of climate resilient seeds. *Technol. Soc.* **63**, 101388. https://doi.org/10.1016/j.techsoc.2020.101388 (2020).
36. Agarwal, T. et al. Gendered impacts of climate-smart agriculture on household food security and labor migration: insights from Bihar, India. *Int. J. Clim. Change Strateg. Manag.* **14** (1), 1–19. https://doi.org/10.1108/IJCCSM-01-2020-0004 (2022).
37. Glazebrook, T. & Opoku, E. Gender and sustainability: learning from women's farming in Africa. *Sustainability* **12** (24), 10483. https://doi.org/10.3390/su122410483 (2020).
38. Theriault, V., Smale, M. & Haider, H. How does gender affect sustainable intensification of cereal production in the West African sahel? Evidence from Burkina Faso. *World Dev.* **92**, 177–191. https://doi.org/10.1016/j.worlddev.2016.12.003 (2017).
39. DFID. Key sheets for sustainable development: overview. (1999).
40. Natarajan, N., Newsham, A., Rigg, J. & Suhardiman, D. A sustainable livelihoods framework for the 21st century. *World Dev.* **155**, 105898. https://doi.org/10.1016/j.worlddev.2022.105898 (2022).
41. UNDP. *Guidance Note: Application of the Sustainable Livelihoods Framework in Development Projects* (United Nations Development Programme, Regional Centre for Latin America and the Caribbean, 2017).
42. Crenshaw, K. Mapping the margins: Intersectionality, identity politics, and violence against women of color. *Stanford Law Rev.* **43** (6), 1241–1299. https://doi.org/10.2307/1229039 (1991).
43. Collins, P. H. *Black Feminist Thought*, 2nd edition, New York: Routledge. (2000).
44. Collins, P. H. *Black Feminist Thought: Knowledge, consciousness, and the Politics of Empowerment* (routledge, 2022).
45. Kimberly, C. Demarginalizing the Intersection of Race and Sex: A Black Feminist Critique of Anti-Discrimination Doctrine, Feminist Theory and Anti-Racist Politics. In The University of Chicago Legal Forum (Vol. 140, p. 139). (1989).
46. Naess, L. O., Wangari-Muneri, E., Nightingale, A. J. & Mehta, L. Climate change and the operation of power: intersectionality, dispossession, and knowledge politics in pastoral communities. *J. Peasant Stud.* 1–26. https://doi.org/10.1080/03066150.2025.2451288 (2025).
47. Tiwari, P. C. & Joshi, B. Gender processes in rural out-migration and socio-economic development in the himalaya. *Migration Dev.* **5** (2), 230–250. https://doi.org/10.1080/21632324.2015.1022970 (2016).
48. Islam, M. S., Sarker, M. F. H., Ehsan, S. M. A. & Sohel, M. S. Rethinking women empowerment in rural bangladesh: male out-migration, left-behind wives, and changing gender roles. *Social Sci. Humanit. Open.* **11**, 101425. https://doi.org/10.1016/j.ssaho.2025.101425 (2025).
49. Pattnaik, I., Lahiri-Dutt, K., Lockie, S. & Pritchard, B. The feminization of agriculture or the feminization of agrarian distress? Tracking the trajectory of women in agriculture in India. *J. Asia Pac. Econ.* **23** (1), 138–155. https://doi.org/10.1080/13547860.2017.1394569 (2018).
50. Collins, A. Saying all the right things? Gendered discourse in climate-smart agriculture. *J. Peasant Stud.* **45** (1), 175–191. https://doi.org/10.1080/03066150.2017.1377187 (2017).
51. Mehta, D., Pandey, R., Gupta, A. K. & Juhola, S. Nature-based solutions in Hindu Kush himalayas: IUCN global standard based synthesis. *Ecol. Ind.* **154**, 110875. https://doi.org/10.1016/j.ecolind.2023.110875 (2023).
52. Thapa, S. & Bhattarai, K. Farming Systems, Food Security and Contemporary Climate Issues in Nepal. In *The Routledge International Handbook of Himalayan Environments, Development and Wellbeing* (pp. 177–189). Routledge. (2025). https://doi.org/10.4324/9781003450894
