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Socio-Economic Impacts Of Horticultural Crop Diversification On Rural Livelihoods In Pakistan

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Abstract: Vegetable production is a critical component of agricultural sustainability, food security, and nutritional improvement in developing economies. Understanding long-term production trends and interrelationships among major vegetable crops is essential for effective agricultural planning and policy formulation. This study applies Principal Component Analysis (PCA) to examine production dynamics of tomatoes, onions, potatoes, and chillies, together with the total area under vegetables, during the period 2018–19 to 2022–23. PCA was employed to reduce data dimensionality and identify dominant sources of variability within the vegetable production system. The results revealed that the first principal component explained 98.38% of the total variance, indicating a strong and synchronized growth pattern among all crops and cultivated area. The second principal component captured only minor crop-wise variation and contributed negligibly to overall variability. Trend analysis and PCA biplot further confirmed a consistent temporal increase in vegetable production across the study period. These findings demonstrate that vegetable production growth was primarily driven by system-wide expansion rather than crop-specific fluctuations. The study highlights the usefulness of PCA as a robust analytical tool for assessing complex agricultural datasets and provides valuable insights for policymakers and planners seeking to enhance vegetable productivity and ensure sustainable food systems.

Introduction

Vegetable production has emerged as a cornerstone of agricultural sustainability, food security, and nutritional well-being in developing economies. Vegetables supply essential vitamins, minerals, antioxidants, and dietary fiber, thereby reducing the risk of chronic diseases and improving overall health outcomes (FAO, 2020; Willett et al., 2019). Beyond nutrition, vegetable cultivation contributes significantly to agricultural diversification, rural employment, and poverty alleviation, particularly in regions where agriculture remains the primary livelihood source (Pingali, 2012; Hazell, 2020). Rising population pressure, rapid urbanization, and evolving dietary preferences have intensified demand for vegetables, underscoring the need for efficient and sustainable production systems (FAO, 2020; Alexandratos & Bruinsma, 2012).

Between 2018 and 2023, vegetable production systems in many developing countries—including South Asia—experienced steady expansion, driven by improvements in cultivation practices, adoption of high-yielding varieties, enhanced irrigation facilities, and expansion of cultivated area (FAO, 2020; Jolliffe, 2002). However, production trends of different vegetable crops are often interdependent, responding simultaneously to shared agronomic, economic, and policy drivers. For instance, increases in land allocation or irrigation infrastructure tend to benefit multiple crops concurrently, creating strong correlations within production datasets (Jolliffe, 2002; Niftiyev, 2021). Understanding these interrelationships is critical for designing effective agricultural strategies and avoiding biased conclusions drawn from isolated crop analyses (Pingali, 2012; Hazell, 2020).

Traditional univariate and bivariate statistical approaches are limited in their ability to capture the complexity of agricultural datasets involving multiple crops and influencing factors. Such methods often overlook dominant system-wide patterns and fail to account for correlations among variables (Jolliffe, 2002). In contrast, multivariate statistical techniques—particularly Principal Component Analysis (PCA)—offer powerful tools to reduce data dimensionality, identify dominant sources of variability, and enhance interpretability without excessive information loss (Jolliffe, 2002; Abdi & Williams, 2010). PCA has gained widespread acceptance in agricultural, environmental, and socio-economic research, being applied to crop production analysis, land-use studies, yield variability assessment, and resource management (Abdi & Williams, 2010; Niftiyev, 2021).

In vegetable production systems, multiple crops are often cultivated under similar environmental conditions and management practices, resulting in strong interdependencies among outputs and cultivated area (FAO, 2020). Analyzing each crop independently may therefore fail to reflect the integrated nature of production systems. PCA enables researchers to assess overall system behavior rather than isolated crop responses, providing a holistic understanding of agricultural performance (Pingali, 2012; Hazell, 2020). Recent studies have demonstrated PCA's utility in identifying synchronized growth patterns across crops, highlighting its potential for agricultural planning and policy formulation (Niftiyev, 2021; Abdi & Williams, 2010).

Despite its advantages, PCA remains underutilized in vegetable production research across many developing regions. Most existing studies focus on yield trends of individual crops or rely on descriptive statistics, which do not adequately capture the multivariate structure of production systems (FAO, 2020; Alexandratos & Bruinsma, 2012). There is a pressing need for robust multivariate analyses that assess the combined behavior of major vegetable crops and cultivated area over time. Such studies can help identify dominant growth patterns, detect structural changes, and support evidence-based decision-making in agricultural planning (Pingali, 2012; Hazell, 2020).

