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ARTICLE

Diversifying Agricultural Growth: Investigating the Economic Consequences of Crop Diversification in Andhra Pradesh, India

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ABSTRACT

Crop diversification is a vital agricultural strategy aimed at reducing risks, improving food security, enhancing farm income, and promoting sustainability. This study analyzes crop diversification indices and their impact on Gross Value Added (GVA) to agriculture in Andhra Pradesh using secondary data from 13 districts (2015–16 to 2022–23), covering agriculture, horticulture, and floriculture. The findings reveal notable regional differences, with Prakasam district exhibiting the highest crop diversification, while Nellore and East Godavari show lower levels. A Fractional Logit Model identifies key positive influencers of diversification, including rainfall, phosphorus fertilizer use, commercial bank access, long-term loans, Rythu Bazars, and Agricultural Market Committees. Conversely, pesticide use, irrigation extent, labour wages, and Public Distribution System (PDS) quantities negatively affect diversification. Instrumental variable regression shows a strong positive link between crop diversification and GVA in agriculture and horticulture. Similarly, phosphorus fertilizers, financial services, and market access positively influence GVA, while high labour costs and PDS interventions have adverse effects. In the livestock sector, greater diversification corresponds with increased GVA, supported by veterinary services and expert availability. In fisheries, higher outputs in marine fish, shrimp, inland fish, and brackish water prawn correlate with greater GVA. The study emphasizes the need for region-specific policies to boost diversification and ensure agricultural re-

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silience and sustainability.

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1. Introduction

Crop diversification refers to the practice of cultivating a wide variety of crops instead of relying heavily on a few major crops. It involves a shift from monoculture to multi-cropping systems, where farmers grow different types of crops on the same land in a particular growing season or across different seasons. It is an important agricultural strategy that offers several benefits, including mitigating risks, improving food security, enhancing farm income, promoting sustainable agriculture, and addressing environmental challenges [1–5]. India has a diverse agro-climatic conditions, which makes it suitable for growing a wide range of crops. Different regions of the country have varying climate, soil types, and water availability, allowing for the cultivation of various crops. The Government of India has been promoting crop diversification through various initiatives. For example, the National Mission on Oilseeds and Oil Palm (NMOOP) aims to increase the production of oilseeds and reduce dependence on imports. The National Food Security Mission (NFSM) encourages farmers to diversify their cropping patterns and provides support for the cultivation of pulses, oilseeds, and coarse cereals. Similarly, Andhra Pradesh, located in southern India has different agro-climatic zones that support a diverse range of crops. The North Coastal Zone, with its tropical climate and moderate rainfall, grows paddy rice, coconut, cashew, sugarcane, tobacco, vegetables, and fruits. The Southern zone and Scarce rainfall zone in Rayalaseema, known for its arid climate and low rainfall, grows groundnut, cotton, chillies, millets, sunflower, pulses, and oilseeds. The Godavari and Krishna Zones are characterized by humid climates and fertile alluvial soils, where crops like paddy rice, sugarcane, tobacco, banana, coconut, and vegetables thrive. This diversity across agro-climatic zones in Andhra Pradesh enables farmers to choose suitable crops and implement appropriate farming practices based on local conditions. By cultivating a variety of crops, farmers can reduce their dependence on a single crop, thereby minimizing the risks associated with crop failure due to pests, diseases, or adverse weather conditions. This diversity acts as a natural insurance mechanism, safeguarding livelihoods and stabilizing incomes. Moreover, diversification improves food security by ensuring a steady supply of multiple food types, catering to dietary needs and nutritional requirements. It also provides farmers with opportunities to respond to changing market demands, enabling them to produce crops with higher economic value and accessing new markets. Additionally, diversified cropping patterns can lead to optimized use of land, water, and other resources, promoting efficient resource allocation and reducing the environmental impact of farming. Encouraging crop diversification also supports sustainable agricultural practices, which are crucial for long-term environmental health and productivity.

Despite the growing emphasis on crop diversification in Andhra Pradesh, several research gaps persist in understanding its comprehensive economic consequences, particularly at the regional and farm-level scales. Existing studies largely focus on the agronomic aspects of crop diversification, such as its impact on productivity and environmental sustainability. However, limited attention has been paid to its broader implications for farm income, risk mitigation, resource use efficiency, and market integration, especially among small and marginal farmers who constitute the majority in the state. Additionally, while government initiatives and policies aim to promote diversification, there is a lack of empirical evidence on the effectiveness of these measures and their ability to address the socio-economic and infrastructural challenges faced by farmers in Andhra Pradesh. The absence of detailed analyses on how specific agro-climatic zones within the state respond to diversification strategies further limits the ability to formulate region-specific policy recommendations.

This study addresses these gaps by investigating the economic consequences of crop diversification across different agro-climatic zones in Andhra Pradesh, as it is crucial for understanding the benefits and implications of diversifying crop production. This will help us measure, evaluate, and compare the level of crop diversity within agricultural systems [6]. This knowledge will certainly guide decision-making processes and promote sustainable and resilient agricultural practices. In addition, studying the determinants for crop diversification in Andhra Pradesh is crucial for understanding the factors that influence farmers' decisions and the barriers they face. It will further inform interventions and policies aimed at enhancing agricultural productivity, climate resilience, market opportunities, resource management, livelihood diversification, and overall sustainability of the agricultural sector in the State [7, 8]. By addressing these determinants, policymakers can support farmers in adopting diversified cropping systems and promote sustainable and resilient agriculture in Andhra Pradesh. This study also aimed to analyze the influence of crop diversification on the Gross Value Added (GVA) of the agricultural and horticulture sectors in Andhra Pradesh (GVA-Agri&Hort). Furthermore, it extended the analysis to examine the determinants of GVA shares across the livestock (GVA-Livestock) and fishing and aquaculture sectors (GVA-Fish&Aqua). By considering these additional sectors, this study provides a comprehensive understanding of the economic implications of diversification and sheds light on the factors influencing GVA distribution within the broader agricultural domain.

2. Review of Literature

Several studies provided valuable insights into the determinants of livelihood diversification and its impact on rural communities in different regions. Nusrat et al. [9] focused on rural rain-fed regions of Pakistan and found that households with higher education tended to have a more diversified livelihood strategy ((Simpson Diversity Index (SDI) = 0.61)), relying on off-farm and non-farm activities as explanatory factors employing a Fractional Multinomial Logit (FMNL) model. Conversely, households with older members, more livestock, and larger farm sizes tended to concentrate their livelihoods on their own farms or engage in off-farm work on other farms. The study emphasized improved access to education and infrastructure in promoting livelihood diversification as a means of mitigating climate change threats.

