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Individual and Interaction Effects of Mechanization and Crop-Livestock Diversification on Household Dietary Diversity in Arsi Zone, Oromia Regional State, Ethiopia

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Individual and Interaction Effects of Mechanization and Crop-Livestock Diversification on Household Dietary Diversity in Arsi Zone, Oromia Regional State, Ethiopia

Abstract

Mechanization has immense potential to improve agricultural productivity and overall production, while crop–livestock diversification plays a crucial role in enhancing nutrition security; however, the combined effects of mechanization and diversification on nutrition security—particularly across mechanization users and non-users—remain underexplored. This study, therefore, examines the relationship between agricultural mechanization, crop livestock diversification, and household dietary diversity (HDDS) using data from 413 rural households in Ethiopia's Arsi Zone, employing a Multinomial Endogenous Switching Regression (MESR) model to analyze both individual and joint effects on nutritional outcomes. The results indicate that crop–livestock diversification significantly improves HDDS and Food Consumption Score (FCS) for both mechanized and non-mechanized households, with stronger effects observed among non-mechanized households. In contrast, mechanization in diversified systems is associated with poorer dietary outcomes than non-mechanized counterparts, indicating a negative moderating effect. Among non-diversified households, mechanization has no significant effect on HDDS but exerts a positive impact on FCS, implying that its influence is context-specific and dependent on the level of diversification. Overall, the findings highlight the importance of aligning mechanization policies with diversification strategies to simultaneously enhance agricultural productivity and improve nutrition outcomes.

Keywords: Mechanization, Agricultural diversification, Dietary diversity score, Multi-treatment endogenous switching regression, Arsi, Ethiopia

1. Introduction

The concept of food security has experienced a significant transformation over the decades. Initially centered on national food production and aggregate supply, it has evolved into a more comprehensive and multidimensional framework. This shift owes much to the influential work of Amartya Sen, whose entitlement theory reframed food security not as a problem of supply alone, but as one of access. In this regard, Sen (1982) identified four critical entitlements: production-based, trade-based, own-labor, and transfer-based, that determine a household's ability to secure food. These entitlements help explain why some households suffer food insecurity even when food is available at the national level.

Building on this, the Sustainable Livelihood Approach (SLA), developed by Chambers and Conway (1992), further expands the understanding of food access by emphasizing the role of households' livelihood assets—human, natural, financial, physical, and social capital—in shaping their ability to secure adequate food and nutrition. As thinking continued to evolve, the concept of food security widened to include the biological utilization of food and the nutritional adequacy of diets.

This broader perspective aligns with UNICEF's conceptual model of malnutrition (UNICEF, 2020), which highlights both immediate causes, such as poor dietary intake, and underlying determinants like inadequate health services and socio-economic constraints. Since the mid-1990s, the focus has increasingly turned to *nutrition security*, a concept that goes beyond food availability and access to include dietary quality, nutrient diversity, and the conditions necessary for nutrient absorption. Maxwell (1996) emphasized that it is not merely the amount of food that matters, but the quality of the entitlement itself. FAO (2012) articulates nutrition security as a condition where consistent access to a nutritious diet is supported by a sanitary environment, adequate health services, and care, ensuring a healthy and active life for all household members. Within this framework, the utilization dimension of food security gains prominence, focusing on the actual intake of diverse, nutrient-rich foods (Pangaribowo et al., 2013).

Drawing on the work of Ruel (2003) and Ruel et al. (2013), this study adopts the Household Dietary Diversity Score (HDDS), to assess nutrition security at the household level. The HDDS was developed by the Food and Nutrition Technical Assistance (FANTA) project (Swindale et al., 2006). As noted by Koppmair et al. (2017b), HDDS captures both food availability and accessibility dimensions, making it a valuable measure of household-level nutrition security. A higher dietary diversity score indicates greater consumption of diverse food groups and correlates positively with socio-economic status, per capita consumption, energy intake, and overall food access (Arimond et al., 2010). The importance of dietary diversity lies in the fundamental nutritional principle that varied diets are more likely to provide the full spectrum of essential nutrients required for good health compared to monotonous diets (Bolo et al., 2024). Since nutrients vary in type and concentration across foods, only a diverse diet can adequately meet the nutritional needs of all age and gender groups (Beal et al., 2024; Berhanu Desalegn et al., 2024)

Nevertheless, inadequate dietary diversity remains a major challenge in many developing countries, particularly in Africa, where diets are largely based on starchy staples and often lack sufficient fruits, vegetables, and animal-source foods rich in essential micronutrients (Adetola et al., 2023). Inadequate dietary diversity is a key factor in Ethiopia's persistent food and nutrition insecurity. A key contributing factor to this nutritional crisis is the lack of dietary diversity. In

Ethiopia, particularly in the study area and many other rural regions, diets mainly consist of staple foods such as traditional bread made from cereals. While these cereal-based meals provide necessary calories, they are often monotonous and lack essential micronutrients (Mengistu et al., 2021; Workicho et al., 2016).

According to Jateno et al. (2023), cereals accounted for 96.4% of the food consumed by Ethiopian households, followed by pulses at 82%. In contrast, the consumption of high-nutrient food groups such as fruits, vegetables, and lean meats remains significantly lower. This dietary pattern highlights a heavy dependence on staple crops, which contributes to micronutrient deficiencies and persistent malnutrition (Yilmaz & Yilmaz, 2025). Moreover, with the increasing introduction of large-scale agricultural machinery on smallholder farms, many farmers are shifting toward crop specialization. Although mechanization can enhance productivity, this specialization often comes at the expense of crop diversity, potentially reducing the cultivation and availability of nutrient-rich foods such as vegetables, fruits, and legumes (Cao et al., 2024).

Thus, the broader implications are concerning. In Ethiopia, malnutrition affects about 22% of the population, placing the country among those with the highest burden in Africa. According to the Global Hunger Index GHI (2024), Ethiopia ranks 102nd out of 127 countries with available data, and its hunger level is categorized as "serious," with a score of 26.2. Micronutrient deficiencies continue to be alarmingly prevalent, posing a significant public health concern. National statistics reveal that deficiencies in essential nutrients such as iron, iodine, zinc, and vitamin A are particularly widespread (Federal Government of Ethiopia, 2022).

To reverse these trends, agriculture must be harnessed not just for production, but also as a driver of nutrition. Agriculture influences diet through its effects on food supply, income, and rural employment—especially for vulnerable communities (Gillespie & van den Bold, 2017; Umesha et al., 2018). Following the 2007–2008 global food crisis, greater emphasis has been placed on *nutrition-sensitive agriculture*, which focuses not only on output but also on ensuring the availability, affordability, and safety of diverse foods throughout the food system (Herforth et al., 2015). Yet within this approach, the role of mechanization in shaping nutrition outcomes remains underexplored.

Mechanization affects dietary diversity through multiple pathways, as illustrated in **Figure 1**. On the positive side, it can raise yields and incomes, enabling households to buy a broader range of foods. On the negative side, it can drive monoculture farming and reduce on-farm crop and livestock diversity. For smallholder farmers, especially in remote or resource-poor areas, maintaining on-farm diversity remains a key strategy for accessing essential micronutrients and proteins (Uccello et al., 2017). Thus, understanding the trade-offs and synergies between mechanization and dietary diversity is critical for promoting nutrition security.

Therefore, this study examines both the individual and joint (interaction) effects of mechanization and crop-livestock diversification on household dietary diversity (HDDS).To rigorously analyze these relationships, we employ econometric techniques that address endogeneity and selection bias inherent in the non-random nature of farmers' decisions. The choice to adopt mechanization or pursue diversification is influenced by both observable and unobservable factors; failure to account for these may result in biased and inconsistent estimates.

To overcome such issues, the study employs a Multinomial Endogenous Switching Regression (MESR) model, which is well-suited for analyzing multiple, overlapping livelihood strategies. Households may follow combinations such as mechanized-diversified, mechanized-specialized, non-mechanized-diversified, or non-mechanized-specialized, each carrying distinct implications for dietary outcomes. The MESR framework jointly estimates (1) a selection equation modeling the probability of choosing each strategy and (2) outcome equations for HDDS within each group. This structure allows for the estimation of counterfactuals. By accounting for both observed and unobserved heterogeneity, the MESR model provides a comprehensive understanding of the individual and combined impacts of mechanization and diversification on nutrition security.

