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Research Article

Canonical Correlation Analysis of bidirectional Linkages Between Agricultural Productivity and Household Welfare Development in Nepal

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ABSTRACT

This study explores how agriculture and household welfare are connected in Nepal using census data from 2001, 2011, and 2021. Two sets of indicators were created to represent structural changes in agriculture and household living conditions. All variables were standardized, and data checks using KMO, Bartlett's test, and Cronbach's alpha confirmed that the indicators were suitable for multivariate analysis (KMO: 0.76–0.84; Bartlett's p-value<0.01; alpha: 0.75–0.89). Canonical Correlation Analysis was then applied to measure how the two domains move together, showing strong correlations across all years (0.90–0.94, $p < 0.01$). Despite the canonical R^2 for the first canonical variate being 81–86%, redundancy analysis revealed that the agricultural variate accounted for approximately 16–17% of the variation in the household welfare variate, whereas the household welfare variate explained 11–12% of the variation in the agricultural variate, indicating an asymmetry between agriculture and household welfare. The results suggest that while agriculture and household welfare are strongly linked, improvements in agricultural structure contribute more to household welfare than the reverse. This research provides an empirical framework demonstrating Nepal's gradual shift from a fragmented agricultural economy to a more connected, although uneven, growth economy.

The results emphasize the critical need for integrated development policies that address both agricultural transformation and persistent socio-economic disparities to foster equitable and sustainable development across the nation.

Keywords: Agricultural productivity, Canonical Correlation Analysis, Household amenities Nepal, Socio-economic Development

INTRODUCTION

Nepal has been developing for several decades but still finds itself among the least developed and poorest countries in the world (K. & Hall, 2020). Agriculture remains the backbone of the Nepalese economy, employing about two-thirds of the population (Larsen et al., 2014) and contributing roughly one-third to the national Gross Domestic Product (Baidya, 2019; Kattel, 2023). Despite notable reductions in poverty over recent decades, the agricultural sector's erratic growth has not fully addressed persistent poverty or widespread food insecurity (Nepali et al., 2020).

Significant regional disparities and limited access to essential household amenities, particularly in rural and mountainous areas, underscore the need for a detailed examination of the linkages between agricultural performance and household socio-economic well-being (K. & Hall, 2020). This study seeks to analyze the bidirectional relationship between agricultural productivity and household welfare, aiming to provide evidence-based policy insights that simultaneously foster agricultural growth and improve living standards. While improvements in agricultural practices are expected to drive socio-economic development, enhanced household amenities such as better health, education, and labor efficiency can also boost agricultural productivity (Gollin, 2023). The application of Canonical Correlation Analysis (CCA) in this study allows for a multivariate exploration of the covariation between these two domains (Jayadevan, 2018). Agricultural growth has more pronounced poverty-reducing effects than non-agricultural growth in low-income countries (Ligon & Sadoulet, 2017), highlighting the relevance of this analytical framework for the Nepalese context.

Operationally, agricultural indicators include crop yield, irrigation coverage, and horticultural and pulse production, whereas household well-being is measured by access to durable goods, electricity, and communication facilities. Understanding these interlinkages is critical for integrated development planning and prioritizing policies that promote sustainable rural transformation in Nepal (Kafle et al., 2022). Agricultural development stimulates rural economies by generating employment and improving food security, which in turn drives economic growth and reduces poverty through optimized resource utilization. Simultaneously, improved household facilities such as housing, clean water, sanitation, and electricity enhance labor productivity and community health, further supporting agricultural productivity (Degefu, 2020; Kafle et al., 2022). Globally, agricultural productivity has historically been pivotal in driving structural transformation and alleviating poverty, particularly in South Asia since the Green Revolution. Sustaining these gains requires continued investment in innovative technologies, modern machinery, and sustainable land management practices, which ultimately improve food security, reduce vulnerability, and diversify dietary patterns at the household level.

In Nepal, however, most research on agriculture and household welfare treats these domains separately or in a unidirectional manner, often overlooking their interactions and mutual influences. Studies tend to focus narrowly on technological adoption or irrigation without considering broader family welfare, while only a few explore how household well-being affects agricultural productivity (Gather et al., 2019). This fragmented approach limits understanding of the integrated processes driving rural development. Conventional regression models, widely used in previous research, may not capture these complex relationships, whereas multivariate techniques like CCA can identify canonical variates that represent shared variance between the two domains (Jayadevan, 2018). Moreover, emerging aspects such as rural digitization remain underexplored as interacting elements of agricultural and household development in the Nepalese context (Chaudhary et al., 2025; Min et al., 2024; Thomas et al., 2024; Upend ram et al., 2023).

This study is grounded in the Sustainable Livelihoods Framework (Serrate, 2017), which emphasizes that household well-being and agricultural productivity are interconnected through human, natural, physical, financial, and social capitals (Bhandari, 2013; Serrate, 2017). The SLF posits that improvements in household assets and capabilities can enhance agricultural outcomes, while productive agricultural systems, in turn, support livelihood sustainability (Bhandari, 2013). This framework provides a robust lens for examining the reciprocal relationship between agricultural performance and household welfare in Nepal (Bhandari, 2013; Liebert & Burger, 2015), supporting the use of CCA to capture multidimensional interactions.

By employing CCA to analyse bidirectional linkages, this study addresses a critical research gap, offering an empirical framework that integrates multiple indicators to explain the covariation between agriculture and household welfare. The findings are expected to identify core canonical dimensions, facilitating the formulation of coherent, evidence-based policies that align agricultural transformation with measurable improvements in living standards.