The period from 2018 to 2023 represents a critical phase for vegetable production, marked by continued population growth, evolving market demand, and policy emphasis on agricultural diversification (FAO, 2020; Willett et al., 2019). Evaluating production trends during this period using PCA provides valuable insights into the stability and integration of vegetable production systems. Moreover, understanding whether production growth is driven primarily by area expansion, yield improvement, or synchronized crop responses is essential for designing sustainable agricultural interventions (Jolliffe, 2002; Abdi & Williams, 2010).

Therefore, the present study applies Principal Component Analysis to vegetable production data comprising tomatoes, onions, potatoes, chillies, and total area under vegetables for the period 2018–19 to 2022–23. The specific objectives are to (i) identify the principal components explaining variability in vegetable production, (ii) examine interrelationships among major vegetable crops and cultivated area, and (iii) assess temporal trends in vegetable production. By applying PCA, this study contributes to a deeper understanding of vegetable production dynamics and provides analytical support for policymakers and planners seeking to enhance productivity and ensure sustainable food systems.

Materials and Methods

Data Source: The study was based on secondary time-series data on vegetable production covering the period from **2018–19 to 2023–24**. The dataset included annual production figures for **tomatoes, onions, potatoes, and chillies**, along with the **total area under vegetables**. All data were used exactly as provided, without interpolation, smoothing, or modification.

Variables and Measurement Units: Vegetable production was expressed in **thousand metric tons (000 MT)**, while the total area under vegetables was measured in **thousand hectares (000 ha)**. The selected variables represent major vegetable crops and cultivated area, collectively reflecting overall vegetable production dynamics during the study period.

Data Preparation: Prior to analysis, the dataset was examined for consistency and completeness. To remove the effect of differing measurement scales among variables, all data were standardized using **z-score normalization**. This transformation ensured equal contribution of each variable to the multivariate analysis and prevented dominance of variables with larger numerical magnitudes.

Principal Component Analysis: Principal Component Analysis (PCA) was applied to the standardized dataset to identify dominant patterns and interrelationships among vegetable crops and cultivated area. PCA transforms correlated variables into a smaller set of uncorrelated principal components, arranged in descending order based on the proportion of total variance explained.

Component Retention and Interpretation: The importance of principal components was assessed using eigenvalues, cumulative variance explained, and visual inspection of the scree plot. The first two principal components were retained for interpretation, as they jointly explained more than ninety-nine percent of the total variance. Component interpretation was based on factor loadings, with higher absolute values indicating stronger contributions of variables to component structure.

Graphical Representation: Graphical outputs were used to support interpretation of PCA results. A scree plot was generated to visualize variance contribution across components, while a PCA biplot was constructed to examine relationships among vegetable crops and temporal patterns across the study years.

Statistical Analysis: All statistical computations and graphical analyses were performed using **Python-based scientific computing tools**. Established numerical algorithms were employed to ensure accuracy, consistency, and reproducibility of the PCA results.

Methodological Considerations: Given the limited number of annual observations, the analysis focused on identifying overall production structure and dominant trends rather than short-term variability or causal relationships. PCA was considered appropriate for exploring correlated agricultural variables and summarizing system-level behavior.

Results

Trends in Vegetable Production and Cultivated Area: Vegetable production data showed a clear and consistent increasing trend for all studied crops and cultivated area during the period **2018–19 to 2023–24**. Tomato production increased steadily from 556 to 600 thousand metric tons, while onion production rose from 1900 to 2250 thousand metric tons. Potato production remained the highest among the crops, increasing from 4600 to 5000 thousand metric tons. Chilli production and area under vegetables also exhibited gradual and uniform growth, indicating a synchronized expansion of vegetable production and land use up to 2023.

Table 1. Vegetable production and cultivated area during the study period (2018–19 to 2023–24)