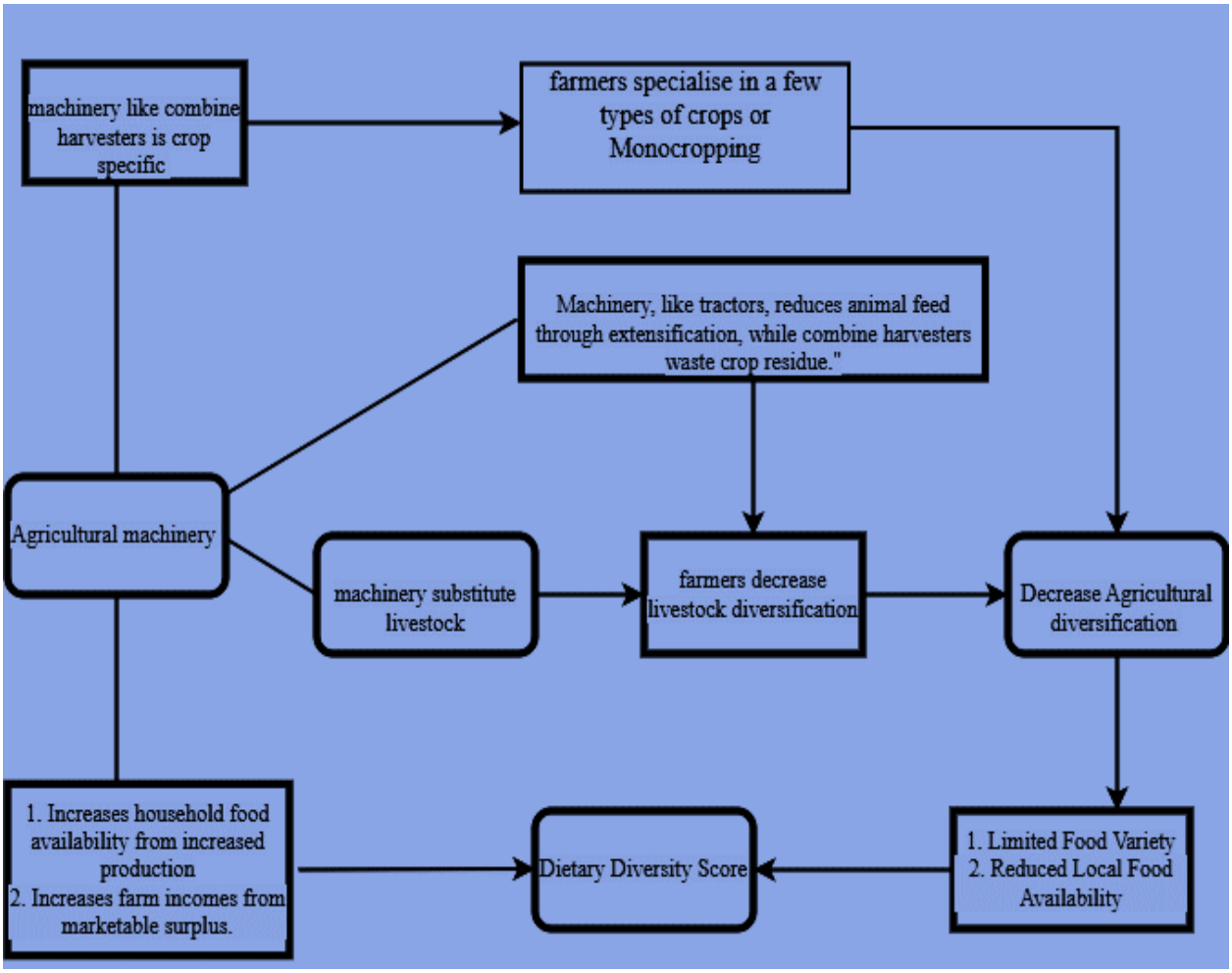


Figure 1: Relationship among farm mechanisation, agricultural diversification and Household Dietary Diversity score

2. Farm Mechanisation, Diversification, and Food and Nutrition Security

Farm mechanization is widely recognized as a central driver of agricultural transformation and food security in both developed and developing economies. As population growth exerts increasing pressure on land and labor, mechanization enhances productivity, reduces drudgery, and supports the timely completion of farming operations. However, while the literature often highlights its role in boosting agricultural output, less attention has been given to its broader

implications for food and nutrition security, particularly through its influence on agricultural diversification and dietary outcomes.

Empirical studies from different contexts underscore the potential of mechanization to strengthen food security through increasing production and productivity. For instance, Negrete (2019) result shows that the adoption of farm machinery significantly improved food security among farming households in Mexico. Similarly, Mutungi et al. (2023) found that the use of postharvest mechanization technologies in Tanzania enhanced household food availability and accessibility by reducing losses and increasing income. In Iran, Emami et al. (2021) demonstrated that aligning mechanization with appropriate cropping patterns can minimize postharvest losses and contribute to improved food utilization, while Ntagu et al. (2022)confirmed that agricultural mechanization substantially contributes to increased food production and availability in Nigeria

Despite these positive contributions, particularly through increased production, mechanization may also have unintended consequences for agricultural diversification. As noted by (Janssen, 2018), mechanization can discourage diversification by promoting specialization in a limited number of crops. However, agricultural diversification remains a critical pathway for achieving food and nutrition security. Many smallholder farmers adopt diversification strategies to reduce the risks associated with crop failure and to stabilize their livelihoods, especially in developing countries (Di Falco et al., 2010; Paut et al., 2019). Beyond risk reduction, crop diversification improves soil health through practices such as crop rotation and nitrogen fixation, enhances productivity and income, and supports long-term sustainability Mussema et al. (2015). It also serves as an important climate adaptation strategy, helping rural households cope with environmental shocks while maintaining food security (Ijaz et al., 2019). In many developing economies, smallholder farmers rely on integrated crop–livestock systems, where diversification strengthens resilience, improves food availability, and enhances nutritional outcomes.

Nevertheless, the interaction between mechanization and crop-livestock diversification introduces a critical trade-off. While mechanization enhances productivity and reduces labor and postharvest losses, it may simultaneously reduce crop diversity, thereby posing challenges for food and nutrition security. For example, Kansanga et al. (2019a), using GIS and field interviews, show that mechanization alters cropping patterns by reducing the variety of crops cultivated, which can influence food prices and limit access to diverse and nutritious foods. The shift toward mechanized farming often encourages mono-cropping, reducing the availability, accessibility, and affordability of nutrient-rich foods. These changes may also lead to price volatility, further constraining households' ability to maintain adequate diets. Likewise, a study conducted by Qiao (2023), using provincial panel data from China, finds that while mechanization boosts grain production, it leads to a decline in non-grain crop cultivation, increasing dependence on global markets and threatening dietary diversity. Although mechanization helps improve productivity for grain crops, it also threatens the diversity and consistency of non-grain crop production, which could have serious consequences for food and nutrition security. These findings emphasize the need for a balanced mechanization strategy that considers both its benefits and potential risks, aiming to preserve crop diversity and protect China's food security against the vulnerabilities linked to heavy reliance on imported agricultural goods.

A decline in agricultural diversity poses significant risks to both food and nutrition security. For instance, Adjimoti and Kwadzo (2018) found that crop diversification can improve food security

by enhancing dietary diversity. Similarly, Waha et al. (2018) conducted a study on households in Africa and found that more diverse crop farming methods contributed to food security. The evidence from Malawi also supports the positive association between crop diversification and food security, as diverse cropping systems contribute to diverse household diets (Jones et al., 2014). In Namibia, Mulwa and Visser (2020) discovered that access to climate data plays a crucial role in the effectiveness of crop and livestock diversification, and they concluded that a higher degree of agricultural or livestock production diversification leads to better food security outcomes. In Ethiopia, crop-livestock diversification has been identified as the best potential livelihood strategy for farm households (Mekuria & Mekonnen, 2018b).

The nexus between mechanization, crop-livestock diversification, and food and nutrition security (FNS) has been understudied in both the study area and the broader literature. This research aims to address this gap and contribute valuable insights to the academic world by investigating and analyzing the relationship between these factors. By exploring the interplay between mechanization, agricultural diversification, and FNS, the study seeks to uncover how the adoption of mechanization impacts agricultural diversification practices and, in turn, the implications for food and nutrition security.

3. Methodology

3.1 Study Setting

The study was conducted in the Arsi Zone of the Oromia Regional State, located in central Ethiopia, as illustrated in the map presented in Figure 2. The zone is one of the country's major highland areas and plays a pivotal role in national agricultural production, particularly in cereal cultivation. Arsi is often referred to as Ethiopia's "wheat belt" due to its favorable agro-ecological conditions, fertile soils, and relatively high level of agricultural mechanization. According to the Central Statistical Agency (CSA, 2021a) cereal crops cover approximately 83.26% of the total cultivated land in the zone, with wheat and barley together accounting for about 47.97% of the total cereal area. This pattern reflects a strong specialization in cereal production, especially in mid- and high-altitude zones where climatic conditions are highly conducive to such crops.

In addition to crop cultivation, livestock production represents a major agricultural activity in Arsi. As reported by CSA (2021a), the zone possesses around 4.7 million cattle, 4.6 million sheep and goats, 3.62 million pack animals (horses, mules, and donkeys), 2.54 million poultry, and 126,956 beehives. These figures indicate that Arsi Zone contributes about 18.6% of Oromia's cattle, 19.9% of its small ruminants, 24.6% of pack animals, 13.3% of poultry, and 3.4% of beehives. This underscores the zone's dual importance in both crop and livestock production, making it one of Ethiopia's most agriculturally intensive areas. The combination of strong agricultural potential and increasing mechanization makes Arsi an ideal setting for examining the relationship between agricultural mechanization and diversification.