53. Sujakhu, N. M., Ranjitkar, S., Su, Y., He, J. & Xu, J. A gendered perspective on climate change adaptation strategies: a case study from Yunnan, China. *Local Environ.* **28** (1), 117–133. https://doi.org/10.1080/13549839.2022.2130883 (2023).
54. Raj, R., Ravula, P., Bhanjdeo, C. M. P., Sogani, A., Rao, N. & R., & Male migration and the transformation of gendered agriculture work: a comparative exploration of heterogeneity across selected Indian States. *Gend. Place Cult.* 1–27. https://doi.org/10.1080/0966369X.2025.2468178 (2025).
55. Southard, E. M. & Randell, H. Climate change, agrarian distress, and the feminization of agriculture in South Asia. *Rural Sociol.* **87** (3), 873–900. https://doi.org/10.1111/ruso.12439 (2022).
56. Coxe, S., West, S. G. & Aiken, L. S. The analysis of count data: A gentle introduction to Poisson regression and its alternatives. *J. Pers. Assess.* **91** (2), 121–136. https://doi.org/10.1080/00223890802634175 (2009).
57. Hilbe, J. M. Poisson regression. In Modeling Count Data (35–73). Cambridge University Press. (2014).
58. Kroll, C. N. & Song, P. Impact of multicollinearity on small sample hydrologic regression models. *Water Resour. Res.* **49** (6), 3756–3769. https://doi.org/10.1002/wrcr.20315 (2013).
59. García García, C., Gomez, S., García Pérez, J. & R., & A review of ridge parameter selection: minimization of the mean squared error vs. mitigation of multicollinearity. *Commun. Statistics-Simulation Comput.* **53** (8), 3686–3698. https://doi.org/10.1080/03610918.2022.2110594 (2024).
60. Long, J. S. & Freese, J. *Regression Models for Categorical Dependent Variables Using Stata* 3rd edn (Stata, 2014).
61. Cameron, A. C., Trivedi, P. K. & Rev Microeconometrics using Stata (.) Stata. (2010).
62. Meinzen-Dick, R., Quisumbing, A., Behrman, J., Biermayr-Jenzano, P., Wilde, V., Noordeloos,M., … Beintema, N. (2019). Engendering agricultural research. Food Security, 11(3),565–574. https://doi.org/10.1007/s12571-019-00917-6.
63. Kandel, G. P., Bavorova, M., Ullah, A. & Pradhan, P. Food security and sustainability through adaptation to climate change: lessons learned from Nepal. *Int. J. Disaster Risk Reduct.* **101**, 104279. https://doi.org/10.1016/j.ijdrr.2024.104279 (2024).
64. Kilic, T., Palacios-Lopez, A. & Goldstein, M. Caught in the productivity trap: A gendered perspective on the commercialization of agriculture in Africa. *World Bank. Economic Rev.* **36** (1), 75–104. https://doi.org/10.1093/wber/lhab006 (2022).
65. Nanda, M. & Ghosh, S. How does male out-migration impact the lives of left-behind women? Trade-off between feminization of agriculture and empowerment of farm women. *Eval. Program Plan.* 102603. https://doi.org/10.1016/j.evalprogplan.2025.102603 (2025).
66. Fertő, I. & Bojnec, Š. Empowering women in sustainable agriculture. *Sci. Rep.* **14** (1), 7110. https://doi.org/10.1038/s41598-024-57933-y (2024).
67. Tourtelier, C., Gorman, M. & Tracy, S. Influence of gender on the development of sustainable agriculture in France. *J. Rural Stud.* **101**, 103068. https://doi.org/10.1016/j.jrurstud.2023.103068 (2023).
68. Zhang, Y., Hu, N., Yao, L., Zhu, Y. & Ma, Y. The role of social network embeddedness and collective efficacy in encouraging farmers' participation in water environmental management. *J. Environ. Manage.* **340**, 117959. https://doi.org/10.1016/j.jenvman.2023.117959 (2023).
69. Beaman, L. & Dillon, A. Do female agricultural extension agents affect female farmers' outcomes? Evidence from Ethiopia. *Am. Economic Journal: Appl. Econ.* **14** (1), 66–95. https://doi.org/10.1257/app.20200265 (2022).