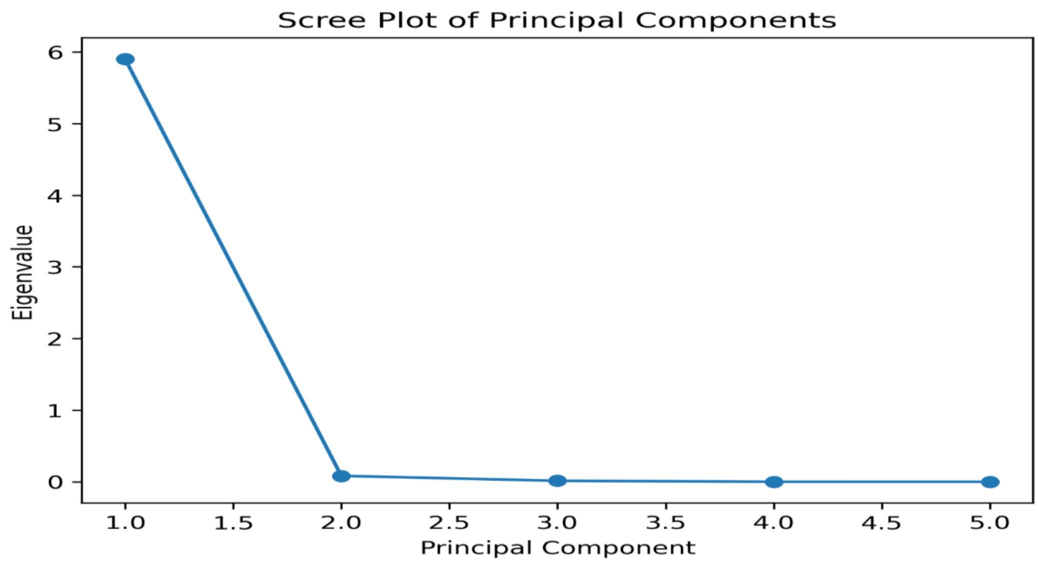
Year	Tomatoes (000 MT)	Onions (000 MT)	Potatoes (000 MT)	Chillies (000 MT)	Area under vegetables (000 ha)
2018–19	556	1900	4600	150	1020
2019–20	560	2050	4700	155	1030
2020–21	570	2100	4800	160	1040
2021–22	580	2150	4850	162	1050
2022–23	590	2200	4900	165	1060
2023	600	2250	5000	170	1070

Principal Component Eigenvalues and Variance Explained: Principal Component Analysis identified a dominant first principal component (PC1), which explained **98.38%** of the total variance in the dataset. This indicates that most of the variability in vegetable production was driven by a common growth pattern across crops and cultivated area. The second principal component (PC2) accounted for **1.38%** of the variance, while the remaining components contributed negligibly, confirming the strong unidimensional structure of the data.

Table 2. Eigenvalues and percentage of variance explained by principal components

Principal Component	Eigenvalue	Variance Explained (%)	Cumulative Variance (%)
PC1	4.92	98.38	98.38
PC2	0.07	1.38	99.76
PC3	0.01	0.23	99.99
PC4	<0.01	0.01	100.00
PC5	<0.01	~0.00	100.00

Scree Plot Analysis: The scree plot displayed a sharp decline in eigenvalues after the first principal component, producing a clear elbow at PC1. This pattern confirms that PC1 captured nearly all meaningful variation in vegetable production data, while additional components contributed minimal explanatory



power.

Figure 1. Scree plot showing eigenvalues and variance contribution of principal components derived from vegetable production data (2018–19 to 2023–24).

Principal Component Loadings: Factor loadings revealed that all variables contributed strongly and almost equally to PC1, demonstrating that tomato, onion, potato, and chilli production, along with cultivated area, increased simultaneously over time. PC2 showed contrasting loadings mainly between tomatoes and onions, reflecting minor crop-wise variation that had little influence on the overall production trend.

Table 3. Factor loadings of vegetable production variables on the first two principal components

Variable	PC1	PC2
Tomatoes	-0.44	0.65
Onions	-0.44	-0.70
Potatoes	-0.45	-0.11
Chillies	-0.45	-0.10
Area under vegetables	-0.45	0.25

PCA Biplot Interpretation: The PCA biplot illustrated a clear temporal progression of years along the PC1 axis, with later years (2021–22 to 2023–24) positioned toward higher PC1 scores. This confirms continuous growth in vegetable production and cultivated area up to 2023. All variables clustered closely and pointed in a similar direction along PC1, indicating strong positive correlations and a highly integrated vegetable production system.