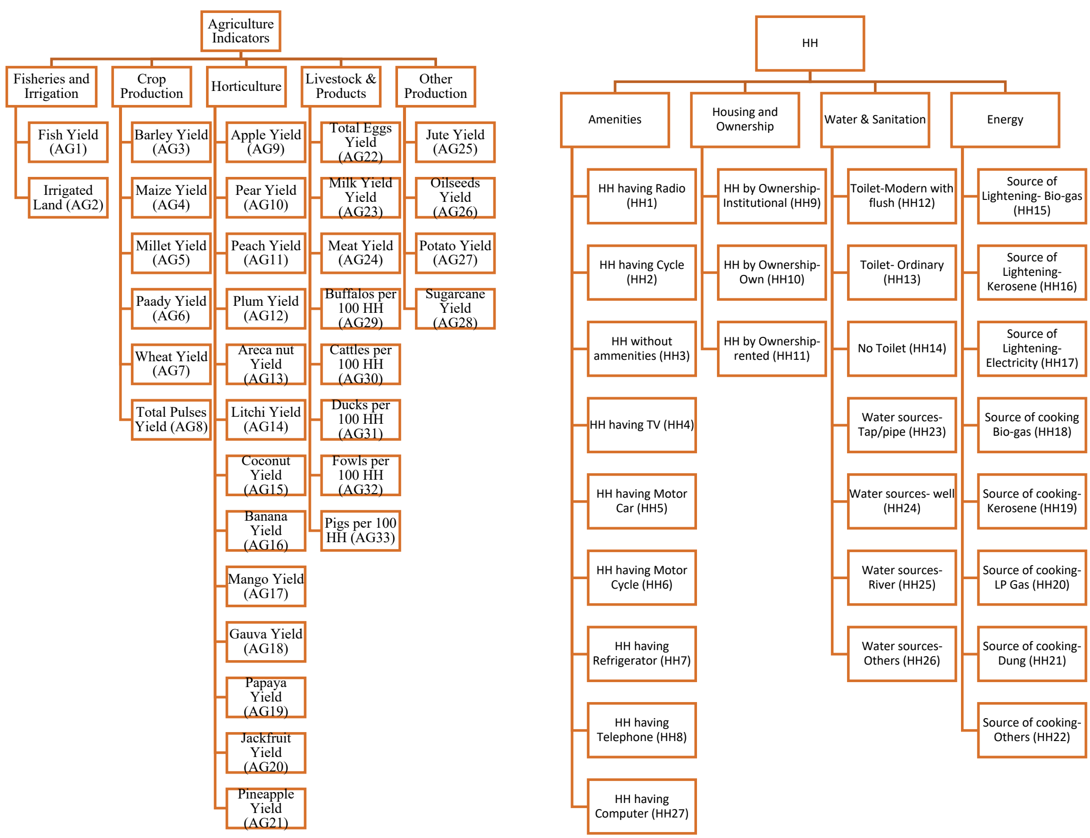
DATA AND METHODS

Selection and Classification of Indicators:

Agriculture and Household Welfare data are multi-dimensional in nature. To capture this, the many indicators were grouped.

Figure-1

Framework of Agriculture and Household Welfare indicators



This longitudinal, quantitative study utilized district-level secondary data from Nepal's Population and Housing Census (2001, 2011, 2021), alongside Agricultural Census datasets, to construct these indicators. All 77 districts served as units of analysis across three census years (2001, 2011, and 2021). Two sets of variables were defined to explore the bidirectional relationship between agricultural productivity and Household Amenities development. The first set comprised indicators of agricultural productivity such as crop yield, irrigated area, horticulture yield etc. The second set included indicators of Household Amenities such as access to electricity, improved drinking water, sanitation, and housing quality.

Data Processing and Standardization

To ensure comparability, all indicators were first screened for missing values. Missing data were handled using mean substitution when the missing rate was below 5%. Since the variables were measured in different units, data were standardized using **z-score normalization**.

Prior to the main analysis, statistical assumptions were tested. The Shapiro Wilk, Lilliefors test and Anderson Darling tests were used to assess the normality of each variable. Highly skewed variables were transform using Yeo- Johnson. In this research we use only apply yeo-Johnson transformation if absolute value of skewness is greater than 1 to preserve originality of data.

The **Yeo Johnson transformation** is defined as follows (Kath & Ziel, 2020; Yu & Li, 2024):

$$x_{ij}^{(\lambda)} = \begin{cases} \dfrac{(x_{ij}+1)^{\lambda}}{\lambda} & \text{if } x_{ij} \geq 0, \lambda \neq 0, \\ \text{in}\,(x_{ij}+1), & \text{if } x_{ij} \geq 0, \lambda = 0, \\ -\dfrac{-(x_{ij}+1)^{(2-\lambda)}-1}{\lambda} & \text{if } x_{ij} < 0, \lambda \neq 2, \\ -\text{in}\,(-x_{ij}+1), & \text{if } x_{ij} < 0, \lambda = 2, \end{cases}$$

Where:

- $x_{ij}x_{ij}$ = value of the j^{th} socio-economic indicator for the ith district
- $x_{ij}^{(\lambda)}x_{ij}^{(\lambda)}$ = Yeo-Johnson transformed value of $x_{ij}x_{ij}$.
- λ=λ = transformation parameter estimated to best normalized the data

The relevancy of the data for dimension reduction/factor analysis was examined by using the **Kaiser Meyer Olkin (KMO)** measure and **Bartlett's Test of Sphericity**. **A KMO value above 0.6** was considered to be adequate, while a **significant Bartlett's test (p<0.05**) demonstrated satisfactory intercorrelations among variables for dimension reduction.

Cronbach's alpha was computed to check for internal consistency of the grouped indicators. Alpha values greater than 0.7 were considered reliable. For multiple indicators measuring seemingly related dimensions, Principal Component Analysis (PCA) was performed to obtain components that would ease interpretation in advance of Canonical Correlation Analysis (CCA).

Canonical Correlation Analysis, first proposed by Hoteling, investigates the multivariate statistical relationship between two sets of variables: agricultural productivity and household indicators. This procedure finds the linear combinations of variables in each variable set that have maximum possible correlation with each other, thereby showing the hidden interdependencies.