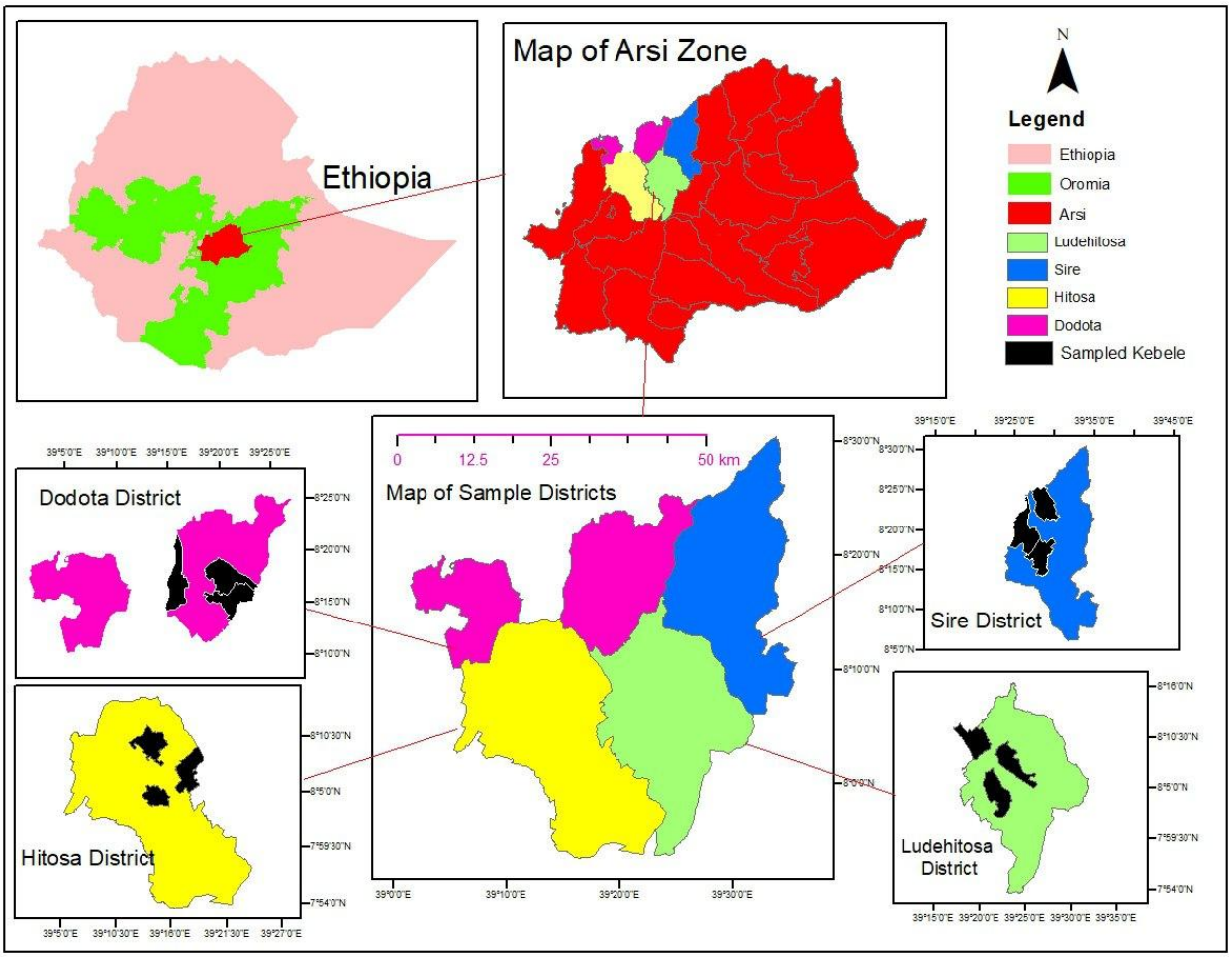


Figure 2 Map of the study area

3.2 Sampling technique and sample size

To ensure representativeness and reliability, a multi-stage sampling technique combining purposive and simple random sampling was employed. The study population comprised rural farm households in four districts (Sire, Dodota, Lode Hetosa, and Hetosa) of the Arsi Zone, Ethiopia. The Arsi Zone was purposively selected due to its significance in wheat production and relatively high level of mechanization. In the second stage, four districts were randomly selected, followed by the random selection of 12 kebeles from these districts after excluding those with unsuitable terrain for tractor ploughing and combine harvesting. Finally, sample households were randomly drawn from the selected kebeles. The sample size was determined using the Krejcie and Morgan (1970) formula, based on a 95% confidence level, population size, and desired precision, resulting in 374 households. To accommodate possible sampling errors, the sample size was increased by 10%, resulting in a final sample of 413 households. Adopters and non-adopters of each machinery type were then identified for subsequent analysis of the impact of mechanization and crop-livestock diversification on HDDS.

3.3 Measurement of Variables

3.3.1 Agricultural Diversification: Concepts, Dimensions, and Measurement

Agricultural diversification (AD) encompasses both crop and livestock diversification and is often used interchangeably with crop–livestock diversification. It represents a vital strategy for improving household income, enhancing food security, and strengthening resilience against agricultural risks. At its core, diversification involves reallocating a farm's productive resources—such as land, labor, capital, and equipment—into a broader range of agricultural activities (Chand, 1996). This process aims to optimize resource use, reduce dependency on a narrow base of agricultural outputs, and increase the stability and sustainability of rural livelihoods.

Crop Diversification: Crop diversification is widely recognized as a significant economic decision with substantial implications for household income levels, food availability, and nutrition security (Herforth, 2010; Pope & Prescott, 1980). It is generally defined as a shift from traditionally grown, less remunerative crops to more profitable and potentially resilient alternatives (Das et al., 2023). This transition can occur either through area augmentation, where new crops are added to the existing land base, or through crop substitution, where less profitable or risk-prone crops are replaced with more advantageous ones. Crop diversification serves not only as an income-boosting strategy but also as a risk mitigation mechanism that enhances soil fertility, improves pest and disease resistance, and allows for better adaptation to climate variability (Dessie et al., 2019; Lin, 2011).

Livestock Diversification: In parallel, livestock diversification, the inclusion or expansion of different types of livestock species within a farming system, is another critical facet of agricultural diversification (Puech & Stark, 2023). This includes raising a variety of animals such as cattle, goats, sheep, poultry, and even bees, depending on local agro-ecological and socio-economic contexts (Ahmadzai et al., 2025; Rahman, 2018). Livestock diversification enhances resilience by providing alternative income sources, increasing nutrient availability through diverse animal products (milk, eggs, meat), and improving asset accumulation for households (Ngigi et al., 2021) . It also complements crop production by offering draft power, organic manure, and insurance against crop failure (Amejo, 2024).

Numerous empirical approaches have been developed to measure crop–livestock diversification and to assess its implications for food security and nutritional outcomes. One commonly used indicator is the Household Biodiversity Index (HBI), which captures the number of different crop and livestock species grown or raised by a household during a specific agricultural season (Herforth, 2010). While the HBI provides a simple and practical indicator of on-farm biodiversity, it has notable limitations. Specifically, it does not take into account the volume of production or the extent of land or resources allocated to each species. Additionally, since it does not directly capture actual food intake or dietary diversity, its application in nutrition-focused studies is constrained.

Consequently, Alternative measures have been introduced in the literature to better capture agricultural diversification. For instance, the Production Diversity Score (PDS) simply counts the number of distinct food crops and livestock products produced by a household (Koppmair et al.,

2017a; Muthini et al., 2020). Building on this, the Aggregated Production Diversity Index (APDI) enhances simple counts by incorporating the relative contribution of each agricultural product to total production (Ayenew et al., 2018) Similarly, the Agricultural Diversity Score (ADS) also considers production shares to provide a more nuanced measure of diversification. Despite this While these indices offer more nuanced insights by considering production shares, they still exhibit a key limitation. Specifically, both the Agricultural Diversity Index (ADI) and Agricultural Diversity Score (ADS) assign equal weight to all items or food groups, regardless of their production quantity, nutritional value, or economic importance. As noted by Arimond and Ruel (2004), the interpretability of ADI and ADS depends heavily on the distribution of output, and they may be more or less meaningful depending on the relative shares of the foods produced.

To overcome these shortcomings, this study employed the Simpson Index (Simpson, 1949)to measure household-level agricultural diversification. The index was chosen for its simplicity and clarity in capturing the relative distribution of food items or crop groups produced by each household (Joshi et al., 2004). The Simpson Index (SI) was computed as follows across different geographic areas (Joshi et al., 2004). The SI was computed as follows:

$$\boldsymbol{Si = 1 - \sum P_{ij}} \quad \textbf{(41)}$$

Where $P_{ij} = \frac{A_{ij}}{\sum A_j}$ represents the proportion of land or Tropical Livestock Units (TLUs) allocated to the ith agricultural enterprise (crop or livestock) by household *j*. Here, **ES** denotes the enterprise share, i.e., the share of land area for crop i or the TLU share for livestock type i and *n* is the total number of crop or livestock types managed by the household.

A Simpson Index (SI) value close to zero indicates a high level of specialization, whereas a value close to one reflects full diversification in agricultural production. Following the classification by Saha and Bahal (2010),, we categorize households into three groups: low diversifiers (SI ≤ 0.39), medium diversifiers (0.39 < SI ≤ 0.63), and high diversifiers (SI > 0.63). In line with Nepali et al. (2024), and to meet the objective of our study, we apply a mean cut-off value: households with an SI above 0.5 are considered diversified, while those with an SI of 0.5 or below are classified as non-diversified. This threshold is based on the mean value of agricultural diversification in the study area.

3.3.2 **Household Dietary Diversity Score (HDDS)**

The Household Dietary Diversity Score (HDDS), developed by USAID's FANTA project, serves as a key indicator of diet quality and food security. This study uses a 24-hour recall method to calculate HDDS based on 12 food groups, each contributing one point, with a total score ranging from 0 to 12. Although longer recall periods may capture broader dietary patterns, they often introduce recall bias. The 24-hour recall is more accurate, easier to administer, and better suited to rural settings with fluctuating food availability (Zimba et al., 2019). Thus, its use in this study is both practical and reliable proxy of nutritional adequacy (Kennedy et al., 2010). The HDDS is calculated using the following formula:

$$HDDS_i = \sum_{n=1}^{N=12} F_j \quad \textbf{(2)}$$

Where F_j denotes each food group (F_j= 0 is an indicator of no consumption of food group and F_j= 1 is consumption of at least one food group), N indicates the total number of food groups. Thus, a greater number indicates a better food security outcome.

In addition, to complement this study, we also use the Food Consumption Score (FCS), which captures not only dietary diversity but also food frequency and the relative nutritional importance of different food groups. Whereas HDDS focuses on the variety of food groups consumed, the FCS provides a more nuanced picture of dietary quality by incorporating the number of days each food group was consumed in the past 7 days and applying weights based on nutritional value.

The Food Consumption Score (FCS) is a continuous composite indicator that ranges from 0 to 112, reflecting the variety and frequency of food groups consumed by a household, regardless of their source. It serves as a proxy for assessing household dietary diversity and food access. The FCS is computed using the formula:

$$FCS_i = \sum_{n=1}^{N=8} W_j F_{ij} \quad \textbf{(3)}$$

where $\mathbf{FCS_i}$ denotes the food consumption score for household i, $\mathbf{f_{ij}}$ indicates the number of days within the past week that household i consumed food group *j*, and $\mathbf{w_j}$ represents the weight assigned to food group *j* based on its relative nutritional importance.