Laishram et al. [10] examined the economic impact of crop diversification in northeast India. Their findings indicated that the crop sector was skewed towards specialization, but crop diversification had a positive and significant impact on household income. Instrumental Variable Regression (IVR) or Two-Stage Least Squares (2SLS) revealed that crop diversification had a positive and significant impact on income. Further, Fractional Logit Model (FLM) estimation found that family members in the working age group, landholding size, crop loss experience, extension contact, and participation in training positively influenced diversification, while variables like irrigated area and access to institutional credit had a negative effect. The authors recommended diversifying towards high-value crops to accelerate agricultural growth and improve farmers' well-being in the region.

Debasis et al. [11] highlighted crop diversification as an essential risk management and income-enhancing strategy for farmers. Their study, conducted in the West Bengal, showed increased crop diversification during the new millennium compared to 1990s. The determinants of diversification included rural literacy rate, the percentage of the urban population, earnings from high-value crops, market density, the percentage of small landholders, area under high-yielding varieties, rainfall patterns, and the availability of crop insurance. These findings highlighted significance of various factors in promoting crop diversification.

James [12] examined land allocation in a multi-crop farming system in Mali through employing FMNL. The study found that ethnic groups not native to the region had smaller shares of maize production, while villages enjoying better market access had higher shares of secondary crops and smaller shares of cotton. These results indicated the importance of understanding the dynamics of farming systems and the need to develop better markets for coarse grains and secondary crops, as well as the role of cotton in the region.

Tran et al. [13] focused on the impacts of farmland loss due to urbanization on nonfarm diversification in Vietnam. Their findings from FLM and FMNL models revealed that farmland loss had a negative effect on farm income but a positive effect on various nonfarm incomes, particularly informal wage income. The study emphasized the role of natural capital in shaping peri-urban livelihoods and identified other asset-related variables that positively influenced diversification into lucrative nonfarm activities.

Overall, these studies underscore the importance of livelihood diversification as a strategy to mitigate climate change threats, enhance income, and improve the well-being of rural communities. Factors such as education, access to infrastructure, landholding size, market access, crop diversity, and natural capital play significant roles in shaping diversification patterns. Policymakers can utilize these findings to promote sustainable agricultural practices, improve market access for diverse crops, and support rural communities in adapting to changing socio-economic and environmental conditions.

Theoretical and Conceptual Framework

This study explores the interplay of socio-economic, institutional, and environmental factors in driving crop diversification. Dependent variables, such as the SDI and GVA shares for agriculture, horticulture, livestock, and aquaculture, are analyzed to measure diversification and sectoral contributions. The study utilizes advanced econometric models, including the FLM, IVR-2SLS and FMNL to ensure robust findings and address endogeneity concerns. The FLM is applied to assess the factors influencing SDI, which represents the extent of diversification. Since SDI is a bounded variable (ranging from 0 to 1), the FLM is particularly suitable for analyzing its fractional nature. It enables the estimation of how independent variables like rainfall, fertilizers, labour wage rates, and institutional support influence the diversification index. To address potential endogeneity concerns between GVA-Agri&Hort and SDI, the study incorporates IVR-2SLS. By using instrumental variable (i.e., Gross Area Irrigated (GAI))—this method ensures unbiased estimates and enhances the reliability of the findings. The FMNL model is employed to analyze the distribution of GVA among agriculture, horticulture, livestock, and aquaculture sectors. By accommodating multiple categories of the dependent variable, the FMNL model captures the trade-offs and reallocations across these sectors, providing insights into how resources and investments shift among them due to changes in independent variables.

The study explores possible influences of various determinants on agricultural diversification, livestock development, and fisheries growth. It is anticipated that positive influences on SDI and sectoral shares of GVA in 'Livestock' and 'Fish & Aqua' sectoral are expected from variables like rainfall, fertilizer use, pesticides consumption, and institutional supports such as Rythu Bazars, Agricultural Market Committees (AMCs), and Public Distribution System (PDS). Rainfall fosters crop growth and diversification by enabling better water availability, while fertilizers and pesticides enhance productivity and support cultivation of diverse crops. Institutional mechanisms like AMCs and Rythu Bazars promote market accessibility, encouraging farmers to diversify their crop portfolios. Both Gross Area Sown (GAS) and GAI are also positively associated with diversification, as they expand the range of viable crops. On the other hand, factors like maximum and minimum temperatures are anticipated to negatively impact SDI, reflecting how climatic stressors limit diversification by reducing crop yields and adaptability. Similarly, high wage rates for male and female labour are expected to constrain diversification efforts due to increased production costs, limiting farmers' capacity to invest in diverse cropping systems.

The study also considers significant influence of veterinary infrastructure and services on sectoral share of GVA in livestock, fisheries, and aquaculture. The number of veterinary institutions, technical experts in veterinary clinics, and veterinary cases treated are critical variables positively influencing the GVA share in the livestock sector. A higher number of veterinary institutions ensures widespread access to essential animal healthcare services, improving livestock productivity and reducing mortality rates. These institutions play a pivotal role in disease prevention and control, ensuring the health and well-being of animals, which directly translates to enhanced livestock output. Similarly, the availability of skilled technical experts in veterinary clinics facilitates timely diagnosis and treatment of diseases, optimizing the efficiency of animal husbandry practices. The number of veterinary cases treated is an indicator of the effectiveness and reach of veterinary services, reflecting the health management of livestock populations. Together, these factors contribute to improved productivity in milk, meat, and other animal products, thereby boosting the sectoral GVA share of livestock. Additionally, the production of marine fish, inland fish, and brackish water shrimp plays a significant role in influencing the sectoral share of GVA in fisheries and aquaculture. Marine fish and shrimp production contribute positively to the GVA sectoral share by leveraging extensive coastal resources, advanced fishing techniques, and export-oriented production. Inland fish and prawn production enhance the GVA share through the optimal utilization of freshwater resources, catering to local consumption demands and domestic markets. Brackish water shrimp production, typically dominated by high-value species, significantly impacts the GVA share due to its profitability, export potential, and adaptability to semi-intensive farming systems. These production systems are positively influenced by the availability of inputs like feed, quality seed stock, and access to credit facilities. However, the extent of these contributions may vary depending on factors like technological advancements, access to infrastructure (e.g., cold storage and processing units), and government policies aimed at promoting aquaculture. Together, these production systems drive sectoral growth in fisheries and aquaculture by increasing income opportunities, improving export revenues, and strengthening the overall GVA share in this sector. Each of these variables plays a distinct and inter-related role in driving crop diversification and sectoral shares of 'GVA-Livestock' and 'GVA-Fish&Aqua' by addressing different aspects of agricultural productivity, risk management, and economic viability. The combined effect of these factors contributes to a more resilient and diversified agricultural economy, ensuring both sustainability and profitability for farmers.