Specifically, CCA constructs canonical variates for both sets, determining canonical correlations and coefficients. These coefficients explain the contribution of each original variable to its respective canonical variate; canonical correlations describe the strength of linear relationships between the variates. The substantive meaning of the variates and the contribution of each variable to shared variance are derived by interpreting canonical loadings and cross-loadings.

$$U_i = a_{1i}X_1 + a_{2i}X_2 + a_{3i}X_3 + \dots + a_{pi}X_p$$
$$V_i = b_{1i}Y_1 + b_{2i}Y_2 + b_{3i}Y_3 + \dots + b_{pi}Y_p$$

Where:

- U_i = the *i-th canonical* variate for the first set of variables X
- V_i = the *i-th* canonical variate for the second set of variables
- $X_1, X_2, \dots\dots\dots, X_p$ = Standardized variables of the first set (e.g., socio-economic indicators)
- $Y_1, Y_2, \dots\dots\dots, Y_q$ = Standardized variables of the second set (e.g., agricultural indicators)
- $a_{1i}, a_{2i}, \dots\dots\dots, a_{pi}$ = canonical coefficients for the X set in the *i-th* canonical variate
- $b_{1i}, b_{2i}, \dots\dots\dots, b_{pi}$ = canonical coefficients for the Y set in the *i-th* canonical variate

Wilks's Lambda:

$$\Lambda = \prod_{i=1}^{s} (1 - r_i^2)$$

Where:

- Λ = Wilks' Lambda (overall multivariate test statistic)
- r_i = the i-th canonical correlation coefficient
- s = min (p,q), where
- p = number of variables in the first set
- q = number of variables in the second set

- $x^2 = -\left(n - 1 - \frac{p + q + 1}{2}\right) in\,(\Lambda)$

The significance of canonical correlations will be assessed using Wilks's Lambda. The smaller value of Λ and a p-value less than 0.05 present the statistically significant canonical relationships (Ariza et al. ,2022) and (Bensalma et al. , 2019). This will then be followed by the redundancy index, which quantifies the variance in one set explained by the canonical variates of the other.

Interpretation of canonical variates involves loadings, representing the correlation of each original variable with its variate, and cross-loadings, showing the correlation of a variable in one set with the canonical variates of the other set. Loadings are considered to contribute meaningfully if their absolute magnitude is 0.3 or greater; some sources use the cut-off value of 0.50 or greater for practical significance. Wilks' lambda provides a test of statistical significance and rejects the null hypothesis of no relation between the two data sets, provided the p-value is small enough. This thus gives an in-depth analysis of multivariate dependence between agricultural productivity and HH rather than simply using bivariate correlations.

This paper will use CCA to examine multiple agricultural productivity and HH amenity variables simultaneously, rather than in isolation, to measure the strength of their interdependencies and identify the combinations of variables contributing most strongly to their relationships.

CCA identifies latent constructs indicating broad dimensions of agricultural development and socioeconomic well-being, while offering a holistic view of their interrelation in a nonlinear feedback relationship. CCA is also useful for reducing complex data sets into a few canonical variates that capture the shared variance. Compared to other techniques, CCA is unique in its ability to maximise the correlation between two sets of variables. This allows for a comprehensive understanding of their co-variation and facilitates a nuanced investigation of the complex interplay between agricultural output and standards of living.

The redundancy index quantifies the percentage of variance within a given dataset that can be attributed to the canonical variates of another dataset. This index improves canonical correlation analysis by focusing on practical significance, rather than just statistical significance. It is computed using both the total explained variance between the two sets of variables and the extracted variance for each canonical function. Lower values suggest that the relationship may be statistically significant but not meaningful in interpretation, whereas higher redundancy values indicate more shared variance and greater explanatory strength.

Therefore, this redundancy index is useful for assessing the relevance and effectiveness of canonical relationships discovered in an analysis.

$$\text{Redundancy}_i = \text{Average Variabce Extracted (AVE)}_x \times r_i^2$$

$$\text{Redundancy} = \left(\frac{1}{p}\sum_{j=1}^{p} r_{xj,ui}^2\right) \times r_i^2$$

Where:

p = number of variables in the X set (independent variables)

$r_{xj,ui}$ = correlation between the *j-th* variable in set X and the *i-th* canonical variate u_i

r_i = canonical correlation for the *i-th* canonical function

$$\text{Average Variance Extracted (AVE)}_x = \frac{1}{p}\sum_{j=1}^{p} r_{xj,ui}^2$$

RESULTS AND DISCUSSION

Generally, indicators for agricultural yields of high-value crops such as barley, apple, mango, and sugarcane, were non-normally distributed across the years, suggesting high degrees of skewed production and arguably wider agri-ecological distributions and non-equal adoption of technology. Whereas nearer normal distributions for staple crops such as pulses and milk, suggested wider production and more equal production. A few indicators fish and paddy with samples indicated normality in 2021; however, these with others continue to show the long-standing inequality in yield high-value crops in Nepal's dual agrarian transformation.

Indicators of household's amenities generally reflected for balanced distributions. Basic amenities such as radio, TV, and toilet indicated wide and even coverage in the year 2001. However, "Electricity" and "LP Gas" have moved from near-normality to highly non-normal in later years, which shows that modernization favoured certain districts, creating new inequalities. Overall, while basic amenities normalized, persistent non-normality in modern infrastructure-related variables highlighted uneven spatial development.

The variabilities in agricultural indicators around normality are greater than those of Household Amenities, indicating that economic development diffused into the countryside more uniformly compared to agricultural productivity. A gradual normalizing trend was observed between 2001 and 2021, but persistent non-normality in the distribution of high value crops, energy use, and transport ownership indicates continuing inequality. Negative values for household amenity indicators have been transformed by multiplying them by 1.