3.4 Methods of analysis

To examine the impact of crop–livestock diversification in conjunction with mechanization on household dietary diversity, it is necessary to construct counterfactual scenarios that estimate, for example, what dietary outcomes households might have experienced had they engaged in less diversification, or if mechanization adopters had not done so under low-diversification conditions. To rigorously capture these relationships and account for the non-random nature of farmers' diversification and mechanization decisions, this study employs the Endogenous Switching Regression (ESR) model, which effectively addresses potential issues of selection bias and endogeneity.

First stage: Modelling agricultural mechanisation and agricultural diversification status

In this study, households are categorized into four groups based on their level of agricultural diversification and adoption of agricultural machinery. Treatment 0 includes non-adopting households that have not diversified, while Treatment 1 comprises households that have adopted mechanization but remain non-diversified. Treatment 2 represents households that are both diversified and have adopted agricultural machinery, and Treatment 3 consists of diversified households that have not adopted mechanization. These categories allow for the analysis of both individual and interaction effects of diversification and mechanization on household dietary diversity.

$$\boldsymbol{M_{it}} = \mu \boldsymbol{X_{it}} + \theta \boldsymbol{Z_{it}} + \boldsymbol{u_{it}},\ t=0, 1, 2, 3 \quad (4)$$

The symbol i indexes farm household, while t indexes their treatment status. The vector $\boldsymbol{M_{it}}$ represents the mechanization status in a household, X denotes the vector of household-level characteristics as well as socio economic that influence mechanization adoption, $\boldsymbol{Z}$ represents a vector of variables that influence farm diversification and adoption status but not outcome variables, u is the error term, and are parameters to be estimated. Credit access is used as an instrument for diversification, while mobile phone ownership and distance to the nearest all-weather road serve as instruments for mechanization.

Access to credit enables households to invest in diverse crops by easing access to improved inputs, thereby promoting agricultural diversification (Adesiyan & Kehinde, 2024; Mango et al., 2018). However, once diversification is controlled for, its direct effect on dietary diversity is minimal, supporting its use as a valid instrument. Likewise, mobile phone ownership improves access to mechanization services through better market information and service coordination but does not directly affect dietary outcomes (Fabregas et al., 2019). Similarly, proximity of farmland to all-weather roads facilitates mechanization adoption by enhancing access and lowering rental costs. However, it is unlikely to directly influence household dietary diversity once mechanization and diversification are accounted for (Kirui, 2019). Therefore, the selected instruments meet the exclusion restriction criterion. This is further supported by a falsification test presented in Appendix Table 7, which shows that the instruments have no significant direct effect on the outcome variable, confirming their validity.

These multiple treatment leads to the formulation of the following multinomial choice models (Baiyegunhi et al., 2022; Bourguignon et al., 2007; Kassie et al., 2020; Mutenje et al., 2016) :

$$\boldsymbol{P_{ij}}=\boldsymbol{\eta_{ij}}<0|\boldsymbol{X_i}=\frac{\boldsymbol{expX_i\beta_j}}{\sum_{\boldsymbol{n=1}}^{\boldsymbol{J}}\boldsymbol{expX_i\beta_n}} \quad (5)$$

Were Pij represents the probability that a farmer i chooses to adopt agricultural machineries and diversification. Xi Is vector of exogenous variable, and βj is a vector of parameters to be estimated, respectively.

Second stage: modelling the impact of agricultural diversification on food security

At this stage we will build a relationship between food security and a set of explanatory variable that include selection correction terms (mill ratios) in addition to household, individual and locational characteristic's, and it specified as follows based on four treatment categories;

$$\begin{cases} \boldsymbol{regime = 0 = HDDS_{i0} = \beta_0 X_{i0} + \sigma_0 \lambda_{i0} + e_{i0}\ if\ T = 0} \\ \quad . \\ \quad . \\ \quad . \\ \boldsymbol{regime = t = HDDS_{it} = \beta_t X_{it} + \sigma_t \lambda_{it} + e_{it}\ for\ T = 1, 2, 3} \end{cases} \quad \textbf{(6)}$$

Where $\boldsymbol{HDDS_{it}}$is the outcome variable (FS) in all cases, xi set of variables capturing household characteristics, institutional characteristics, λ_i is the vector of the Inverse Millis Ratio, σ denotes the covariance between the error terms, and β are vectors of parameters to be estimated, e are regression error terms. Then we generate the expected, actual, and counterfactual outcomes, which are then used to estimate the average treatment effects (ATT). For instance, the counterfactual outcome for treatment 1 is defined as the expected counterfactual outcomes of adopting (belonging

to non-diversified households). If the returns on their observed ($\boldsymbol{X_{it}}$) and unobserved ($\boldsymbol{\lambda_{it}}$) it characteristics had the same effect as the current returns (and) 0 non-adopting households to non-diversified households (treatment 0) observed ($\boldsymbol{X_{i0}}$) and unobserved ($\boldsymbol{\lambda_{i0}}$) characteristics. The counterfactual for other treatments can be generated in a similar way, depending on which treatment is used as the counterfactual.

$$\boldsymbol{E(HDDS_{i1}|T_{i1}=1;X_{i1},\lambda_{i1})=\beta_1 X_{i1}+\sigma_1\lambda_{i1}} \quad \textbf{(7)}$$

$$\boldsymbol{E(HDDS_{i0}|T_{i0}=0;X_{i0},\lambda_{i0})=\beta_0 X_{i0}+\sigma_0\lambda_{i0}} \quad \textbf{(8)}$$

The counterfactual outcome for treatment 1 to estimate the effect of adopting mechanization on dietary diversity is measured as follows:

$$\boldsymbol{E(HDDS_{i0}|T_{i1}=1;X_{i1},\lambda_{i1})=\beta_0 X_{i1}+\sigma_0\lambda_{i1}} \quad \textbf{(9)}$$

In Equation (**(9)**, $\boldsymbol{\beta_0}$ and $\boldsymbol{\sigma_0}$ are the regression coefficients obtained from the outcome equation for the regime t=0 or treatment 0. Equation **(8)**. We bootstrapped Equations **(7-(9)** to account for generated regressor, i.e., the inverse Mills ratios. Equations **(7-(9)** are used to compute the average treatment effects (ATT), which is derived as the difference between Equations **(7)** and **(9)**, as specified in Equation.

$$ATT=\boldsymbol{E(HDDS_{i1}|T_{i1}=1;X_{i1},\lambda_{i1})-E(HDDS_{i0}|T_{i1}=1;X_{i1},\lambda_{i1})}$$

$$\boldsymbol{ATT=(\beta_1 X_{i1}+\sigma_1\lambda_{i1})-(\beta_0 X_{i1}+\sigma_0\lambda_{i1})} \quad \textbf{(10)}$$

$$\boldsymbol{ATT=(\beta_1-\beta_0)X_{i1}+(\sigma_1-\sigma_0)\lambda_{i1}}$$

In equation (10), the terms$\boldsymbol{(\beta_1-\beta_0)X_{i1}}$and $\boldsymbol{(\sigma_1-\sigma_0)\lambda_{i1}}$respectively denote the impact of observed and unobserved characteristics on outcomes.

4 Result and Discussion

4.1 Descriptive Statistics

This **Table-1** reports descriptive statistics and pairwise mean comparisons of variables across household groups categorized by mechanization adoption and crop–livestock diversification. The results provide preliminary insights into systematic differences among groups prior to econometric analysis.

According to the **Table-1** below, households that are diversified but have not adopted mechanization exhibit a statistically significant improvement in their Household Dietary Diversity Score (HDDS) compared to those that are neither diversified nor mechanized. Similarly, households that are both diversified and have adopted mechanization show a higher HDDS than those that have adopted mechanization but remain undiversified. In terms of the Food Consumption Score (FCS), households that have adopted mechanization perform better than those that are neither diversified nor mechanized. Likewise, diversified households have a higher FCS compared to non-diversified and non-mechanized households. Moreover, households that are both diversified and mechanized achieve better FCS outcomes than those that are mechanized but not diversified.

Across the different treatment groups (based on adoption and diversification status), factors such as age, land size, financial savings, distance from farmland to the nearest road, and mobile phone ownership significantly influence household dietary diversity.

Table-1 Summarized descriptive statistics for independent, treatment and outcome variables by sample farmers

Variables	Overall mean	Adopter, but not diversified compared to non-adopter and not diversified HHS (t1/t0)	Adopter and diversified compared to non-adopter but diversified (t2/t3)	Diversified but not adopter compared non-adopter and not diversified HHS (t3/t0)	Adopter and diversified compared to adopter but not diversified (t2/t1)
HDDS	5.409201	0.224	0.212	0.735*	0.722***
HFCS	40.39	3.399***	0.781	7.171***	2.991***
Age	46.48668	3.665*	2.385*	-1.208	-2.488**
HHS	.8474576	0.016	-0.042	0.042	-0.016
Sex	5.532688	0.628	0.261	0.297	-0.070
Education years	5.445521	0.624	0.391	0.933	0.700*
Distance mrk	1.636017	0.123	-0.519*	0.723	0.081
Land size	2.276755	0.647***	0.810***	0.068	0.231*
Fertility	.6828087	0.209**	0.028	0.322***	0.141***
Extension	24.89346	-4.603	-11.326***	0.448	7.171**
Electricity	.5375303	0.474***	0.378***	0.129	0.033
Credit access	.2324455	0.105	0.107*	0.082	0.084
Asset mobile	.7288136	0.040	0.315***	0.211**	0.064
Dista.land_road	1.733815	-0.635**	-0.548**	0.696*	0.783***

Source: own survey (2023)
***, **, * represent 1%, 5%, and 10% significance level, respectively.