Higher SDI is hypothesized to positively correlate with favourable climatic factors, such as rainfall, and supportive institutional mechanisms like PDS, AMCs, and Rythu Bazars, which improve market linkages and reduce risks for farmers. Conversely, adverse climatic factors, such as extreme temperatures, are hypothesized to negatively impact SDI by reducing crop viability and yield stability. Development within the livestock sector, measured by the share of GVA in livestock, is anticipated to benefit significantly from increased institutional support, including veterinary institutions, technical experts, and treated veterinary cases. Similarly, growth in fisheries and aquaculture sectors is likely to be positively influenced by higher production levels of marine fish, shrimp, inland fish, and brackish water shrimp, supported by resource availability, disease management, and veterinary care. Agricultural diversification is also expected to correlate positively with increased GAS and GAI, as larger areas under cultivation and enhanced irrigation infrastructure provide more opportunities for varied cropping systems. Additionally, institutional mechanisms such as AMCs, access to loans, and better market facilities are expected to drive both diversification and sectoral growth across agriculture, livestock, and fisheries. However, higher labour costs, particularly for male and female workers, are hypothesized to hinder diversification and sectoral development by lowering profitability and limiting investment capacity.

3. Methodology

This study was based on panel data across all 13 districts in Andhra Pradesh regarding the area under agriculture, horticulture, and floriculture crops to provide valuable insights about the agricultural landscape in Andhra Pradesh.

3.1. Data Collection

The relevant secondary data pertaining to selected variables in **Table 1** are collected from Statistical Abstract of Andhra Pradesh from 2015-16 to 2022-23. The data regarding Gross Value Added (GVA) realized from Agriculture and Horticulture sectors (GVA-Agri&Hort), Livestock (GVA-Livestock) and Fishing and Aquaculture sectors (GVA-Fish&Aqua) are collected from Planning Department [14], Directorate of Economics & Statistics, Government of Andhra Pradesh.

Table 1. Description of variables used in selected models.

Variables	Expected Sign	FLM	IVR	FMNL Model: 'GVA-Livestock' Sectoral Share	FMNL Model: 'GVA-Fish& Aqua' Sectoral Share	Literature Source
Dependent variable(s)						
SDI		✓				
Log-GVA-Agri&Hort			✓			
Share of GVA-Livestock (GVA-Agri&Hort as base)				✓		
Share of GVA-Fish&Aqua (GVA-Agri&Hort as base)					✓	
Independent variables						
SDI	+		✓	✓	✓	Laishram et al, 2021 [10]
Rainfall	+	✓	✓	✓	✓	Bedane et al, 2022 [15]
Maximum temperature	-	✓	✓	✓	✓	Renard et al., 2023 [16]
Minimum Temperature	-	✓	✓	✓	✓	Montana et al., 2020 [17]
Nitrogenous fertilizers	+	✓	✓			Bayu, 2020 [18]
Phosphorous fertilizers	+	✓	✓			Bayu, 2020 [18]
Potassium fertilizers	+	✓	✓			Bayu, 2020 [18]
Pesticides consumption	+	✓	✓			Guinet et al., 2023 [19]
GAS	+	✓	✓			Hufnagel et al., 2020 [20]
GAI	+	✓				LaFevor et al., 2022 [21]
Number of commercial banks	+	✓	✓	✓	✓	Ullah et al., 2020 [22]
Long-term loans issued	+	✓	✓	✓	✓	Gianluca et al., 2024 [23]
Short-term loans issued	+	✓	✓	✓	✓	Gianluca et al., 2024 [23]
Wage rate-men labour	-	✓	✓	✓	✓	Derek et al, 2024 [24]
Wage rate-female labour	-	✓	✓	✓	✓	Derek et al, 2024 [24]
Rythu Bazars	+	✓	✓	✓	✓	Parthasarathy et al., 2008 [25]; Anuja et al., 2020 [26]
AMCs	+	✓	✓	✓	✓	Parthasarathy et al., 2008 [25]; Anuja et al., 2020 [26]
PDS	+	✓	✓			Anjani et al., 2016 [27]
Number of veterinary institutions	+			✓		Enticott et al., 2011 [28]; Department of Animal Husbandry and Dairying, 2023-24 [29].
Number of technical experts in Veterinary clinics	+			✓		Enticott et al., 2011 [28]; Department of Animal Husbandry and Dairying, 2023-24 [29].
Number of veterinary cases treated	+			✓		Enticott et al., 2011 [28]; Department of Animal Husbandry and Dairying, 2023-24 [29].
Marine fish & shrimp production	+				✓	Jayanthi et al., 2018 [30]; Boyd et al., 2022 [31]
Inland fish & prawn production	+				✓	Jayanthi et al., 2018 [30]; Boyd et al., 2022 [31]
Brackish water shrimp production	+				✓	Jayanthi et al., 2018 [30]; Boyd et al., 2022 [31]

3.2. Analytical Tools Employed

3.2.1. Diversification Indices

There are several indices for measuring crop diversification in a particular cropping season, each providing unique insights into the extent and distribution of crop variety within a farming system [10, 11]. These methods include the Gibbs-Martin Index (DMI), Herfindahl Index (HI), Simpson Diversity Index (SDI) and Entropy Index (EI).

- **DMI:** This index is useful for measuring the extent of diversification in cropping pattern in an area and is given by:
  GMI = $1 - \frac{\sum_{i=1}^{N} P_i^2}{(\sum P_i)^2}$
  where, '*N*' is the total number of crops cultivated and

P_i accounts for the land share of *i*th crop in total cropped area.

- **HI:** It is calculated by squaring the market share of each individual entity within a market, and summing these squared values. It can be utilized as a measure of concentration or dominance of certain crops within a farming system. A higher HI value indicates a more concentrated or less diversified crop distribution. It is given by:
  HI = $\sum_{i=1}^{N} P_i$
- **SDI:** The SDI, which is mathematically equivalent to the square root of the HI, measures the probability that two randomly selected individuals (or species) in a community belong to the same category. A lower SDI value implies greater diversity within the system.
  SDI = $1 - \sum_{i=1}^{N} P_i^2$
  The SDI offers a distinctive advantage by circumventing the necessity for all districts to cultivate every type of crop. Instead, it focuses on evaluating the distribution of crops within a cropping system, considering the dominance of specific crops and the overall diversity. This unique approach enables the assessment of diversification levels without imposing the expectation that every district engages in the cultivation of all crop types. Consequently, the SDI was employed to examine the impact of crop diversification on the GVA-Agri&Hort, GVA-Livestock and GVA-Fish&Aqua.
- **EI:** Lastly, the EI assesses diversification by calculating the information entropy based on probabilities of each crop's presence. The EI approaches zero when the farm is specialized and takes a maximum value when there is perfect diversification.
  EI = $(-\sum_{i=1}^{N} P_i * \log P_i)$

3.2.2. FLM

This model is used to study the determinants of SDI, particularly when SDI is a proportion or a value between 0 and 1, as is the case with diversity indices. So, this model estimates how changes in independent variables influence extent of diversity (SDI) in agricultural system (**Table 1**). The objective is to estimate conditional mean of y given x, expressed as i.e., $E(y/x)$ $\phi(x\beta)$, where ϕ represents a function and β represents the model parameters. The study considers a continuous dependent variable y (SDI), which takes values between 0 and 1, representing a measure of crop diversification. The advantage of employing this model lies in its ability to provide consistent parameter estimates without requiring knowledge of the true distribution of the dependent variable [32]. Additionally, this model automatically computes robust standard errors, enhancing the reliability of the estimates [33–36]. This model takes the form,

$$E(y_i|x_i) = G(x_i\ \beta) + \mu_i, \qquad i = 1,2\ldots\ldots N \ldots \quad (1)$$

where, $0 < y_i < 1$ denotes the dependent variable SDI and (the N × 1 vector) x_i refers to the explanatory variables of observation *i*, *G* (.) denotes a cumulative distribution function.