Table 1

Sampling Adequacy and Reliability Tests

Domain	Year	KMO (Overall)	Bartlett's χ² (Sig.)	Cronbach's α
Agriculture	2001	0.778	3118.561 ($p < 0.01$)	0.75
	2011	0.765	2180.343 ($p < 0.01$)	0.825
	2021	0.763	2000.161 ($p < 0.01$)	0.767
Household Amenities	2001	0.798	7257.528 ($p < 0.01$)	0.806
	2011	0.794	2726.911 ($p < 0.01$)	0.887
	2021	0.844	2764.154 ($p < 0.01$)	0.752

Table 1 Kaiser–Meyer–Olkin values range from 0.76 to 0.84 for both sectors and census years, ensuring good to very good sampling adequacy for multivariate analysis. Bartlett's Test of Sphericity consistently showed highly significant chi-square statistics for the assumption of sufficient inter-correlations among variables for dimensional reduction.

Cronbach's Alpha coefficients further establish satisfactory to high internal consistency. Agricultural indicators show alpha values between 0.75 and 0.82, while Household Amenities indicators range from 0.75 to 0.89, with 2011 exhibiting excellent internal consistency.

These results affirm the statistical appropriateness of both agricultural and Household Amenities data sets for further factor extraction and composite index construction, which captures meaningful latent dimensions of socio-economic development in Nepal.

Figure-2

Results of Principal Component Analysis of Agriculture Indicators

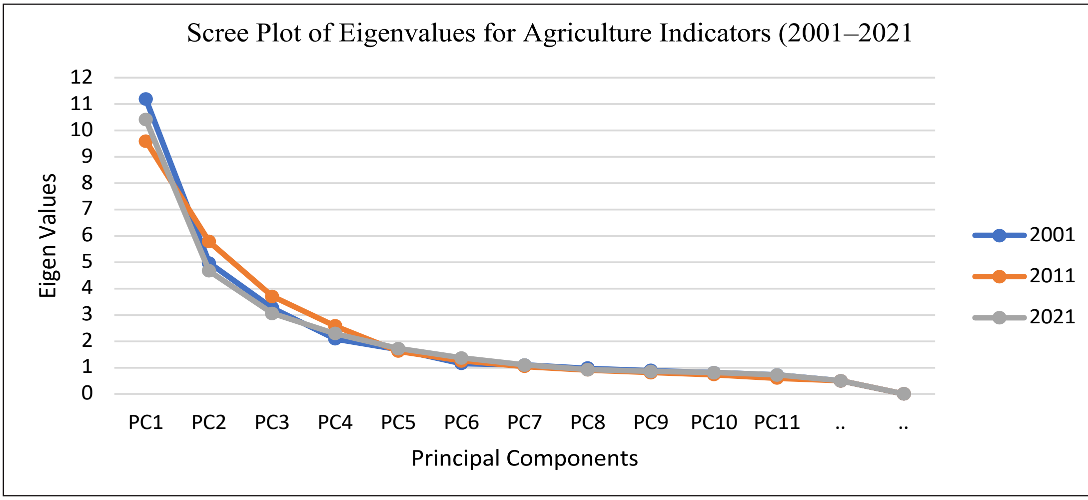
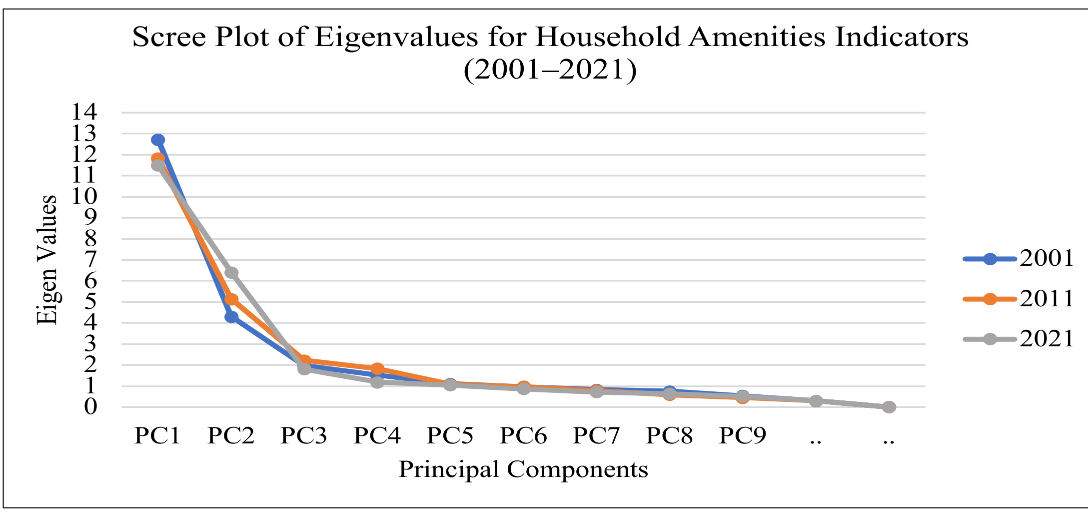


Figure 3

Results of Principal Component Analysis of Household Amenities Indicators



Principal Component Analysis of the agricultural sector for 2001, 2011, and 2021 showed a multivariate and complex structure with a fair variance concentration. The share of variance explained by the first principal component changed between years, for example, being 33.4% in 2001 and 28.7% in 2011. The accumulated share of explained variance of the first three factors varied between 54.2% and 58%. That can be interpreted as increasing diversification, enduring complexity, and structural heterogeneity for the agricultural performance over time.

In contrast, PCA for Household Amenities indicated that the data showed a much more coherent and organized structure, reflected in a stronger concentration of variance within the initial components. PC1 regularly emerged as the strongest, accumulating between 42.0% and 46.5% of the total variance, whereas up to 69.4-72.0% is explained by the first three components together. The unified developmental trajectory is indicated by high correlations among basic amenities and the gradual decrease of spatial disparities.