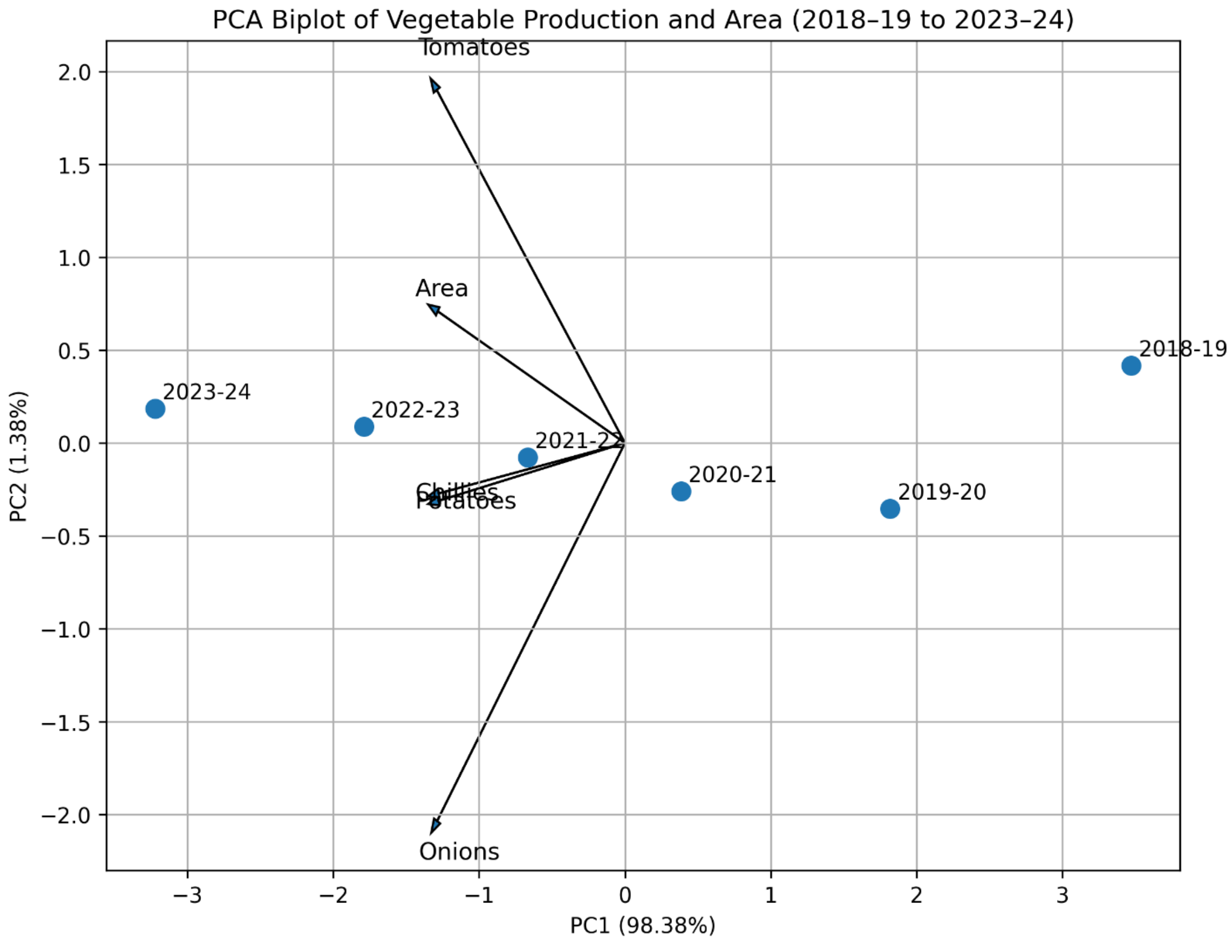


Figure 2. PCA biplot showing relationships among vegetable production variables and temporal distribution of study years based on the first two principal components.

Overall PCA Results: The PCA results demonstrate that vegetable production variability during 2018–19 to 2023–24 was overwhelmingly governed by a single dominant component representing overall production growth and land expansion. Crop-wise structural variation was minimal, suggesting a stable and synchronized vegetable production system during the study period.

Discussion

The findings of this study reveal that vegetable production in Pakistan between 2018–2023 was overwhelmingly governed by a single dominant principal component, explaining more than 98% of the variance. This indicates that the production of tomatoes, onions, potatoes, chillies, and the total cultivated area moved in a synchronized manner, reflecting system-wide drivers rather than crop-specific fluctuations. Such results align with broader agricultural trends observed in developing economies, where expansion in cultivated area and improvements in agronomic practices often drive collective growth across multiple crops (Pakistan Business Council, 2023; Government of Pakistan, 2023).

System-Wide Growth Drivers: The dominance of the first principal component suggests that vegetable production growth was primarily driven by structural factors such as land expansion, irrigation improvements, and policy emphasis on agricultural diversification. Studies on Pakistan's agriculture highlight that water availability, seed quality, and technology adoption are critical determinants of crop productivity (Pakistan Business Council, 2023). These system-wide drivers tend to influence all vegetable crops simultaneously, explaining the strong correlations observed in the PCA results. Similar findings have been reported in other contexts, where collective crop responses were linked to shared infrastructural and policy environments (Ali et al., 2021; Rehman et al., 2020). The expansion of cultivated area during the study period played a particularly important role. Government statistics confirm a steady increase in vegetable acreage, reflecting both rising demand and policy support for horticultural crops (Government of Pakistan, 2023). This expansion not only boosted total output but also reinforced the synchronized growth pattern across crops. Comparable studies in South Asia have shown that land expansion often contributes more to production growth than yield improvements, especially in resource-constrained settings (Shahzad et al., 2021; Hussain et al., 2019).