3.2.3. IVR-2SLS Model

The impact of crop diversification on GVA-Agri&Hort was estimated with an OLS regression (Equation (2)).

$$\text{Log GVA-Agri \& Hort} = \beta_0 + \beta_1 \text{SDI}_i + \beta_2 X_i + \eta_i + \mu_i \quad (2)$$

In the above model, the log of GVA-Agri&Hort of selected districts is regressed on SDI of each district in panel data format for the above reference period; η_i - a term capturing unobserved heterogeneity assumed to be unrelated to the explanatory variables vector X_i (**Table 1**) and applying to each district; and μ_i capture all the remaining variation with $i \sim$IIDN (0, 1). However, endogeneity between crop diversification and net income realized from crops has been reported by several studies that may lead to inconsistent estimates [37, 38]. So, IVR or 2SLS was employed to control endogeneity between GVA-Agri&Hort and SDI as shown below:

$$SDI_i = \beta X_i + \phi Z_i + \varepsilon_i \quad (3)$$

$$\text{Log GVA-Agri \& Hort} = \lambda X_i + \delta SDI_i + \gamma_i \quad (4)$$

In Equation (3), Z_i represents instrument (GAI) for endogenous regressor, i.e., SDI. X_i and Z_i are collectively called instruments and are assumed to influence SDI, without exerting any 'direct' effect on Log GVA-Agri&Hort. The γ_i and ε_i are zero-mean error terms, and the correlations between them are presumably non-zero [39]. In Equation (4), the log of GVA-Agri&Hort for ith district (panel data) is the dependent variable, $\widehat{SDI}$ of each district represents fitted values of SDI; X_i represents the included exogenous regressors. This IVR-

2SLS model addresses the issue of endogeneity and isolates true causal effect of SDI on GVA-Agri&Hort, ensuring that their relationship is not confounded by simultaneous causality or other unobserved factors. This results in consistent and reliable estimates, even in the presence of endogeneity, thereby providing more accurate insights into the effect of crop diversification on agricultural income.

3.2.4. FMNL Model

This model extends the FLM to accommodate multiple categories of the dependent variable. It is used when the outcome variable has more than two discrete categories, and each category (GVA-Agri&Hort, GVA-Livestock and GVA-Fish&Aqua) represents a fraction or proportion of the total response (total GVA across all the above sectors). Thus, this model is well-suited for analyzing fractional outcomes (sectoral shares of GVA) in the presence of multiple categories. It allows for a nuanced understanding of how determinants affect relative proportions of total GVA across sectors like Agri & Hort, Livestock, and Fish & Aqua. By modelling the interdependencies and mutual exclusivity of these sectors, the FMNL approach offers valuable insights into the dynamic allocation of resources and the sectoral shifts within an economy. Mathematically, Y_{it} represents the fraction or share of the desired dependent variable that is used where i ($i = 1, 2, 3 \ldots I$) represents the cross-sectional variables (i.e., districts) in the equations and t ($t = 1, 2, 3 \ldots T$) is the time series component [40, 41]. For the level of aggregation, it must hold that:

$$0 \le Y_{it} \le 1 \qquad \sum Y_{it} = 1 \tag{5}$$

Since Y_{it} is bounded between zero and one, linear methods may generate fitted values that fall outside this unit interval. To address this issue, the problem can be modelled using a logistic function [42] considering explanatory variables in **Table 1**.

$$\mathrm{E}(Y_{it}|X_{it}) = p_{it} = \frac{\exp(X_{it}\beta_k)}{1+\exp(X_{it}\beta_k)} \tag{6}$$

where, 'exp' signifies that $(X_{it}\beta_k)$ is a power function and 'p_{it}' is the percent measure of the dependent variable.

Thus,

$$Y_{it} = \frac{\exp(X_{it}\beta_k)}{1+\exp(X_{it}\beta_k)} + \varepsilon_{it} \tag{7}$$

where, β_k represents the coefficient vector, and ε_{it} is the independently and identically distributed error term. The asymptotic analysis is carried out as $N \rightarrow \infty$ and for all of i,

$$\mathrm{E}(Y_{it}|X_{it}) = \mathrm{G}(X_{it}\beta) \tag{8}$$

Here, G(•) (where i = 1, 2, ..., I) is a predetermined function with properties that ensure the predicted fraction lies within the interval (0, 1) and sums to one across all i [43]. The logistic function is commonly chosen as the cumulative distribution function for G(•). Estimating G(•) can be done using Non-linear Least Squares (NLS). However, heteroscedasticity is likely to be present since the variance of Y_{it} conditional on X_{it} is unlikely to be constant when $0 \le Y_{it} \le 1$. As a result, the NLS estimates do not possess efficiency properties and to address this a quasi-likelihood method was proposed [44–46]. The log-likelihood function is expressed as Equation (9):

$$\mathrm{l_i(b)} \equiv \mathrm{Y_i}\log[\mathrm{G}(\mathrm{x_i b})] + (1-\mathrm{Y_i})\log[1-\mathrm{G}(\mathrm{x_i b})] \tag{9}$$

Maximizing the above equation is straightforward, and since it belongs to the Linear Exponential Family (LEF), the estimated βs are consistent and asymptotically normally distributed [44]. To establish a fractional logit equation for each dependent variable, it is necessary to ensure identification of these equations. This is achieved by estimating only k - 1 equations [42]. The equation that is not estimated serves as the base or comparison, against which the results from each estimated equation represent the choices made in relation to the base. The effects of explanatory variables on the base choice are calculated as one minus the sum of effects on the other k-1 equations.

It is well-known that the use of shares or percentages is common in agricultural studies. Examples of this include the allocation of land under different tillage practices or the distribution of land for specific crops. While a few studies have applied this model in agriculture [9, 12, 13, 44, 46–48], no studies have yet been conducted for crop diversification studies and its influence on GVA shares across different sectors. By reviewing these previous studies, it becomes evident that the FMNL model holds great potential for various applications in agriculture. One significant advantage of this model is that it can be utilized without the need for conducting expensive and time-consuming surveys. In the given context, where information regarding the cultivated area across different crops and GVA-Agri&Hort, GVA-Livestock and GVA-Fish&Aqua in Andhra Pradesh are available from secondary sources, the FMNL model can be employed to analyze the determinants affecting the realization of their respective shares. Furthermore, this research adopts an aggregate level approach rather than a micro level one. This suggests that aggregate models are superior to micro models when it comes to predicting response studies [49].