4.2 Household Dietary Diversity

The dietary data in **Table-2** how that nearly all households (98.55%) consumed cereals in the previous 24 hours, indicating a strong dependence on staple grains. High consumption was also observed for spices, condiments, and beverages (83.54%), sweets (75.54%), and oils and fats

(73.85%), suggesting a dietary pattern dominated by energy-dense and flavor-enhancing foods, consistent with previous studies.

In contrast, the intake of nutrient-rich foods was relatively low. Only 26.15% of households consumed vegetables, 11.38% consumed fruits and eggs, and 8.96% consumed meat. Notably, no household reported consuming fish. While legumes, nuts, and seeds were consumed by 63.68% of households, milk and milk products were consumed by only 42.13%.

Furthermore, based on the Household Dietary Diversity Score (HDDS) (see **Figure 3**), respondents were classified into three dietary diversity categories: low (1-3), medium (4-5), and high (6-12) following Setsoafia (2021). The results indicate that, on average, households consumed 5.73 food groups.

The distribution shows that 17.68% of households fall into the low dietary diversity category, consuming fewer than four food groups. About 32.45% are categorized as having medium dietary diversity, with consumption ranging between four and five food groups. Notably, nearly half of the households (49.88%) exhibit high dietary diversity, consuming six or more food groups.

Overall, while a substantial proportion of households maintain relatively diverse diets, a significant share still experiences limited dietary diversity, which may have implications for nutritional outcomes and food security.

Table-2 Household Dietary diversity Score in previous 24 hours (n=413)

Food group consumption in previous 24 hours	Number (percent)
Cereals	407/98.55
White tuber and roots	189/45.76
Vegetables	108/26.15
Fruits	47/11.38
Meat	37/8.96
Eggs	47/11.38
Fish	0/0
Legumes, nuts and seeds	263/63.68
Milk and milk products	174/42.13
Oils and fats	305/73.85
Sweets	312/75.54
Spices, condiments and beverages	345/83.54

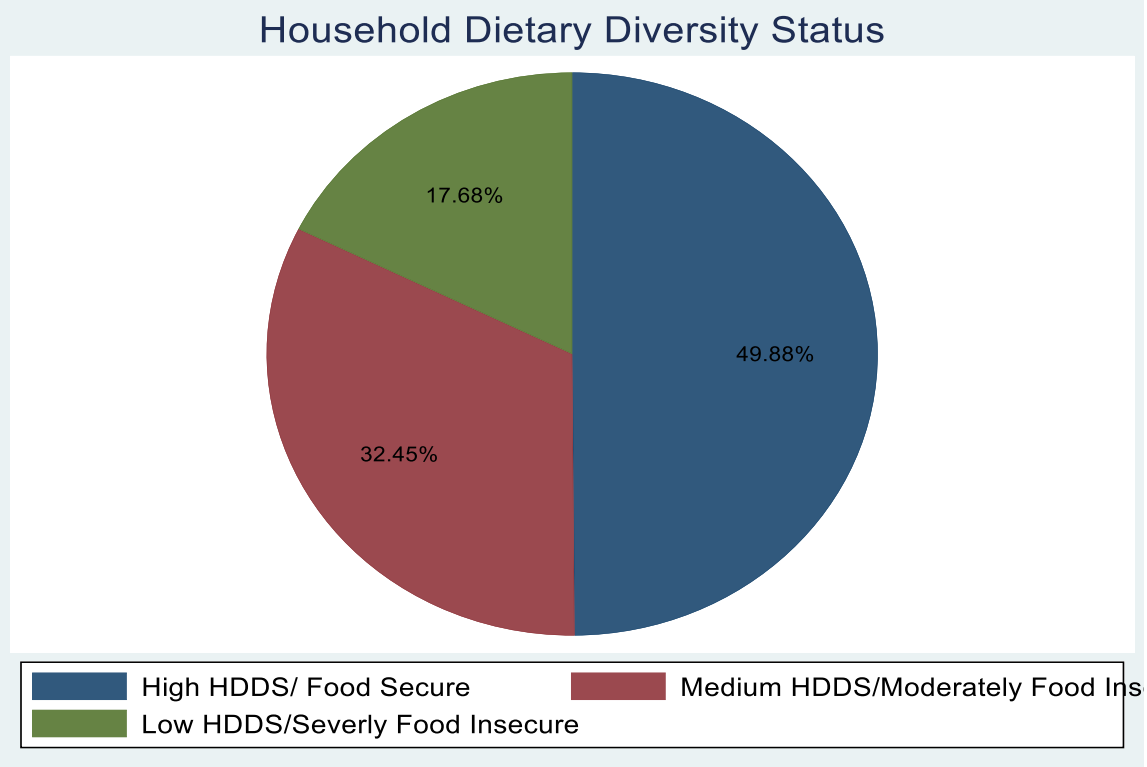


Figure 3 Household Dietary Diversity of Study Site

4.3 Treatment Effect Model

This section presents the results from the multinomial endogenous switching regression (MESR) model. The discussion primarily focuses on the estimated treatment effects, while the detailed results of the first-stage selection equations and regime-specific outcome equations are reported in the Appendix (see Table **4**, 18, and Table 6). Table 3 presents the results of the multiple treatment effects, examining how agricultural mechanization interacts with crop–livestock diversification to influence household dietary outcomes, as measured by Household Dietary Diversity Scores (HDDS) and Food Consumption Scores (FCS).

The analysis shows that for non-diversified households, mechanization (t1 vs. t0) results in a not statistically significant effect on HDDS. However, the corresponding FCS result is both positive and statistically significant (1.15, $t = 2.224$), indicating that if non-diversified, non-mechanized households had adopted mechanization, their overall food access and frequency would have improved. This suggests that while mechanization still contributes to better food security in terms of quantity and nutritional weighting.

In contrast, among diversified households**,** mechanization (t2 vs. t3) is associated with a significant reduction in HDDS (−0.609, $t = -5.985$), implying a negative moderating effect of mechanization on dietary diversity. This result may reflect a shift toward monoculture or commercial crops, which are often facilitated by mechanization but may reduce household-level dietary variety (Alves et al., 2017; Kansanga et al., 2019b). The FCS result supports this, showing a significant decline

(−1.24, t = −4.16) under the same treatment, reinforcing concerns that mechanization without nutrition-sensitive planning may undermine dietary quality in diversified systems.

Diversification in the absence of mechanization (t3 vs. t0) shows a significant and positive effect on HDDS (0.761, t = 4.15), affirming that diverse crop production improves household dietary diversity through direct access to varied food items (Dwivedi et al., 2017; Feyisa et al., 2025; Nahar et al., 2024). This is further confirmed by the FCS result (5.60, t = 12.60), highlighting the foundational role of diversification in improving food and nutrition outcomes.

Finally, when households are both diversified and mechanized (t2 vs. t1), HDDS improves by 0.65 units and FCS by 1.41 units, both statistically significant. These findings indicate that diversification among already mechanized households positively influences dietary outcomes, although the improvement in HDDS is smaller than that observed for non-mechanized households. This suggests that mechanization has a negative moderating effect, partially offsetting the dietary benefits of diversification if not carefully managed. The result indicates that mechanization has a negative implication on HDDS. This might be due to the specialized role of mechanization in the farm fields. Previous studies support this result, see for example (Berhane et al., 2017; Daum, 2022; Janssen, 2018; Kansanga et al., 2019a).

Table 3 Impact of farm mechanization interaction with farm diversification on HDDS, treatment results

Outcome	Treatment Description	Actual	Counterfactual	Treat Effect	T-statistics
HDDS	Machinery adopter for non-diversified HHS (t1 vs. t0)	5.057	5.18	-.12466	-0.5573
	Machinery adopter for diversified HHS (t2 vs. t3)	5.78	6.38	-.609***	-5.985
	Diversified households and non-adopters (t3 vs. t0)	5.57	4.80	.761***	4.15
	Diversified HHS with machinery adopter (t2 vs. t1)	5.78	5.13	.653***	10.8392
FCS	Machinery adopter for non-diversified HHS (t1 vs. t0)	38.80	37.64	1.15**	2.224
	Machinery adopter for diversified HHS (t2 vs. t3)	41.79	43.04	-1.24***	-4.1613
	Diversified households and non-adopters (t3 vs. t0)	42.57	36.96	5.60***	12.6305
	Diversified HHS with machinery adopter (t2 vs. t1)	41.79	40.38	1.41***	3.7807

Source: own survey (2023)

***, **, * represent 1%, 5%, and 10% significance level, respectively.

Notes: Treatments are non- diversified HHS belonging to households that did not adopt agricultural machinery (t0), machinery adopter belonging to households that did not diversify (t1), adopter of machinery belonging to households that diversify (t2), and diversified HHS belonging to households that did not adopted PPT (t3).

5 Conclusion and Policy Implication

This study examined the relationship between agricultural mechanization, diversification, and household dietary diversity (HDDS) using data from 413 rural households in Ethiopia's Arsi Zone. By employing multinomial endogenous switching regression models, the analysis accounted for endogeneity and self-selection bias. The findings indicate that crop–livestock diversification is strongly linked to improved household dietary diversity, whereas mechanization alone has no positive effect and may reduce dietary diversity in non-diversified systems. When mechanization is adopted within diversified farming systems, it can yield modest improvements in dietary diversity, highlighting a conditional or context-specific moderating effect.

Therefore, to achieve sustainable agricultural development and improved nutrition outcomes, mechanization policies should be designed to support diversified production systems rather than promote mono-cropping. This includes promoting technologies adaptable to a range of nutritionally important crops, such as legumes and root vegetables, and prioritizing crop varieties that are both nutrient-dense and compatible with mechanized practices. Strengthening agricultural extension services is essential to encourage integrated farm planning that aligns machinery use with diversification strategies. Enhancing rural financial services, particularly credit tailored to diversified farming, will enable farmers to invest in diverse inputs and appropriate technologies. Improvements in land access and rural infrastructure can facilitate better market integration and reduce transaction costs for diversified crops. Finally, farmer education and awareness programs should emphasize the nutritional benefits of crop diversity, empowering households to adopt farming systems that support both income generation and improved dietary outcomes.