Comparatively, the agricultural sector turned out to be more structurally complex and variable than Household Amenities, in which PC1 had maintained more stable dominance. The analysis hence indicates that the development trajectory of Nepal from 2001 to 2021 has been characterized by an increasing diversification of factors of influence, reduced regional disparities, and a shift toward multidimensional growth patterns in both sectors.

Table 2

Agriculture Component Loadings

Year	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC10	PC11
2001	AG1 (-0.834), AG2 (-0.65), AG3 (0.522), AG7 (-0.644), AG9 (0.87), AG10 (0.825), AG11 (0.766), AG12 (0.848), AG13 (-0.803), AG14 (-0.66), AG15 (-0.803), AG16 (-0.661), AG17 (-0.643), AG19 (-0.678), AG20 (-0.731), AG21 (-0.734), AG28 (-0.795), AG31 (-0.6)	AG18 (0.566), AG23 (0.727), AG29 (0.524), AG33 (0.683)	AG4 (0.47), AG6 (0.628), AG22 (0.753), AG24 (0.481), AG27 (0.491), AG32 (0.673)	AG30 (0.551)	AG5 (0.632)	AG8 (0.468)	AG25 (0.654)			AG26 (0.527)

2011	AG1 (0.894), AG2 (0.7), AG6 (0.553), AG7 (0.574), AG9 (-0.748), AG10 (-0.618), AG11 (-0.664), AG12 (-0.698), AG13 (0.763), AG14 (0.59), AG15 (0.767), AG16 (0.692), AG19 (0.611), AG21 (0.727), AG28 (0.694), AG31 (0.675)	AG5 (0.579), AG17 (0.574), AG18 (0.65), AG20 (0.533), AG23 (0.732), AG24 (0.671), AG29 (0.602)	AG3 (-0.511), AG4 (-0.577), AG26 (-0.486), AG27 (-0.562), AG33 (0.588)	AG22 (0.718), AG32 (0.718)	AG25 (0.579)	AG30 (0.579)	AG8 (0.54)		
2021	AG1 (0.926), AG2 (0.754), AG4 (0.665), AG6 (0.623), AG7 (0.77), AG9 (-0.778), AG11 (-0.65), AG12 (-0.633), AG13 (0.605), AG14 (0.612), AG15 (0.665), AG16 (0.813), AG17 (0.835), AG19 (0.555), AG20 (0.639), AG21 (0.644), AG28 (0.713), AG31 (0.569))	AG10 (0.553), AG18 (0.47), AG22 (0.583), AG23 (0.655), AG24 (0.813), AG29 (0.591), AG32 (0.62), AG33 (0.671)	AG27 (0.733), AG30 (-0.478)	AG5 (0.559), AG25 (0.573)		AG26 (0.541)		AG3 (0.608)	AG8 (0.53)

The time-series change in the component structure of the agricultural indicators indicates a significant change in Nepal's production trajectory over the past two decades. In the first round in 2001, the first principal component (PC1) highlighted temperate fruit, including apple and peach, compared to tropical fruit and major crops. In 2011 and then again in 2021, PC1 describes the first component of high-yielding tropical crops and livestock. The loading for temperate fruits remained consistently negatively weighted. This behavior also represents a structural change in agricultural productivity toward industry. During this time frame, livestock indicators of milk, meat, and poultry become increasingly present in PC2 from 2001 to 2021.

It reflects the increasing role of livestock in agricultural diversification across districts. Crop-specific components like potato, jute, and millet tend to load on higher-order components Importantly, negative loadings in PC1 should not be interpreted as "adverse" outcomes; rather, they signify an inverse relationship with other indicators—for instance, districts specializing in temperate fruits like apple and peach may naturally show lower production of tropical crops such as mango or banana.

Table-3: *Household Welfare Component Loadings*

Year	PC1	PC2	PC3	PC4	PC5	PC6
2001	HH2 (0.837), HH3 (-0.924), HH4 (0.963), HH5 (0.94), HH6 (0.927), HH7 (0.948), HH8 (0.924), HH10 (-0.674), HH11 (0.718), HH12 (0.901), HH16 (-0.538), HH17 (0.878), HH18 (0.594), HH19 (0.905), HH20 (0.929), HH25 (-0.673), HH27 (0.552)	HH1 (0.819), HH13 (0.767), HH14 (0.683), HH21 (-0.578), HH23 (0.827), HH26 (-0.631)	HH24 (0.756)	HH9 (0.634)		HH15 (0.566), HH22 (-0.552)
2011	HH2 (0.834), HH3 (0.756), HH4 (0.916), HH5 (0.927), HH6 (0.954), HH7 (0.937), HH8 (0.823), HH12 (0.617), HH17 (0.844), HH18 (0.635), HH19 (0.809), HH20 (0.926), HH22 (0.603), HH25 (-0.738), HH26 (0.634), HH27 (0.938)	HH1 (0.705), HH11 (0.644), HH14 (0.808), HH21 (-0.748), HH23 (0.85)	HH10 (0.623), HH13 (0.512), HH15 (0.579), HH16 (0.656)		HH9 (-0.502), HH24 (0.644)	
2021	HH2 (0.815), HH3 (0.846), HH4 (0.936), HH5 (0.915), HH6 (0.903), HH7 (0.96), HH8 (0.707), HH10 (-0.673), HH17 (0.791), HH19 (-0.657), HH20 (0.951), HH23 (0.688), HH25 (-0.67), HH26 (0.651), HH27 (0.957)	HH1 (0.548), HH11 (0.62), HH12 (0.872), HH13 (-0.784), HH14 (0.883), HH15 (-0.666), HH16 (-0.703), HH21 (-0.776), HH22 (-0.635)	HH9 (0.629)		HH24 (0.644)	HH18 (0.513)

The loadings for household well-being consistently reflect the modernization along with persistent structural disparities. PC1 invariably captured modernization, driven advanced assets and modern energy by 2011, incorporated by computer ownership. Conversely, "households without well-being" reliance on traditional resources adverse loaded onto this factor. Reinforcing an urban-affluent versus rural-traditional divide. PC2 and subsequent components reflected the disparities; from an initial focus on basic utilities, PC2 came to include semi-urban/lower-income characteristics. Due to 2021, the sanitation variables had become a differentiating factor.