4. Results and Discussion

4.1. Descriptive Statistics

The findings (**Table 2**) highlight significant regional disparities across agricultural, economic, and social indicators in Andhra Pradesh. SDI ranges from 0.50 to 0.92, averaging 0.76, with coastal districts such as East and West Godavari, Krishna, and Guntur exhibiting higher values, while Chittoor and Ananthapuramu lag due to limited irrigation and weak market infrastructure. Rainfall varies widely, averaging 985.98 mm, with coastal Andhra receiving up to 1624.22 mm, whereas Rayalaseema remains drier with a minimum of 279.49 mm. Maximum temperatures fluctuate between 34.59 °C and 48.15 °C, averaging 41.66 °C, with Chittoor, Kadapa, and Ananthapuramu experiencing extreme heat, while minimum temperatures range from 10.18 °C to 22.19 °C, reflecting climatic diversity. Fertilizer consumption varies significantly, with nitrogenous fertilizers averaging 78.69 million tonnes, phosphorous at 36.85 million tonnes, and potassium at 16.42 million tonnes. Intensive agriculture in East and West Godavari, Guntur, and Krishna drives higher usage, whereas arid regions like Anantapur report lower consumption. Pesticide application averages 184.88 tonnes, with monoculture-intensive areas such as Chittoor showing elevated usage due to pest pressure. Land-use patterns indicate GAS at 5.79 lakh hectares, with larger cultivated areas in Guntur and West Godavari, while Anantapur and Srikakulam report lower figures. GAI averages 2.91 lakh hectares, with Krishna and Godavari districts benefiting from better irrigation infrastructure, whereas Anantapur remains dependent on rain-fed cultivation. Financial indicators reveal disparities in access to banking and credit. The number of commercial banks averages 509.80, with urbanized and economically developed districts such as Visakhapatnam, Krishna, and Guntur hosting higher concentrations. Long-term loan disbursements stand at Rs. 5,893.44 lakhs, while short-term loans average Rs. 50,645.18 lakhs, with credit availability favoring agriculturally intensive districts. Wage rates reflect economic diversity, with male labor earning Rs. 318.47/day and female labor Rs. 227.41/day, with higher wages in high-intensity farming districts and lower rates in arid regions. Market infrastructure disparities manifest in the distribution of Rythu Bazars, averaging 7.32 per district, with East and West Godavari, Krishna, and Guntur having greater access. AMCs average 15 per district, supporting well-developed agricultural regions. PDS upliftment averages 0.18 million tonnes, with higher figures in agriculturally productive districts, while lower uptake occurs in sparsely populated and less productive Rayalaseema districts. Veterinary services reveal regional imbalances, with an average of 243.56 veterinary institutions concentrated in livestock-rich regions such as Krishna, Nellore, Kadapa, and Chittoor. Cases treated per district average 8.27 million, reflecting higher livestock density in some areas. Aquaculture production showcases spatial variations. Marine fish and shrimp production averages 0.42 lakh tonnes, concentrated in coastal districts, while inland fish and prawn production stands at 1.72 lakh tonnes, thriving in freshwater-abundant regions such as Godavari and Prakasam. Brackish water shrimp farming averages 0.28 lakh tonnes, benefiting from coastal access. These variations underscore the diverse agricultural and economic landscape across Andhra Pradesh.

Table 2. Descriptive statistics of selected variables.

Variables	Units	Mean	Std. Dev.	Min	Max
SDI	-	0.76	0.11	0.50	0.92
Rainfall	mm	985.98	335.78	279.49	1624.22
Maximum temperature	°C	41.66	2.84	34.59	48.15
Minimum Temperature	°C	15.54	3.26	10.18	22.19
Nitrogenous fertilizers	Million tonnes	78.69	45.49	19.80	184.71
Phosphorous fertilizers	Million tonnes	36.85	25.76	4.00	113.36
Potassium fertilizers	Million tonnes	16.42	12.05	2.00	54.20
Pesticides consumption	Tonnes	184.88	96.90	41.43	484.00
GAS	Lakh ha	5.79	2.15	2.92	11.06
GAI	Lakh ha	2.91	1.50	1.25	6.43
Number of commercial banks	-	509.80	175.91	215.00	849.00
Long-term loans issued	Rs. Lakhs	5893.44	9246.99	35.77	49,188.02
Short-term loans issued	Rs. Lakhs	50,645.18	29,073.18	7442.00	151,738.00
Wage rate-men labour	Rs/day	318.47	74.02	182.92	543.00
Wage rate-female labour	Rs/day	227.41	55.46	129.81	386.00
Rythu Bazars	-	7.32	6.30	1.00	28.00
AMCs	-	15.00	4.27	8.00	24.00
PDS	Million tonnes	0.18	0.04	0.12	0.28
Number of veterinary institutions	-	243.56	59.85	155.00	352.00
Number of technical experts in Veterinary clinics	-	402.32	82.57	248.00	545.00
Number of veterinary cases treated	Million	8.27	6.69	1.89	38.40
Marine fish & shrimp production	Lakh Tonnes	0.42	0.43	0.00	1.34
Inland fish & prawn production	Lakh Tonnes	1.72	3.18	0.01	14.13
Brackish water shrimp production	Lakh Tonnes	0.28	0.48	0.00	2.52

4.2. Diversification Indices

Figure 1 provide crop diversification patterns across districts and zones in Andhra Pradesh, revealing significant variations. Prakasam exhibits the highest diversification (SDI = 0.904), reflecting a well-distributed cropping structure. In contrast, Nellore and East Godavari register lower diversification, with Nellore showing an SDI of 0.596. Srikakulam, Vizianagaram, and Visakhapatnam display moderate to high diversification, whereas Krishna and Guntur maintain balanced cropping patterns. Crop concentration also varies, with Nellore exhibiting a more concentrated structure, while Srikakulam, Vizianagaram, Visakhapatnam, and Chittoor show relatively lower concentration levels. At the zonal level, North Coastal stands out with high diversification (GMI = 0.758, SDI = 0.796), serving as a model for diverse farming systems. Krishna zone records the highest GMI (0.770) while maintaining a less concentrated cropping structure (HI = 0.172). The Godavari zone benefits from policies promoting a wider range of crops, fostering an optimal balance. The Southern zone sustains moderate diversification with well-distributed cropping patterns, ensuring agricultural stability. Despite inherent challenges, the Scarce Rainfall zone demonstrates commendable diversification, reflecting adaptive agricultural strategies that warrant further exploration and support.