Declarations

Ethics Approval: The study received ethical approval from Bahir Dar University, Bahir Dar, Ethiopia, and was authorized by the Research and Community Services Office in August 2023, under reference number RCS/121/2023. All procedures involving human participants and data collection were conducted in accordance with established ethical guidelines and regulations.

Consent to Participate: All participants in this research were fully informed about the study's aims and procedures. They provided their consent to participate voluntarily.

Consent to publish: Research participants consented to the use of the study's findings for academic purposes, including presentation at conferences and publication.

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Availability of data and materials: The dataset supporting this paper will be provided upon request

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Appendix

Table 4 First stage results of the multiple treatments – Multinomial logit model results.

Variable	Adopter, but not diversified (1) Coef. (Std. Err.)	P-value	Adopter and diversified (2) Coef. (Std. Err.)	P-value	Non-adopter but diversified (3) Coef. (Std. Err.)	P-value
Age	0.02487 (0.03192)	0.436	-0.00877 (0.03227)	0.786	-0.01238 (0.03274)	0.705
HHS	0.10446 (0.13114)	0.426	0.09916 (0.13194)	0.452	0.09381 (0.13845)	0.498
Sex	0.00104 (0.56388)	0.999	-0.29879 (0.58017)	0.607	0.1405 (0.61704)	0.820
Education_years	0.13445 (0.08472)	0.113	0.13037 (0.08498)	0.125	0.12364 (0.08082)	0.126
d_mainroadKM	0.16290 (0.12424)	0.190	0.16405 (0.12227)	0.180	0.12495 (0.12508)	0.318
totalareacrop	0.63641 (0.27040)*	0.019	0.86361 (0.27108)**	0.001	0.11178 (0.28681)	0.697
Fertility	0.55811 (0.50867)	0.273	0.98657 (0.51418)*	0.055	1.33029 (0.52925)**	0.012
access_electricity	2.26536 (0.56609)***	0.000	2.61409 (0.58607)***	0.000	0.84844 (0.60990)	0.164
extesion_service	0.03098 (0.01080)**	0.004	0.03935 (0.01073)***	0.000	0.00939 (0.01138)	0.409
Assets_mobile	-0.21817 (0.50814)	0.668	-0.18485 (0.52468)	0.725	-1.54684 (0.52852)***	0.003
distance_la_road	-0.70040 (0.31216)*	0.025	0.00497 (0.26616)	0.985	0.23572 (0.25602)	0.357
credit_access	0.42465 (0.63650)	0.505	0.66684 (0.62568)	0.287	0.40315 (0.62805)	0.521
_cons	-3.24937 (2.1200)	0.125	-3.67399 (2.2009)	0.095	-0.89495 (2.1962)	0.684
Number of obs = 413 Wald chi2(36) = 142.42 Prob > chi2 = 0.0000 LL= -414.33448 Pseudo R2 = 0.2141						

Notes: Robust standard errors in parenthesis; non-adoption and non-diversified is the reference category. *, ** and * represent significance levels at 1 %, 5 %, and 10 % respectively.**

Table 50 Second stage regression results of the determinants of HDDS - Multiple treatment endogenous switching regression.

Variables	Non-adopter and not diversified (HDDS0)	Adopter and not diversified (HDDS1)	Adopter and diversified (HDDS2)	Diversified and not adopter (HDDS3)
Age	0.099 (0.131)	0.018 (0.024)	0.018 (0.030)	-0.022 (0.045)
HHS	-0.376 (0.620)	-0.123 (0.091)	0.081 (0.098)	0.081 (0.134)
Sex	3.731 (3.983)	-0.384 (0.635)	-0.056 (0.579)	-0.153 (0.894)
Education years	-0.385 (0.462)	0.111 (0.067)*	0.150 (0.069)**	-0.054 (0.131)
Distance to main road (KM)	-1.046 (1.024)	0.357 (0.128)**	0.129 (0.106)	-0.115 (0.157)
Farm size (ha)	-3.508 (2.840)	0.595 (0.232)**	0.036 (0.245)	-0.417 (0.572)
Fertility	-1.332 (3.285)	0.765 (0.483)	1.351 (0.526)**	0.849 (0.953)
Access to electricity	-12.975 (15.489)	1.681 (0.909)*	-0.294 (0.546)	-2.469 (1.553)
Extension service	-0.127 (0.117)	0.028 (0.013)**	0.006 (0.010)	0.008 (0.025)
_m0	—	-3.809 (1.695)**	-2.070 (2.070)	1.964 (2.840)

Variables	Non-adopter and not diversified (HDDS0)	Adopter and not diversified (HDDS1)	Adopter and diversified (HDDS2)	Diversified and not adopter (HDDS3)
_m1	5.338 (6.699)	—	0.685 (1.083)	0.295 (1.861)
_m2	-17.654 (10.407)*	3.298 (1.699)**	—	-3.008 (2.715)
_m3	8.757 (6.547)	0.290 (1.571)	1.639 (1.639)	—
_cons	6.842 (8.352)	1.432 (1.876)	2.813 (1.864)	5.926 (3.070)**
Sigma²	326.30 (338.31)	18.63 (9.24)**	5.77 (6.15)	13.18 (15.89)
rho0	—	-1.132 (0.506)**	-1.184 (0.784)	0.694 (0.791)
rho1	0.379 (0.565)	—	0.296 (0.467)	0.104 (0.552)
rho2	-1.253 (0.742)*	0.980 (0.479)**	—	-1.063 (0.715)
rho3	0.622 (0.568)	0.086 (0.546)	0.858 (0.653)	—

Source: own survey (2023)
***, **, * represent 1%, 5%, and 10% significance level, respectively.

Table 6 Second stage regression results of the determinants of FCS- Multiple treatment endogenous switching regression.

Variable	Non-adopter and not diversified FCS0 Coeff (SE)	Adopter and not diversified FCS1 Coeff (SE)	Adopter and diversified FCS2 Coeff (SE)	Diversified and not adopter FCS3 Coeff (SE)
Age	0.0715 (0.2522)	0.0350 (0.0749)	0.0935 (0.0944)	0.0398 (0.1726)
HHS	-0.0358 (1.0312)	-0.1545 (0.2661)	0.2529 (0.3435)	0.2872 (0.4999)
Sex	0.9822 (6.4424)	-0.5580 (1.7682)	0.2705 (2.2431)	-0.6822 (3.8767)
Education_years	0.5350 (1.1070)	0.0508 (0.2103)	0.3225 (0.2424)	-0.5265 (0.5722)
Distance_mainroadKM	-1.3105 (1.8081)	1.1946 (0.4817)**	-0.0395 (0.4123)	-1.4328 (0.5938)**
Total_area_crop	-1.8330 (4.5580)	2.1546 (0.6257)***	-0.8162 (1.0150)	-4.9136 (2.4449)**
Fertility	9.8726 (8.1006)	2.6540 (1.6631)	7.2917 (1.7816)***	3.6204 (3.7745)
Access_electricity	-4.1116 (15.8818)	3.5893 (3.3968)	-6.3314 (2.6256)**	-12.7084 (6.4109)**
Extension_service	-0.0611 (0.2557)	0.0731 (0.0418)*	0.0038 (0.0335)	-0.0886 (0.0928)
_m0	–	-8.4061 (5.5988)	-2.6013 (7.9013)	23.4978 (11.1333)**
_m1	-4.9331 (13.5860)	–	-4.5219 (3.7645)	-5.8835 (6.2440)
_m2	-0.3187 (23.0692)	3.8818 (6.2245)	–	-18.6032 (11.0620)*
_m3	4.3801 (10.6531)	2.4991 (5.2217)	8.0564 (5.5197)	–
_cons	29.7055 (18.0988)	25.0386 (5.3435)***	35.0806 (6.6865)***	51.8334 (12.1061)***
Sigma²	50.4510 (1746.0810)	80.1495 (86.6877)	105.0349 (85.3002)	669.5082 (449.2753)
ρ_0 (rho0)	–	-1.2043 (0.5685)**	-0.3255 (0.7458)	1.1647 (0.6663)*
ρ_1 (rho1)	-0.8907 (0.7010)	–	-0.5659 (0.3487)	-0.2916 (0.5088)
ρ_2 (rho2)	-0.0576 (0.9763)	0.5561 (0.6870)	–	-0.9221 (0.6717)
ρ_3 (rho3)	0.7909 (0.5894)	0.3580 (0.5762)	1.0082 (0.4644)**	–

Source: own survey (2023) for
***, **, * represent 1%, 5%, and 10% significance level, respectively.

Table 70 Simple falsification test of excluded instruments for MESR.

Treatment Group Description	F-statistic (HDDS)	P-value (HDDS)	F-statistic (FCS)	P-value (FCS)
Machinery adopter, non-diversified HHS	.6808649	.5727353	.7983808	.5074232
Machinery adopter, diversified HHS	.0723266	.9746908	1.175562	.3218068
Diversified HHS, non-adopters	.7943808	.4990114	1.378472	.2520109
Diversified HHS with machinery adopters	1.756235	.1628385	.6388039	.592387

Reference

Adesiyan, A. T., & Kehinde, A. D. (2024). Is there a LINKAGE between credit access, land use, and crop diversification in achieving food security? Evidence from cocoa-producing households in Nigeria. *Heliyon, 10*(16).