Notably, the consistent negative loading of "HH by ownership-own" in PC1 suggests that rural ownership does not always relate to higher amenities. Further persistent high loadings of either "no toilet" or "ordinary toilet" in later components is also justified the persistent disparities in sanitation. while PCA indicates a clear modern trajectory in a nutshell, large disparities exist, along with household ownership, access to sanitation and reliance on traditional resources, indicating urban advancement in rural lag of Nepal's development.

Table 4

Canonical Correlation and Wilks' Lambda test Results

Year	Function	Canonical Corr.	Wilks' Lambda	Chi-Sq	*df*	p-value
2001	1	0.936	0.013	295.44	35	<0.01
	2	0.788	0.102	154.11	24	<0.01
	3	0.712	0.269	88.56	15	<0.01
	4	0.61	0.546	40.82	8	<0.01
	5	0.361	0.87	9.42	3	0.024
2011	1	0.904	0.016	280.27	35	<0.01
	2	0.827	0.086	165.33	24	<0.01
	3	0.763	0.273	87.76	15	<0.01
	4	0.562	0.653	28.8	8	<0.01
	5	0.214	0.954	3.15	3	0.369
2021	1	0.929	0.017	284	35	<0.01
	2	0.846	0.123	145.89	24	<0.01
	3	0.667	0.431	58.51	15	<0.01
	4	0.397	0.777	17.54	8	<0.01
	5	0.279	0.922	5.63	3	0.131

The CCA results in Table-4 indicate that, strong and statistically significant relationship between agricultural and household well-being across the three census years. In 2001, this was dominated by the first canonical function in explaining the shared variance, although functions 2–4 were also significant. This pattern essentially held in 2011, except that Function 5 became nonsignificant, so it reduces the weaker dimensions of relationship. By 2021, Function 1 strengthened again to show robust linkages, while functions 2 and 3 retained moderate significance. Fact is, the Function 1 remained dominant across years underlines a strong and persistent structural link between agriculture at district level and household development. Secondary functions reduced in strength or effectiveness over time. It suggests that modernization and urbanization are indeed required the more homogeneous development patterns in Nepal's districts.

Table 5

Canonical Loading of Agriculture Indicators

Canonical Variate	2001 PCs	2011 PCs	2021 PCs
U_1	0.830, 0.525, -0.117, -0.138, 0.025, -0.010, -0.040	0.876, -0.293, -0.165, 0.282, 0.049, -0.120, 0.151	0.933, -0.277, 0.171, 0.046, 0.145, 0.005, -0.044
U_2	-0.454, 0.721, -0.339, 0.302, -0.167, -0.151, 0.135	-0.087, 0.626, -0.038, 0.522, 0.054, -0.486, 0.285	0.122, 0.608, 0.671, 0.044, 0.388, -0.089, 0.072
U_3	-0.262, 0.387, 0.615, 0.562, -0.095, 0.177, 0.222	0.408, 0.506, 0.633, -0.101, -0.214, 0.256, 0.235	-0.290, -0.529, -0.583, 0.404, 0.197, 0.245, 0.372
U_4	0.165, 0.040, 0.654, 0.485, -0.180, -0.153, 0.502	-0.216, -0.268, -0.244, 0.759, -0.100, 0.488, -0.002	0.121, 0.421, -0.227, -0.408, 0.355, 0.090, 0.651
U_5	-0.079, 0.221, 0.128, 0.060, 0.424, 0.841, 0.197	0.076, 0.338, -0.349, -0.141, 0.118, 0.638, -0.564	0.066, -0.271, -0.311, 0.359, -0.527, 0.477, 0.589

Example Formula of Canonical variate (U_1) 2001: $U_1=0.830AGPC_1+0.525AGPC_2-0.117AGPC_3-0.138AGPC_4+0.025AGPC_5-0.010AGPC_6-0.040AGPC_7$

The canonical variate analysis of the agriculture dimension to show a dynamic shift in the interrelationship between agricultural indicators across 2001, 2011, and 2021. In 2001, the first canonical variate (U_1) showed strong loadings on a broad set of yield indicators. Agricultural productivity initially focused on fruits like apple, pear, and peach. This suggests farming relied heavily on fruit and irrigated land. By 2011, farming diversified. It started including fish, coconut, banana, and sugarcane. It shows a shift to mixed farming practices. Strong links between farming indicators (U_1 and U_2) to regional specialization. They also show effective use of resources. In 2021, U_1 showed strong links to both crop yields and livestock. This means farming moved from just growing crops to combining crops and animals. The changing patterns in 2011 to 2021 show more variate and connections in the farming system.

Overall, farming has changed. It moved from depending on land and yields to a more varied and accumulated system. This matches the modern farming trends analysis.