S.No	District/Zone	GMI	HI	SDI	EI
1	Srikakulam	0.717	0.283	0.717	0.083
2	Vizianagaram	0.780	0.162	0.838	0.142
3	Visakhapatnam	0.777	0.166	0.834	0.218
North Coastal zone		**0.758**	**0.204**	**0.796**	**0.148**
4	East Godavari	0.634	0.366	0.634	0.136
5	West Godvari	0.724	0.375	0.625	0.133
Godavari zone		**0.679**	**0.371**	**0.630**	**0.135**
6	Krishna	0.677	0.243	0.757	0.128
7	Guntur	0.766	0.176	0.824	0.132
8	Prakasam	0.866	0.096	0.904	0.238
Krishna zone		**0.770**	**0.172**	**0.828**	**0.166**
9	Nellore	0.596	0.404	0.596	0.205
10	Chittoor	0.804	0.142	0.858	0.18
11	Kadapa	0.801	0.127	0.873	0.122
Southern zone		**0.734**	**0.224**	**0.776**	**0.169**
12	Kurnool	0.680	0.273	0.727	0.134
13	Ananthapuramu	0.703	0.216	0.784	0.198
Scarce rainfall zone		**0.692**	**0.245**	**0.756**	**0.166**

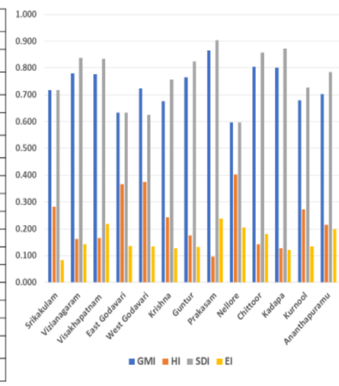

Figure 1. Indices for crop diversification across districts in Andhra Pradesh.

4.3. Determinants for Crop Diversification in Andhra Pradesh

The determinants of crop diversification (SDI) in Andhra Pradesh were analyzed using marginal effects computed from FLM (**Table 3**)[34, 50, 51]. The findings showed that higher rainfall was found to have a significant positive effect (0.399%), as it supports the growth of a wider range of crops, thereby increasing diversification. The application of phosphorus fertilizers also had positive influence (1.532%). An increase in GAS contribute to higher SDI at significant note (0.375%). Similarly, a larger GAI increases SDI as it enhances agricultural potential. The presence of a greater number of commercial banks (2.060%) and access to long-term loans (0.183%) significantly promoted crop diversification. Similarly, strengthening of Rythu Bazars (0.413%) and AMCs (2.038%) provided farmers with market infrastructure, information, and support services that encouraged diversification. Conversely, certain factors such as higher pesticide use (−0.053%), a larger GAI (−1.787%), higher wage rate of male labour (−4.762%), higher wage rate of female labour (−3.228%), and a larger quantity lifted in the PDS (−3.141%) had significant negative impact on crop diversification. However, the effects of maximum temperature, minimum temperature, nitrogenous and potassium fertilizers, pesticides consumption and short-term loans are relatively small or statistically insignificant.

Table 3. Determinants for SDI in Andhra Pradesh using FLM (2015-16 to 2022-23).

Variables	Marginal Effects	Robust Std. Err.
Rainfall	0.399*	0.191
Maximum temperature	−3.656	3.015
Minimum Temperature	−0.356	1.073
Nitrogenous fertilizers	−1.5227	1.0945
Phosphorous fertilizers	1.532*	0.718
Potassium fertilizers	−0.908	0.575
Pesticides consumption	−0.053**	0.017
GAS	0.375**	0.086
GAI	1.787**	0.659
Number of commercial banks	2.060**	0.808
Long-term loans issued	0.183*	0.091
Short-term loans issued	−0.215	0.297
Wage rate-men labour	−4.762**	0.854
Wage rate-female labour	3.228**	0.842
Rythu Bazars	0.413*	0.205
AMCs	2.038**	0.504
Quantity lifted in PDS	−3.141**	0.974
_Cons	30.891**	9.923
Observations	104	
Log pseudolikelihood	−37.5233919	

Note: ** - Significant at 1% level, * - Significant at 5% level.

4.4. SLS-IVR for Determinants of GVA-Agri&Hort

An initial OLS regression was performed to examine factors influencing GVA-Agri&Hort in Andhra Pradesh. However, findings indicated endogeneity between SDI and GVA-Agri&Hort (**Table 4**), as evidenced by the Wald test (Wald $chi^2(2)$ = 13.23**). To address this, an IVR approach was implemented, selecting GAI as an instrumental variable [52–55]. This choice was based on the expectation that GAI primarily influences GVA-Agri&Hort through its effect on SDI, without directly impacting the error term or other omitted variables. IVR aimed to enhance reliability by mitigating endogeneity concerns. Weak Identification Test results confirmed GAI as a strong instrument, with a significant Cragg-Donald Wald F statistic (50.83**), establishing its relevance in explaining SDI while remaining uncorrelated with the error term. Sargan's statistic (0.702^{NS}) indicated no over-identification concerns, reinforcing instrument validity. Anderson's canonical correlation LM statistic (0.033^{NS}) suggested no under-identification, affirming the appropriateness of IVR for analyzing determinants of GVA-Agri&Hort. These results validate IVR as a robust framework for deriving meaningful insights.

Further analysis of OLS regression results in **Table 4** showed a significant positive effect of SDI on GVA-Agri&Hort at the 1% level, with a coefficient of 0.297. However, endogeneity concerns suggested that SDI might be influenced by factors also affecting GVA-Agri&Hort. Simple OLS regression, therefore, risked biased parameter estimates. To obtain a more precise estimate, a 2SLS (IVR-Fixed Effects) model was applied, addressing selection bias and potential endogeneity. After correcting for endogeneity, findings revealed a stronger, statistically significant impact of SDI on GVA-Agri&Hort at the 1% level, with an increased coefficient of 0.437. This demonstrated that employing IVR effectively mitigated endogeneity concerns, providing more reliable estimates compared to OLS. Results highlighted that crop diversification, as represented by SDI, contributed more substantially to GVA-Agri&Hort in Andhra Pradesh than specialization alone. Enhanced production through diversified cropping systems and reduced production risks explained this positive influence, aligning with insights from earlier studies [26, 37]. Several variables exhibited positive and significant associations with GVA-Agri&Hort, including phosphorous fertilizers (0.439**), number of commercial banks (1.181*), long-term loans issued (0.114**), short-term loans issued (0.150**), Rythu Bazars (0.231**), and AMCs (0.572). Conversely, wage rates for male labor (−0.666**) and female labor (−0.625**), along with the quantity lifted in PDS (−0.844), showed negative and statistically significant effects on GVA-Agri&Hort. Rainfall, maximum temperature, and minimum temperature did not show statistically significant effects on GVA-Agri&Hort. Although these weather factors influence production and yield, their direct impact on GVA-Agri&Hort was not statistically evident within this study's framework [48].

Table 4. OLS and 2SLS estimates for determinants of 'logGVA-Agri&Hort' sector (n = 104).