70. Doss, C., Meinzen-Dick, R., Quisumbing, A. & Theis, S. Women in agriculture: four Myths. *Global Food Secur.* **16**, 69–74. https://doi.org/10.1016/j.gfs.2017.10.001 (2018).
71. Ragasa, C., Aberman, N. L. & Alvarez-Mingote, C. Does providing agricultural and nutrition information to both men and women improve household food security? *J. Agric. Econ.* **70** (3), 940–963. https://doi.org/10.1111/1477-9552.12314 (2019).
72. Spangler, K. & Christie, M. E. Renegotiating gender roles and cultivation practices in the Nepali mid-hills: unpacking the feminization of agriculture. *Agric. Hum. Values*. **37**, 415–432. https://doi.org/10.1007/s10460-019-09997-0 (2020).
73. Holmelin, N. B. Competing gender norms and social practice in Himalayan farm management. *World Dev.* **122**, 85–95. https://doi.org/10.1016/j.worlddev.2019.05.018 (2019).
74. Fry, C. et al. Migrants as sustainability actors: contrasting nation, City and migrant discourses and actions. *Glob. Environ. Change*. **87**, Article 102860. https://doi.org/10.1016/j.gloenvcha.2024.102860 (2024).
75. Head, L., Klocker, N., Dun, O., Waitt, G., Goodall, H., Aguirre-Bielschowsky, I.,… Toole, S. (2021). Barriers to and enablers of sustainable practices: insights from ethnic minority migrants. Local Environment, 26(5), 595–614. https://doi.org/10.1080/13549839.2021.1904856.
76. Batista, C., Han, D., Haushofer, J., Khanna, G., McKenzie, D., Mobarak, A. M., … Yang,D. (2025). Brain drain or brain gain? Effects of high-skilled international emigration on origin countries. Science, 388(6749), eadr8861. https://www.science.org/doi/full/10.1126/science.adr8861.
77. Tambo, J. A. & Wünscher, T. Migration and conservation agriculture in Northern ghana: exploring the role of social networks and environmental perceptions. *Food Secur.* **9** (4), 685–698. https://doi.org/10.1007/s12571-017-0682-1 (2017).
78. De Brauw, A. et al. Biofortification, crop adoption and health information: impact pathways in Mozambique and Uganda. *Am. J. Agric. Econ.* **100** (3), 906–930. https://doi.org/10.1093/ajae/aay005 (2018).
79. Ram Mohan, R., Puskur, R., Chandrasekar, D. & Valera, H. G. A. Do gender dynamics in intra-household decision making shift with male migration? Evidence from rice-farming households in Eastern India. *Gend. Technol. Dev.* **27** (2), 157–183. https://doi.org/10.1080/09718524.2022.2140381 (2022).
80. Aryal, J. P., Thapa, G. & Simtowe, F. Mechanisation of small-scale farms in South asia: empirical evidence derived from farm households survey. *Technol. Soc.* **65**, 101591. https://doi.org/10.1016/j.techsoc.2021.101591 (2021).
81. Khatri, N. D., Paudel, D., Bhusal, P., Ghimire, S. & Bhandari, B. Determinants of farmers' decisions to adopt agroforestry practices: insights from the Mid-hills of Western Nepal. *Agroforest Syst.* **97** (5), 833–845. https://doi.org/10.1007/s10457-023-00830-6 (2023).
82. Bhatta, L. D., Shrestha, A., Neupane, N., Jodha, N. S. & Wu, N. Shifting dynamics of nature, society and agriculture in the Hindu Kush himalayas: perspectives for future mountain development. *J. Mt. Sci.* **16** (5), 1133–1149. https://doi.org/10.1007/s11629-018-5146-4 (2019).
83. Stark, O. & Bloom, D. E. The new economics of labor migration. *Am. Econ. Rev.* **75** (2), 173–178 (1985). https://www.jstor.org/stable/1805591
84. Yu, Z., Zhang, K., Wang, Z. & Liu, C. Immigration remittances, agricultural investment, and household wealth accumulation. *Finance Res. Lett.* **68**, 105991. https://doi.org/10.1016/j.frl.2024.105991 (2024).
85. Mutai, N. C., Ibeh, L., Nguyen, M. C., Kiarie, J. W. & Ikamari, C. Sustainable economic development in kenya: influence of diaspora remittances, foreign direct investment and imports. *Afr. J. Economic Manage. Stud.* **16** (1), 61–78. https://doi.org/10.1108/AJEMS-01-2024-0059 (2025).
86. Wu, X., Chen, L., Ma, L., Cai, L. & Li, X. Return migration, rural household investment decision, and poverty alleviation: evidence from rural Guangdong, China. *Growth Change*. **54** (1), 304–325. https://doi.org/10.1111/grow.12656 (2023).
87. Cui, H., Wang, Y. & Zheng, L. Livelihood sustainability of rural households in response to external shocks, internal stressors and geographical disadvantages: empirical evidence from rural China. *Environ. Dev. Sustain.* 1–30. https://doi.org/10.1007/s10668-024-04666-7 (2024).
88. Jijin, P. Remittances and labour force heterogeneity: can the disincentive effect vary? *Int. Rev. Appl. Econ.* 1–23. https://doi.org/10.1080/02692171.2024.2404947 (2024).
89. Vemireddy, V. & Choudhary, A. A systematic review of labor-saving technologies: implications for women in agriculture. *Global Food Secur.* **29**, 100541. https://doi.org/10.1016/j.gfs.2021.100541 (2021).