Adetola, O. Y., Taylor, J. R., Duodu, K. J. I. J. o. F. S., & Nutrition. (2023). Can consumption of local micronutrient-and absorption enhancer-rich plant foods together with starchy staples improve bioavailable iron and zinc in diets of at-risk African populations? *, 74*(2), 188-208.

Adjimoti, G. O., & Kwadzo, G. T.-M. (2018). Crop diversification and household food security status: evidence from rural Benin. *Agriculture & Food Security, 7*(1), 1-12.

Ahmadzai, M. R., Ismail, M. H., Hassan Zaki, P., Magiman, M. M., Bawon, P., Rahmawaty, & Ullah, H. (2025). Transforming livestock production: unraveling the impact of socioeconomic dynamics and land use changes in Khost Province. *Journal of Land Use Science, 20*(1), 82-97.

Alves, B. J., Madari, B. E., & Boddey, R. M. (2017). Integrated crop–livestock–forestry systems: prospects for a sustainable agricultural intensification. *Nutrient Cycling in Agroecosystems, 108*, 1-4.

Amejo, A. G. (2024). Resilience, Sustainability, and the Role of Livestock in Rural Food Systems: A Case Study from Ethiopia.

Arimond, M., & Ruel, M. T. (2004). Dietary diversity is associated with child nutritional status: evidence from 11 demographic and health surveys. *The Journal of nutrition, 134*(10), 2579-2585.

Arimond, M., Wiesmann, D., Becquey, E., Carriquiry, A., Daniels, M. C., Deitchler, M., . . . Martin-Prevel, Y. J. T. J. o. n. (2010). Simple food group diversity indicators predict micronutrient adequacy of women's diets in 5 diverse, resource-poor settings. *140*(11), 2059S-2069S.

Ayenew, H. Y., Biadgilign, S., Schickramm, L., Abate-Kassa, G., & Sauer, J. (2018). Production diversification, dietary diversity and consumption seasonality: panel data evidence from Nigeria. *BMC public health, 18*, 1-9.

Baiyegunhi, L., Akinbosoye, F., & Bello, L. (2022). Welfare impact of improved maize varieties adoption and crop diversification practices among smallholder maize farmers in Ogun State, Nigeria. *Heliyon, 8*(5), e09338.

Beal, T., Manohar, S., Miachon, L., & Fanzo, J. J. P. o. t. N. A. o. S. (2024). Nutrient-dense foods and diverse diets are important for ensuring adequate nutrition across the life course. *121*(50), e2319007121.

Berhane, Dereje, M., Minten, B., & Tamru, S. (2017). *The rapid–but from a low base–uptake of agricultural mechanization in Ethiopia: Patterns, implications and challenges* (Vol. 105): Intl Food Policy Res Inst.

Berhanu Desalegn, B., Biazin, B., Amede, T., Low, J. J. F. S., & Nutrition. (2024). Nutrition profiles of farm households across different farming systems in Ethiopia: Unpacking the determinants and implications for nutrition-sensitive interventions. *12*(8), 5442-5462.

Bolo, A., Verger, E., Fouillet, H., & Mariotti, F. J. A. i. N. (2024). Exploring multidimensional and within-food group diversity for diet quality and long-term health in high-income countries. 100278.

Bourguignon, F., Fournier, M., & Gurgand, M. (2007). Selection bias corrections based on the multinomial logit model: Monte Carlo comparisons. *Journal of Economic surveys, 21*(1), 174-205.

Cameron, A. C., & Trivedi, P. K. (2010). *Microeconometrics using stata* (Vol. 2): Stata press College Station, TX.

Cao, S., Sun, F., Wang, L., & Hong, W. J. F. i. S. F. S. (2024). "Less is more?" The association between crop specialization and dietary diversity in China. *8*, 1439989.

Chambers, R., & Conway, G. (1992). Sustainable rural livelihoods: practical concepts for the 21st century.

Chand, R. (1996). Diversification through High Value Crops in Westerm Himalayan Region: Evidence from Himachal Pradesh. *Indian Journal of Agricultural Economics, 51*(4), 652-663.

CSA. (2020). *Agricultural Sample Survey, 2018/19 Volume I: Report On Area and Production of Major Crops (Private Peasant Holdings, Meher Season). In: Statistical Bulletin 589, Addis Ababa. 2020. p. 54.*

CSA. (2021a). *CSA (The Federal Democratic Republic of Ethiopia Central Statistical Agency). (2021a). Agricultural Sample Survey 2020 / 2021 (2013 E.C.) (September – September 2021) volume vii report on area and production of major crops (private peasant holdings, Meher season).*

Danso-Abbeam, G., Dagunga, G., Ehiakpor, D. S., Ogundeji, A. A., Setsoafia, E. D., & Awuni, J. A. (2021). Crop–livestock diversification in the mixed farming systems: implication on food security in Northern Ghana. *Agriculture & Food Security, 10*, 1-14.

Das, S., Patra, S., & Darshan, N. (2023). Agricultural diversification: necessity, drivers, and future pro-spects. *Emerging Trends in Agricultural Extension Education. Bhubaneswar, Odisha*, 102-113.

Daum, T. (2022). Agricultural mechanization and sustainable agrifood system transformation in the Global South.

Derso, D., Tolossa, D., & Seyoum, A. (2022). A double hurdle estimation of crop diversification decisions by smallholder wheat farmers in Sinana District, Bale Zone, Ethiopia. *CABI Agriculture and Bioscience, 3*(1), 25.

Dessie, A. B., Abate, T. M., Mekie, T. M., & Liyew, Y. M. (2019). Crop diversification analysis on red pepper dominated smallholder farming system: Evidence from northwest Ethiopia. *Ecological processes, 8*(1), 1-11.

Di Falco, S., Bezabih, M., & Yesuf, M. (2010). Seeds for livelihood: crop biodiversity and food production in Ethiopia. *Ecological Economics, 69*(8), 1695-1702.

Duflo, E., Glennerster, R., & Kremer, M. (2007). Using randomization in development economics research: A toolkit. *Handbook of development economics, 4*, 3895-3962.

Dwivedi, S. L., Van Bueren, E. T. L., Ceccarelli, S., Grando, S., Upadhyaya, H. D., & Ortiz, R. (2017). Diversifying food systems in the pursuit of sustainable food production and healthy diets. *Trends in plant science, 22*(10), 842-856.

Emami, M., Almassi, M., Bakhoda, H., & Kalantari, I. (2021). Agricultural mechanization as the driver of reducing food loss and waste in developing countries: Evidence from Iran. *Russian Agricultural Sciences, 47*, 530-535.

Fabregas, R., Kremer, M., & Schilbach, F. (2019). Realizing the potential of digital development: The case of agricultural advice. *Science, 366*(6471), eaay3038.

FAO, W. J. T. s. o. f. i. i. t. w. (2012). IFAD. *65*.

Feder, G., Just, R. E., & Zilberman, D. (1985). Adoption of agricultural innovations in developing countries: A survey. *Economic development and cultural change, 33*(2), 255-298.

Federal Government of Ethiopia, M. o. H., Ethiopian Public Health Institute. (2022). *(2022).Ethiopia: Food-Based Dietary Guidelines–2022.* Addis Ababa, Ethiopia

Feyisa, B. W., Mavrotas, G., Lejissa, T., Sileshi, M., & De Steur, H. (2025). Does livestock-crop diversification improve food and nutrition security? Evidence from Eastern Ethiopia. *Journal of Development Effectiveness, 17*(1), 50-70.

Gebiso, T., Ketema, M., Shumetie, A., & Leggesse, G. (2023a). Crop diversification level and its determinants in Ethiopia. *Cogent Food & Agriculture, 9*(2), 2278924.

Gebiso, T., Ketema, M., Shumetie, A., & Leggesse, G. (2023b). Determinants of farm mechanization in central and southeast oromia region, Ethiopia. *Heliyon, 9*(7).

GHI. (2024). Global Hunger Index: how gender justice can advance climate resilience and zero hunger. https://www.globalhungerindex.org/. doi:https://www.globalhungerindex.org/

Gillespie, S., & van den Bold, M. J. G. C. (2017). Agriculture, food systems, and nutrition: meeting the challenge. *1*(3), 1600002.

Herforth, A. (2010). Promotion of traditional African vegetables in Kenya and Tanzania: a case study of an intervention representing emerging imperatives in global nutrition.

Herforth, A., Dufour, C., & Noack, A.-L. (2015). Designing nutrition-sensitive agriculture investments. Checklist and guidance for programme formulation.

Ijaz, M., Nawaz, A., Ul-Allah, S., Rizwan, M. S., Ullah, A., Hussain, M., . . . Ahmad, S. (2019). Crop diversification and food security. *Agronomic Crops: Volume 1: Production Technologies*, 607-621.

Janssen, B. (2018). Small farms, big plans: Mechanization and specialization as measures of "the middle". *Culture, Agriculture, Food and Environment, 40*(2), 96-104.

Jateno, W., Alemu, B. A., & Shete, M. (2023). Household dietary diversity across regions in Ethiopia: evidence from Ethiopian socio-economic survey data. *Plos one, 18*(4), e0283496.

Jones, A. D., Shrinivas, A., & Bezner-Kerr, R. (2014). Farm production diversity is associated with greater household dietary diversity in Malawi: Findings from nationally representative data. *Food policy, 46*, 1-12.

Joshi, P. K., Gulati, A., Birthal, P. S., & Tewari, L. (2004). Agriculture diversification in South Asia: patterns, determinants and policy implications. *Economic and political weekly*, 2457-2467.

Kansanga, Andersen, P., Kpienbaareh, D., Mason-Renton, S., Atuoye, K., Sano, Y., . . . Luginaah, I. (2019a). Traditional agriculture in transition: Examining the impacts of agricultural modernization on smallholder farming in Ghana under the new Green Revolution. *International Journal of Sustainable Development & World Ecology, 26*(1), 11-24.