Table 6

Canonical Loading of Household Amenities indicators

Canonical Variate	2001 PCs	2011 PCs	2021 PCs
V_1	-0.632, 0.678, 0.274, -0.217, 0.135	0.875, -0.405, -0.140, 0.194, 0.117	0.688, -0.701, -0.186, 0.005, 0.031
V_2	-0.012, 0.095, 0.717, 0.683, 0.074	0.349, 0.282, 0.268, 0.359, 0.038	0.601, 0.667, 0.333, 0.109, -0.268
V_3	0.666, 0.303, 0.952, 0.448, -0.133	0.042, -0.196, 0.871, -0.207, -0.397	0.336, 0.090, 0.905, 0.241, -0.048
V_4	0.374, 0.649, -0.405, 0.508, 0.132	0.329, 0.260, -0.076, -0.882, 0.200	0.021, 0.098, 0.150, 0.646, 0.742
V_5	-0.130, 0.134, -0.031, 0.152, -0.970	0.046, -0.231, 0.379, 0.118, 0.887	-0.228, -0.216, 0.117, 0.716, -0.612

Example for 2021, V_1: $V_1=0.688HHPC_1-0.701HHPC_2-0.186HHPC_3+0.005HHPC_4+0.031HHPC_5$

This shows that household well fare in Nepal changed significantly over time. In 2001, the data indicated the basic items, like household amenities and electricity, were moderately linked to households. By 2011, there was a clear trend of development become more similar across different areas. It was more households adopted modern facilities, better sanitation, and improved energy sources. As a result, living standards in cities and semi-urban areas became much more alike.

In 2021, a complex structure visibly high but compressed loadings on PC1 and PC2 resulted in the division of various segments of high and low well fare households, with persistent disparities between urban and rural areas.

Table7

Canonical Cross Loading Agriculture PCs and Household Variates

Household Variate	2001 AGPCs	2011 AGPCs	2021 AGPCs
V_1	0.777, 0.491, -0.109, -0.131, -0.027, -0.009, -0.037	0.793, -0.265, -0.149, 0.255, 0.044, -0.108, -0.137	0.866, -0.257, 0.158, -0.042, 0.134, -0.005, -0.041

V_2	-0.358, 0.568, -0.267, 0.237, -0.132, -0.119, 0.106	-0.072, 0.517, -0.032, 0.437, 0.045, -0.402, -0.236	0.104, 0.515, 0.567, 0.037, -0.328, -0.075, 0.061
V_3	-0.186, 0.276, 0.438, -0.400, 0.068, -0.123, -0.158	0.311, 0.386, 0.483, -0.077, -0.163, 0.195, 0.180	-0.194, -0.353, 0.393, -0.152, 0.132, -0.164, 0.248
V_4	0.100, 0.025, 0.399, 0.296, -0.110, -0.093, 0.306	-0.121, -0.151, 0.137, 0.426, -0.056, 0.274, -0.001	0.048, 0.167, -0.090, -0.177, 0.141, 0.035, 0.258
V_5	-0.028, 0.080, 0.045, 0.022, 0.153, 0.304, 0.071	0.016, 0.072, -0.075, -0.030, 0.025, 0.136, -0.120	0.018, -0.075, -0.028, 0.094, -0.147, 0.117, 0.164

The canonical cross-loading analysis between Household Amenity Variates and Agricultural Principal Components from 2001 to 2021 exposes the dynamic evolution in the association between agricultural productivity and rural household welfare. In 2001, the strong positive association of the first household variate with major agricultural components-essentially crops and fruits-indicated a mainly agrarian economy in which amenities were heavily dependent on agricultural wellbeing, though benefits were distributed in a highly unequal manner. By 2011, while the direct positive relation persisted, household variates increasingly shared their variance with livestock and mixed farming, indicating a diversification of the rural economy whereby agricultural gains were becoming more general, even as inequalities persisted. In 2021, the structure was more complex: a modernized and diversified agricultural base, such as broader crops, livestock, poultry, and horticulture, still strongly correlated with V1, but mixed and negative loadings in later variates pointed out the presence of growing disparities and partial decoupling of household welfare from direct agricultural activity. This general tendency indicates a shift away from reliance on agriculture towards a more varied rural economy, where factors outside of farming have a growing impact on the welfare of households. This situation requires integrated development policies.

Table 8

Canonical Cross Loading of Agriculture Variate and Household Welfare PCs

Agriculture Variate	2001 HHPCs	2011 HHPCs	2021 HHPCs
U_1	-0.592, 0.635, 0.257, -0.204, 0.127	0.791, -0.367, -0.127, 0.174, -0.106	0.639, -0.651, -0.173, 0.004, 0.029

U_2	-0.010, -0.076, 0.565, 0.541, 0.0579	0.289, 0.680, 0.222, 0.296, 0.028	0.508, 0.565, -0.281, 0.092, -0.226
U_3	0.474, 0.216, 0.353, -0.319, -0.095	0.031, -0.150, 0.665, -0.158, -0.303	0.224, 0.060, 0.604, 0.161, -0.032
U_4	0.228, 0.400, -0.248, 0.310, 0.080	0.185, 0.147, -0.043, -0.496, 0.112	0.008, 0.039, -0.060, 0.256, 0.294
U_5	-0.047, 0.048, -0.011, 0.055, -0.350	0.010, -0.049, 0.081, 0.025, 0.190	-0.064, -0.060, -0.033, 0.200, -0.171

The canonical cross-loadings indicate a significant change in the links between agricultural development and household modernization over the period from 2001 to 2021. In 2001, there was a weak and inconsistent association reflecting the traditional dominance of rural-urban dualism in which agriculture, as practiced in a traditional way, did not translate into better household amenities. In 2011, linkages were stronger but unevenly, due to agricultural commercialization and irrigation. These were selectively distributed across regions. In 2021, service mediation intensity and non-farm income increased in the relationship between agriculture and household welfare. This suggests that the rural economy is shifting from an agriculture-based economy to one that supports diverse economic activities. As a result, household welfare is no longer determined solely by agricultural production but has become more closely associated with alternative sources of income.