Variables	OLS		2SLS (2nd Stage) – FE Model$	
	Coefficient	Std. Err.	Coefficient	Std. Err.
SDI	0.297*	0.136	0.437**	0.157
Rainfall	0.084	0.074	0.089	0.079
Maximum temperature	−0.077	0.509	1.032	0.627
Minimum Temperature	−0.317	0.199	−0.069	0.319
Nitrogenous fertilizers	−0.240	0.191	0.240	0.210
Phosphorous fertilizers	0.407**	0.140	0.439**	0.146
Potassium fertilizers	0.132	0.083	−0.133	0.099
Pesticides consumption	−0.078	0.055	−0.096	0.052
GAS	−0.064	0.155	0.613*	0.297
GAI	0.315	0.221	–	–
Number of commercial banks	0.421*	0.208	1.181**	0.461
Long-term loans issued	−0.005	0.022	0.114**	0.022
Short-term loans issued	0.031	0.073	0.150**	0.057
Wage rate-men labour	−0.976**	0.335	−0.666*	0.325
Wage rate-female labour	−1.368**	0.293	−0.625*	0.290
Rythu Bazars	−0.131**	0.048	0.231**	0.053
AMCs	−0.238	0.135	0.572**	0.209
Quantity lifted in PDS	0.777**	0.270	−0.844*	0.386
_Cons	5.374**	1.900	6.479**	2.480
Model Statistics	Wald chi^2(18) = 485.74 (Prob >chi^2 = 0.0000)		Hausman test$: chi^2(17) = 142.34** Wald chi^2(17) = 3.14e+06 (Prob >chi^2 = 0.0000)	
Endogeneity test (SDI vs. GVA-Agri-Hort)	Coefficient of SDIresiduals: −2.366**		Instrumented: SDI; Excluded instrumental variable: GAI Weak identification test (Cragg-Donald Wald F statistic) = 50.83** Sargan statistic: 0.702^{NS} Under-identification test (Anderson canon. corr. LM statistic): 0.033 (Chi-sq(1) P-val = 0.8548)	

Note: ** - Significant at 1% level, * - Significant at 5% level.

4.5. Sector-Wise Contributions towards GVA in Selected Districts

Sector-wise contributions to total GVA across districts reveal distinct economic patterns and variations (**Table 5**). Agriculture and horticulture, represented by GVA-Agri&Hort, hold a significant share in many districts, particularly in Srikakulam, Vizianagaram, and Visakhapatnam in the North Coastal zone, as well as Krishna and Guntur in the Krishna zone. Livestock, captured by GVA-Livestock, plays a crucial role in districts like Guntur, Prakasam, and Chittoor. Fish and aquaculture, reflected in GVA-Fish & Aqua, contribute notably in certain areas, with West Godavari in the Godavari zone standing out due to its economic reliance on this sector. Nellore in the Southern zone also shows a strong presence in fish and aquaculture. Comparisons across districts highlight variations in sector-wise contributions. The North Coastal zone leans heavily on agriculture and horticulture, whereas West Godavari focuses predominantly on fish and aquaculture. The Krishna zone maintains a relatively balanced sectoral distribution, including a notable presence in aquaculture. The Southern zone exhibits strong engagement in agriculture and horticulture, with moderate involvement in livestock and aquaculture. Meanwhile, Kurnool and Ananthapuramu in the scarce rainfall zone rely primarily on agriculture and horticulture due to challenging climatic conditions. While agriculture and horticulture dominate many regions, livestock and aquaculture contribute to varying extents, underscoring the diverse economic landscape across districts. These sectoral differences reflect unique resource availability, climatic factors, and economic activities shaping each district's GVA composition.

Table 5. Sector-wise contributions to GVA in Andhra Pradesh.

S.No	District/Zone	GVA-Agri&Hort	GVA-Livestock	GVA-Fish&Aqua
1	Srikakulam	0.523	0.319	0.158
2	Vizianagaram	0.603	0.267	0.130
3	Visakhapatnam	0.574	0.285	0.141
North Coastal zone		0.567	0.290	0.143
4	East Godavari	0.744	0.170	0.086
5	West Godavari	0.327	0.246	0.427
Godavari zone		0.536	0.208	0.256
6	Krishna	0.296	0.261	0.443
7	Guntur	0.534	0.346	0.119
8	Prakasam	0.453	0.433	0.114
Krishna zone		0.428	0.347	0.225
9	Nellore	0.339	0.266	0.396
10	Chittoor	0.578	0.419	0.004
11	Kadapa	0.751	0.246	0.003
Southern zone		0.556	0.310	0.134
12	Kurnool	0.604	0.376	0.020
13	Ananthapuramu	0.689	0.306	0.004
Scarce rainfall zone		0.647	0.341	0.012

4.6. Determinants for GVA-Livestock and GVA-Fish&Aqua Sectoral Shares

FMNL model estimates [56–58] provide valuable insights into shares of GVA-livestock and GVA-Fish&Aqua, with GVA-Agri as the base category (**Table 6**). The model demonstrates a strong fit, with a Chi-square Wald statistic of 8578.80, surpassing critical values at all significance levels. Expected coefficient signs align with economic reasoning where applicable. A positive and significant coefficient (0.236*) for SDI suggests that greater crop diversification corresponds with a higher share of GVA-livestock, holding other factors constant. Diversification enhances feed availability and provides a sustainable resource base for livestock farming. Financial access also plays a crucial role, as indicated by positive and significant coefficients for commercial banks (0.411*) and long-term loans (0.059**). Rising labour costs negatively impact livestock sector performance, as shown by negative relationships between wage rates for male (−0.426*) and female (−0.465*) labour. Higher wages reduce competitiveness and profitability, leading to a diminished share of GVA-livestock. Marketing efficiency contributes significantly, with Rythu Bazars (0.101**) and AMCs (0.315*) showing positive effects. Veterinary services emerge as key determinants of livestock sector success. Positive and significant coefficients for veterinary institutions (0.252*), technical experts in veterinary clinics (0.572*), and cases treated (0.033*) highlight their role in improving animal health, productivity, and overall sector performance.

FMNL model estimates for GVA-Aqua, with GVA-Agri as the base category, reveal key determinants of aquaculture sector performance. Positive and significant coefficients for marine fish & shrimp production (0.027**), inland fish & prawn production (0.133**) and brackish water shrimp production (0.040**) indicate that increased output in these categories enhances GVA-Fish&Aqua. Climatic factors, particularly maximum and minimum temperatures, showed negative and significant effects on GVA-Fish&Aqua. Financial access plays a crucial role, as reflected in positive and significant coefficients for commercial banks (0.177*) and long-term loans (0.024**). Labour costs emerge as a constraint, with negative coefficients for wage rates of male (−0.269*) and female (−0.221*) labour. Efficient market infrastructure strengthens aquaculture performance, with Rythu Bazars (0.041**) and AMCs (0.142*) showing positive effects. These findings offer insights for policymakers and stakeholders aiming for sustainable sectoral development.

Table 6. FMNL estimates (marginal effects) for determinants of GVA shares of 'Livestock' and 'Fish&Aqua' sectors.