Kansanga, M., Andersen, P., Kpienbaareh, D., Mason-Renton, S., Atuoye, K., Sano, Y., . . . Luginaah, I. (2019b). Traditional agriculture in transition: Examining the impacts of agricultural modernization on smallholder farming in Ghana under the new Green Revolution. *International Journal of Sustainable Development & World Ecology, 26*(1), 11-24.

Kassie, M., Fisher, M., Muricho, G., & Diiro, G. (2020). Women's empowerment boosts the gains in dietary diversity from agricultural technology adoption in rural Kenya. *Food Policy, 95*, 101957.

Kennedy, G., Berardo, A., Papavero, C., Horjus, P., Ballard, T., Dop, M., . . . Brouwer, I. D. (2010). Proxy measures of household food consumption for food security assessment and surveillance: comparison of the household dietary diversity and food consumption scores. *Public health nutrition, 13*(12).

Kidane, M. S. (2019). *The nexus of crop and income diversification, commercialisation and household welfare: empirical evidence from Ethiopia.* Doctoral dissertation, University of KwaZulu-Natal, Pietermaritzburg, South …,

Koppmair, S., Kassie, M., & Qaim, M. (2017a). Farm production, market access and dietary diversity in Malawi. *Public health nutrition, 20*(2), 325-335.

Koppmair, S., Kassie, M., & Qaim, M. J. P. h. n. (2017b). Farm production, market access and dietary diversity in Malawi. *20*(2), 325-335.

Krejcie, R. V., & Morgan, D. W. (1970). Determining sample size for research activities. *Educational and psychological measurement, 30*(3), 607-610.

Lin, B. B. (2011). Resilience in agriculture through crop diversification: adaptive management for environmental change. *BioScience, 61*(3), 183-193.

Makate, C., Angelsen, A., Holden, S. T., & Westengen, O. T. (2022). Crops in crises: Shocks shape smallholders' diversification in rural Ethiopia. *World Development, 159*, 106054.

Mango, N., Makate, C., Mapemba, L., & Sopo, M. (2018). The role of crop diversification in improving household food security in central Malawi. *Agriculture & Food Security, 7*(1), 1-10.

Maxwell, S. J. F. p. (1996). Food security: a post-modern perspective. *21*(2), 155-170.

Mekuria, W., & Mekonnen, K. (2018a). Determinants of crop–livestock diversification in the mixed farming systems: evidence from central highlands of Ethiopia. *Agriculture & Food Security, 7*(1), 1-15.

Mekuria, W., & Mekonnen, K. (2018b). Determinants of crop–livestock diversification in the mixed farming systems: evidence from central highlands of Ethiopia. *Agriculture & Food Security, 7*, 1-15.

Mengistu, D. D., Degaga, D. T., & Tsehay, A. S. (2021). Analyzing the contribution of crop diversification in improving household food security among wheat dominated rural households in Sinana District, Bale Zone, Ethiopia. *Agriculture & Food Security, 10*, 1-15.

Mohammed, K., Batung, E., Saaka, S. A., Kansanga, M. M., & Luginaah, I. (2023). Determinants of mechanized technology adoption in smallholder agriculture: Implications for agricultural policy. *Land Use Policy, 129*, 106666.

Mulwa, C. K., & Visser, M. (2020). Farm diversification as an adaptation strategy to climatic shocks and implications for food security in northern Namibia. *World Development, 129*, 104906.

Mussema, R., Kassa, B., Alemu, D., & Shahidur, R. (2015). Determinants of crop diversification in Ethiopia: Evidence from Oromia region. *Ethiopian Journal of Agricultural Sciences, 25*(2), 65-76.

Mutenje, M., Kankwamba, H., Mangisonib, J., & Kassie, M. (2016). Agricultural innovations and food security in Malawi: Gender dynamics, institutions and market implications. *Technological Forecasting and Social Change, 103*, 240-248.

Muthini, D., Nzuma, J., & Nyikal, R. (2020). Farm production diversity and its association with dietary diversity in Kenya. *Food Security, 12*, 1107-1120.

Mutungi, C., Manda, J., Feleke, S., Abass, A., Bekunda, M., Hoschle-Zeledon, I., & Fischer, G. (2023). Adoption and impacts of improved post-harvest technologies on food security and welfare of maize-farming households in Tanzania: a comparative assessment. *Food Security*, 1-17.

Nahar, N., Rahman, M. W., Miah, M. M., & Hasan, M. M. (2024). The impact of crop diversification on food security of farmers in Northern Bangladesh. *Agriculture & Food Security, 13*(1), 9.

Negrete, J. (2019). The role of agricultural mechanization in food security. *Journal of Agricultural Research Adcances, 1*(3), 12-15.

Nepali, B., Jackson, T., & Johns, C. (2024). Exploring the Potential of Agriculture Diversification as a Pathway to an Improved Smallholder Livelihood Dietary System in Nepal. *Sustainability, 16*(21), 9384.

Ngigi, M. W., Mueller, U., & Birner, R. (2021). Livestock diversification for improved resilience and welfare outcomes under climate risks in Kenya. *The European Journal of Development Research, 33*(6), 1625-1648.

Ntagu, M. P., Nyam, V., & Promise, C. V. (2022). Policy of Agricultural Mechanization and Food Security in Nigeria: Challenges and Prospects. *KIU Journal of Social Sciences, 8*(1), 233-245.

Pangaribowo, E. H., Gerber, N., & Torero, M. (2013). Food and nutrition security indicators: a review.

Papke, L. E., & Wooldridge, J. M. (2008). Panel data methods for fractional response variables with an application to test pass rates. *Journal of econometrics, 145*(1-2), 121-133.

Paut, R., Sabatier, R., & Tchamitchian, M. (2019). Reducing risk through crop diversification: An application of portfolio theory to diversified horticultural systems. *Agricultural systems, 168*, 123-130.

Pope, R. D., & Prescott, R. (1980). Diversification in relation to farm size and other socioeconomic characteristics. *American Journal of Agricultural Economics, 62*(3), 554-559.

Puech, T., & Stark, F. (2023). Diversification of an integrated crop-livestock system: Agroecological and food production assessment at farm scale. *Agriculture, Ecosystems & Environment, 344*, 108300.

Qiao, F. (2023). The impact of mechanization on crop production in China. *Applied Economics, 55*(15), 1728-1741.

Rahman, S. (2018). Agroecological, land-elevation and socioeconomic determinants of raising livestock in Bangladesh. *Agriculture, 8*(1), 12.

Ruel, M. T., Harris, J., & Cunningham, K. J. D. Q. A. E.-B. A., Volume 2. (2013). Diet quality in developing countries. 239-261.
Ruel, M. T. J. T. J. o. n. (2003). Operationalizing dietary diversity: a review of measurement issues and research priorities. *133*(11), 3911S-3926S.
Saha, B., & Bahal, R. (2010). Livelihood diversification pursued by farmers in West Bengal. *Indian Research Journal of Extension Education, 10*(2), 1-9.
Sen, A. (1982). *Poverty and famines: an essay on entitlement and deprivation*: Oxford university press.
Setsoafia, E. D. (2021). *The impact of the adoption of sustainable agricultural practices on farm income and household food security in Northern Ghana: A thesis submitted in partial fulfilment of the requirements for the Degree of Doctor of Philosophy at Lincoln University.* Lincoln University,
Simpson, E. H. (1949). Measurement of diversity. *nature, 163*(4148), 688-688.
Sisay, T., Tesfaye, K., Ketema, M., Dechassa, N., & Getnet, M. (2023). Climate-smart agriculture technologies and determinants of farmers' adoption decisions in the Great Rift Valley of Ethiopia. *Sustainability, 15*(4), 3471.
Staiger, D. O., & Stock, J. H. (1994). Instrumental variables regression with weak instruments. In: National Bureau of Economic Research Cambridge, Mass., USA.
Swindale, A., Bilinsky, P. J. W., DC: Food, & Nutrition Technical Assistance Project, A. f. E. D. (2006). Household dietary diversity score (HDDS) for measurement of household food access: indicator guide.
Tesafa, F., Mulugeta, M., & Tsehay, S. (2023). Impact of agricultural diversification and off-farm income on food security of rural households in northwest Ethiopia: A dose-response analysis. *Ethiopian Journal of Development Research, 45*(1), 1-30.
Uccello, E., Kauffmann, D., Calo, M., & Streissel, M. (2017). Nutrition-sensitive agriculture and food systems in practice.
Umesha, S., Manukumar, H. M., & Chandrasekhar, B. (2018). Sustainable agriculture and food security. In *Biotechnology for sustainable agriculture* (pp. 67-92): Elsevier.
UNICEF. (2020). *UNICEF ConceptualFrameworkontheDeterminantsof MaternalandChildNutrition, 2020. A framework for the prevention of malnutrition in all its forms.* . Retrieved from
Waha, K., Van Wijk, M. T., Fritz, S., See, L., Thornton, P. K., Wichern, J., & Herrero, M. (2018). Agricultural diversification as an important strategy for achieving food security in Africa. *Global change biology, 24*(8), 3390-3400.
Wooldridge, J. M. (2010). *Econometric analysis of cross section and panel data*: MIT press.
Workicho, A., Belachew, T., Feyissa, G. T., Wondafrash, B., Lachat, C., Verstraeten, R., & Kolsteren, P. (2016). Household dietary diversity and animal source food consumption in Ethiopia: evidence from the 2011 welfare monitoring survey. *BMC public health, 16*, 1-11.
Yilmaz, H., & Yilmaz, A. (2025). Hidden Hunger in the Age of Abundance: The Nutritional Pitfalls of Modern Staple Crops. *Food Science & Nutrition*.
Zimba, T. R., Mwangwela, A. M., Mtimuni, B., & Chisala, P. W. (2019). Seasonality of food availability influences dietary patterns in two farming districts of Malawi. *BioRxiv*, 607606.