90. Arslan, A., McCarthy, N., Lipper, L., Asfaw, S. & Cattaneo, A. Adoption and intensity of adoption of conservation farming practices in Zambia. *Agricultural Ecosyst. Environ.* **254**, 124–134. https://doi.org/10.1016/j.agee.2017.11.025 (2020).
91. Slavchevska, V., de la Campos, O., Brunelli, A. P., Doss, C. & C., & Beyond ownership: women's and men's land rights in sub-Saharan Africa. *Food Policy*. **102**, 102065. https://doi.org/10.1016/j.foodpol.2021.102065 (2021).
92. Marty, E., Bullock, R., Cashmore, M., Crane, T. & Eriksen, S. Adapting to climate change among transitioning Maasai pastoralists in Southern kenya: an intersectional analysis of differentiated abilities to benefit from diversification processes. *J. Peasant Stud.* **50** (1), 136–161. https://doi.org/10.1080/03066150.2022.2121918 (2022).
93. Oyetunde-Usman, Z., Olagunju, K. O. & Ogunpaimo, O. R. Determinants of adoption of multiple sustainable agricultural practices among smallholder farmers in Nigeria. *Int. Soil. Water Conserv. Res.* **9** (2), 241–248. https://doi.org/10.1016/j.iswcr.2020.10.007 (2021).
94. Mgomezulu, W. R., Edriss, A. K., Machira, K. & Pangapanga-Phiri, I. Towards sustainability in the adoption of sustainable agricultural practices: implications on household poverty, food and nutrition security. *Innov. Green. Dev.* **2** (3), 100054. https://doi.org/10.1016/j.igd.2023.100054 (2023).
95. Adigun, G. T. Determinants of credit access among smallholder women farmers in Kwara State, Nigeria. *Nigeria Agricultural J.* **53** (2), 121–128 (2022).
96. Fares, M. H., Raza, S. & Ahmad, T. I. Complementarity in mixed farming systems enhances the smallholders income: evidence from Punjab, Pakistan. *PloS One*. **20** (4), e0319995. https://doi.org/10.1371/journal.pone.0319995 (2025).
97. Achmad, B., Sanudin, Siarudin, M., Widiyanto, A., Diniyati, D., Sudomo, A., Hani,A., Fauziyah, E., Suhaendah, E., Widyaningsih, T. S., Handayani, W., Maharani, D.,Suhartono, Palmolina, M., Swestiani, D., Budi Santoso Sulistiadi, H., Winara, A.,Nur, Y. H., Diana, M., … Ruswandi, A. (2022). Traditional Subsistence Farming of Smallholder Agroforestry Systems in Indonesia: A Review. Sustainability, 14(14), 8631. https://doi.org/10.3390/su14148631.
98. Roy, D. et al. Impact of long term conservation agriculture on soil quality under cereal based systems of North West India. *Geoderma* **405**, 115391. https://doi.org/10.1016/j.geoderma.2021.115391 (2022).
99. Chaudhuri, S. et al. Reflections on farmers' social networks: a means for sustainable agricultural development? *Environ. Dev. Sustain.* **23**, 2973–3008. https://doi.org/10.1007/s10668-020-00762-6 (2021).
100. Kiros, S. & Meshesha, G. B. Factors affecting farmers' access to formal financial credit in Basona Worana District, North Showa Zone, Amhara regional State, Ethiopia. *Cogent Econ. Finance*. **10** (1). https://doi.org/10.1080/23322039.2022.2035043 (2022).
101. Habib, N., Alauddin, M., Cramb, R. & Rankin, P. A differential analysis for men and women's determinants of livelihood diversification in rural rain-fed region of pakistan: an ordered logit model (OLOGIT) approach. *Social Sci. Humanit. Open.* **5** (1), 100257. https://doi.org/10.1016/j.ssaho.2022.100257 (2022).

Author contributions

Giri Prasad Kandel: Conceptualization; Methodology; Data curation; Formal analysis; Writing – original draft; Project administration.Mustapha Yakubu Madaki: Methodology; Validation; Writing – review & editing.Tereza

Pilarova: Methodology, Validation, Writing – review & editing.Ayat Ullah: Formal analysis; Visualization; Writing – review & editing.Prajal Pradhan: Supervision; Writing – review & editing.Ioannis Manikas: Supervision; Funding acquisition, Writing – review & editing.Miroslava Bavorova: Conceptualization; Supervision; Funding acquisition; Writing – review & editing.

Funding

We would like to express our gratitude to the Faculty of Tropical AgriSciences of the Czech University of Life Sciences in Prague for financially supporting this research (IGA 20223113). This project has also received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101084201 (ECO-READY). Moreover, we acknowledge funding from the European Research Council for the BeyondSDG project, the European Union (101077492). The sponsors had no role in the study design, data collection and analysis, decision to publish, or preparation of this manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-025-31848-8.

Correspondence and requests for materials should be addressed to G.P.K.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.