Variables	Share of 'GVA-Livestock'		Share of 'GVA-Fish&Aqua'	
	Marginal Effects	Std. Err.	Marginal Effects	Std. Err.
SDI#	0.236*	0.102	0.099	0.065
Rainfall	0.033	0.044	−0.029	0.031
Maximum temperature	−0.317	0.373	−0.556**	0.222
Minimum Temperature	−0.129	0.176	−0.207*	0.090
Number of commercial banks	0.411*	0.167	0.177*	0.084
Long-term loans issued	0.059**	0.014	0.024**	0.008
Short-term loans issued	0.020	0.042	−0.040	0.023
Wage rate-men labour	−0.426*	0.208	−0.269*	0.115
Wage rate-female labour	−0.465*	0.194	−0.221*	0.104
Rythu Bazars	0.100**	0.037	0.041**	0.016
AMCs	0.315*	0.126	0.142*	0.070
Number of veterinary institutions	0.252*	0.108	--	--
Number of technical experts in Veterinary clinics	0.572*	0.259	--	--
Number of veterinary cases treated	0.033*	0.017	--	--
Marine fish & shrimp production	--	--	0.027**	0.008
Inland fish & prawn production	--	--	0.133**	0.019
Brackish water shrimp production	--	--	0.040**	0.012

Note: ** - Significant at 1% level, * - Significant at 5% level.
- No endogeneity issues (SDIresiduals (-3.482^{NS}) with Share of GVA-livestock); (SDIresiduals (-2.091^{NS}) with Share of GVA-Fish&Aqua).

5. Summary and Conclusions

Crop diversification plays a vital role in overcoming challenges faced by farmers in Andhra Pradesh. Cultivating a variety of crops instead of depending on a few major ones helps mitigate risks, improve food security, enhance income, promote sustainability, and address environmental concerns. Diverse agro-climatic conditions across regions support a broad range of crops, enabling farmers to select those best suited to local conditions. Government initiatives such as NMOOP and NFSM encourage diversification by supporting pulses, oilseeds, and coarse cereals.

An analysis of crop diversification indices across districts and zones revealed significant variations. Prakasam district exhibited high diversification, whereas Nellore and East Godavari showed relatively lower levels. FLM highlighted that several factors significantly influenced SDI, including rainfall, phosphorus fertilizers, commercial bank presence, long-term loan availability, and strengthened Rythu Bazars and AMCs. Application of 2SLS (IVR-Fixed Effects) effectively corrected selection bias and endogeneity concerns, revealing strong positive associations between GVA-Agri&Hort and key determinants such as phosphorous fertilizers (0.439**), commercial banking presence (1.181*), long-term (0.114**) and short-term credit (0.150**), Rythu Bazars (0.231**), and AMCs (0.572). Conversely, wage rates for male (−0.666**) and female labor (−0.625**), along with PDS quantity lifted (−0.844), exhibited adverse effects. Climatic variables, including rainfall and temperature fluctuations, lacked statistical significant influences on GVA-Agri&Hort. Regarding sector-wise contributions to GVA, the North Coastal zone relies heavily on agriculture and horticulture, while West Godavari exhibits a strong focus on aquaculture. Krishna zone maintains a balanced distribution across agriculture, horticulture, and fisheries. Southern districts contribute significantly to agriculture and horticulture, with moderate participation in livestock and aquaculture. Scarce rainfall zones, including Kurnool and Ananthapuramu, remain highly dependent on agriculture and horticulture due to climatic challenges.

FMNL model estimates offer profound insights into GVA-livestock and GVA-Fish&Aqua shares, using GVA-Agri as a reference category. Crop diversification (0.236*) boosts GVA-livestock by enhancing feed availability. Financial access (number of commercial banks 0.411*; long-term loans 0.059**) supports growth, while rising labor costs (male (−0.426*); female (−0.465*)) reduce competitiveness. Marketing (Rythu Bazars (0.101**); AMCs (0.315*)) and veterinary services (institutions (0.252*); expertise (0.572*)) drive sectoral resilience. Similarly, GVA-Aqua is driven by marine (0.027**), inland (0.133**), and brackish water (0.040**) output. Rising temperatures hinder performance, while financial access (number of commercial banks (0.177*); long-term loans (0.024**)) supports expansion. High labor costs (male (−0.269*); female (−0.221*)) reduce competitiveness, whereas market efficiency (Rythu Bazars (0.041**); AMCs (0.142*)) boosts sectoral resilience.

Findings of this study underscore critical policy imperatives aimed at enhancing agricultural resilience and sustainability across Andhra Pradesh. A multifaceted approach to crop diversification is essential, encompassing improved credit accessibility, expanded financial institutions, and strengthened market infrastructure. Precision-targeted investments in livestock, fisheries, veterinary services, and sustainable aquaculture are crucial for sectoral diversification, ensuring economic stability amid climatic uncertainties. Strengthening institutional frameworks for climate-smart agriculture, integrating water conservation initiatives, and optimizing land-use strategies further fortify agricultural resilience. Additionally, promoting agroforestry, organic farming, and permaculture within existing agrarian landscapes fosters ecosystem restoration while augmenting farmer incomes through diversified produce. Developing robust value chains and fortified market linkages requires synergistic engagement through public-private partnerships and dynamic involvement of Farmer Producer Organizations (FPOs). Capacity-building initiatives must be prioritized through expansive agricultural extension services, interdisciplinary research collaborations, and well-structured awareness campaigns. Dissemination of knowledge on regenerative farming, organic inputs, and sustainable irrigation techniques accelerates the adoption of environmentally harmonious practices. Addressing systemic inefficiencies, such as excessive pesticide reliance, labor cost escalations, and complexities within the PDS, remains vital for effective policymaking. Furthermore, aligning cropping patterns with regional agro-climatic conditions, integrating climate-adaptive farming models like mixed cropping and conservation agriculture, and fostering institutional support for natural farming through policy realignments can significantly enhance agronomic stability. Expanding Participatory Guarantee Systems (PGS) for organic certification, strengthening research and evaluation mechanisms, and implementing adaptive governance frameworks underpinned by evidence-based decision-making are indispensable for advancing sustainable and resilient agricultural paradigms across Andhra Pradesh.

This study has several limitations that can be addressed in future research. The geographical scope is limited to select districts in Andhra Pradesh, so expanding the research to include a broader range of areas would enhance its generalizability. Socio-economic factors affecting crop diversification adoption were not deeply analyzed, and addressing these factors could provide more insights. Additionally, the study did not assess the effectiveness of government policies at the grassroots level, an area that warrants future exploration. Examining policy implementation challenges would also be beneficial in future studies. These directions could enhance understanding of crop diversification's benefits and challenges in Andhra Pradesh and beyond.

Author Contributions

K.N.R.K.: conceptualization, review, methodology, data collection, data curation, data analysis, writing initial draft; T.R.B.: expert comments and suggestions. Both the authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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