Table 9

Canonical Redundancy Index of Agriculture and Household Amenities Dimensions (2001–2021)

Year	Function	Canonical R^2	Average Square Loading Agriculture	Redundancy Agriculture	Average Square Loading Household Welfare	Redundancy Household Welfare
2001	1	0.877	0.143	0.125	0.200	0.175
	2	0.621	0.143	0.089	0.200	0.124
	3	0.507	0.143	0.072	0.200	0.101
	4	0.372	0.143	0.053	0.200	0.074
	5	0.130	0.143	0.019	0.200	0.026

2011	1	0.818	0.143	0.117	0.200	0.164
	2	0.683	0.143	0.098	0.200	0.137
	3	0.582	0.143	0.083	0.200	0.116
	4	0.316	0.143	0.045	0.200	0.063
	5	0.046	0.143	0.007	0.200	0.009
2021	1	0.863	0.143	0.123	0.200	0.173
	2	0.716	0.143	0.102	0.200	0.143
	3	0.445	0.143	0.064	0.200	0.089
	4	0.157	0.143	0.022	0.200	0.031
	5	0.078	0.143	0.011	0.200	0.016

The redundancy analysis from 2001 to 2021, in its canonical form, shows the evolution of insights into the relationship between agricultural dimensions and household amenities, showing the variance explained by one set in another. In 2001, the first two canonical functions commanded the highest explanatory weight as given by Redundancy values of 0.175 and 0.124, respectively, indicating 17.5% and 12.4% variance explained in household amenities by agriculture. It is suggested that a nascent but irregular association typical in early rural transformation.

By 2011, a stronger, more balanced association emerged, with the first three functions explaining substantial shared variance: Canonical R^2 values of 0.818, 0.683, and 0. 582. This indicated that agricultural dimensions were more systematically related to household modernization possibly due to diversification and infrastructure; however, gaps remained.

In 2021, redundancy values revealed stronger primary associations but diminished marginal effects. While the first two functions had reasonable explanatory capacity, this indicated stronger linkages in circumstances where agricultural modernization co-occurred with improvements in core services. Nevertheless, the steep decline in redundancy of the subsequent functions illustrated the lessening influence of agriculture with a growing diversified set of determinants for rural living standards that included non-agricultural income and digital infrastructure.

While there remained a strong canonical link in total, it was clear that explained variance was becoming concentrated in the first two dimensions. This represented structural consolidation: agriculture remained important but specialized. Outside of the first dominant functions, aside from agriculture's contributions, only diminished explanation of variance remained; rural transition involved agriculture becoming one of many contributors to a semi-structured and multi-sectoral livelihood, and to household well-being more intra-farm viability was derived from studies of non-agriculture determinants.

DISCUSSION

This study demonstrates a strong structural relationship between agricultural productivity and household welfare in Nepal across two decades. Household welfare includes a "Modern Affluence and Digital Integration" axis, driven by advanced assets and digital connectivity, consistent with global trends. Studies in China, Bangladesh, and Ecuador show that digital infrastructure enhances rural welfare by improving income, services, and living standards (Fluhrer & Kraehnert, 2023; Galperín et al., 2022; Hossain & Samad, 2020; Xie & Liu, 2024). However, a persistent "Basic Living Standards and Transitional Housing" axis reveals disparities in basic amenities, especially in semi-urban or rented housing, mirroring uneven rural development elsewhere (Li & Wen, 2023; Pan et al., 2022; System, 2023).

Nepal's agriculture has shifted from traditional temperate fruits to diversified high-yielding tropical crops and livestock integration. This approach boosts livelihoods, food security, and risk mitigation in developing countries (Gautam & Andersen, 2016; Ghosh, 2021; Nepali et al., 2024; Thapa et al., 2017). Redundancy analysis indicates asymmetry: agriculture explains more variance in household amenities than vice versa, underscoring its poverty-reducing impact in agrarian economies (Dangour et al., 2012; García-Cebro et al., 2022; Ligon & Sadoulet, 2017). Evolving canonical cross-loadings signal a diversified rural economy, with non-farm income and services partially decoupling welfare from agriculture—a pattern seen in Bangladesh and Vietnam (Briones, 2017, p. 15; Iqbal et al., 2023, p. 367; Mulia et al., 2021)

CONCLUSION

This study meticulously investigated the bidirectional linkages between agricultural productivity and household welfare in Nepal over two decades, to provide evidence-based policy insights into this critical relationship. By applying a robust multivariate analytical framework, including Principal Component Analysis and Canonical Correlation Analysis, we have revealed the complicated inter-dependencies and dynamic shifts shaping Nepal's socio-economic development.

Our findings consistently demonstrate a strong and statistically significant structural relationship between agriculture and household welfare across all analysed years, with primary canonical correlations persistently above 0.9. This enduring linkage underscores the fundamental connection between the two domains, yet the relationship is asymmetrical. Redundancy analysis revealed that agricultural dimensions explain a greater proportion of variance in household welfare than vice versa. This indicates that improvements in agricultural structure significantly boost household welfare, while enhancements in household welfare yield a weaker impact on agricultural structure.

PCA of household welfare shows a clear path of modernization, more and more influenced by better assets and digital technology, but still highlighted by ongoing disparities in basic living conditions. This dual reality manifests as a "Modern Affluence and Digital Integration" axis alongside a "Basic Living Standards and Transitional Housing" axis, reflecting uneven development: some households rapidly modernize, while others grapple with fundamental amenity gaps, often in semi-urban or rented housing.

Conversely, the agricultural sector exhibits growing structural complexity and diversification over time from a focus on temperate fruits to high-yielding tropical crops and increased livestock integration. Canonical cross-loadings highlight a pivotal transition: from a predominantly agrarian economy, where household amenities were directly tied to agricultural well-being, toward a more diversified rural economy. In this evolving landscape, non-farm income and service mediation increasingly shape household welfare, suggesting a partial decoupling from direct agricultural activity, particularly in later years.

This research provides a comprehensive empirical framework for Nepal's gradual, although uneven, shift from a fragmented agricultural economy to a more connected, multi-sectoral one. The persistent strong canonical link which combined with observed asymmetries and evolving internal structures in both domains underscores the need for integrated development policies. These must foster sustainable agricultural transformation, enhance digital infrastructure nationwide, and address persistent socio-economic disparities in basic amenities and living standards, thereby promoting truly equitable and sustainable national development.

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