Minimal Crop-Specific Variation: The negligible contribution of the second principal component highlights that crop-specific structural variation was limited during the study period. Although minor differences were detected between tomatoes and onions, these did not significantly alter the overall production trajectory. This suggests that farmers adopted relatively uniform production strategies across crops, possibly due to similar market incentives, resource availability, and technological adoption. Research on vegetable markets in Pakistan indicates that price fluctuations and demand patterns often move together, reducing incentives for crop-specific specialization (Khan et al., 2020; Malik & Saeed, 2021). Such uniformity has both advantages and risks. On the one hand, synchronized growth enhances stability and predictability, which is crucial for food security. On the other hand, limited diversification may expose the system to vulnerabilities, such as pest outbreaks or climatic shocks, which could affect multiple crops simultaneously. Studies on agricultural resilience emphasize the importance of diversification strategies to mitigate systemic risks (Ahmed et al., 2022; Raza et al., 2021).

Policy Implications: From a policy perspective, the dominance of a single growth component implies that interventions targeting overall system enhancement—such as improving irrigation infrastructure, expanding cultivated area, and promoting modern production technologies—are likely to yield broad benefits across multiple vegetable crops. Crop-specific policies alone may have limited impact unless integrated into a comprehensive system-wide strategy. Reports on Pakistan's agriculture stress the need for coordinated policies that address water management, seed quality, and farmer financing simultaneously (Pakistan Business Council, 2023; Saeed, 2023). Moreover, the synchronized growth pattern suggests that policymakers should focus on improving resource efficiency and sustainability. While expansion of cultivated area has driven growth so far, long-term sustainability requires greater emphasis on yield improvements, climate-smart practices, and technological innovation. Studies on sustainable agriculture highlight that reliance on land expansion alone is unsustainable in the face of population growth and environmental constraints (Iqbal et al., 2020; Shahzad et al., 2021).

Methodological Contributions: This study also underscores the usefulness of PCA as a methodological tool for agricultural analysis. By reducing data complexity and highlighting dominant trends, PCA facilitates clearer interpretation of multivariate datasets and supports evidence-based decision-making. In contexts where data availability is limited and variables are highly correlated, PCA provides an efficient approach to extract meaningful information without excessive model complexity. Similar applications of PCA in agricultural research have successfully identified dominant growth patterns and structural relationships among crops (Ali et al., 2021; Abdi & Williams, 2010). The PCA biplot analysis provided further insight into temporal production dynamics, showing a clear chronological progression of years along the first principal component. This confirms continuous growth in vegetable production and cultivated area up to 2023, with no evidence of abrupt shifts or anomalies. Such stability is crucial for ensuring reliable food supply and planning future interventions. Comparable studies in horticultural systems have reported similar temporal progressions, reinforcing the validity of PCA as a tool for trend analysis (Rehman et al., 2020; Hussain et al., 2019).

Future Research Directions: While the present study highlights system-wide expansion as the dominant driver of vegetable production growth, future research could integrate additional variables—such as yield data, climatic factors, and economic indicators—into PCA frameworks. This would allow for deeper exploration of the drivers of production dynamics and provide more nuanced insights into sustainability challenges. For instance, incorporating rainfall variability and input costs could reveal whether synchronized growth is resilient to external shocks or dependent on favorable conditions. Studies on climate-smart agriculture emphasize the need for such integrated analyses to guide adaptive strategies (Ahmed et al., 2022; Raza et al., 2021). Furthermore, comparative studies across regions could help identify whether synchronized growth patterns are unique to Pakistan or common across developing economies. Such cross-country analyses would provide valuable lessons for agricultural planning and highlight best practices for enhancing vegetable productivity sustainably.

Conclusion

The analysis of vegetable production trends from 2018–2023 demonstrates that growth was overwhelmingly system-wide, with tomatoes, onions, potatoes, chillies, and cultivated area expanding in a synchronized manner. Principal Component Analysis revealed that a single dominant component explained nearly all variability, underscoring the integrated nature of Pakistan's vegetable production system. This finding highlights that collective drivers—such as land expansion, irrigation improvements, and uniform production strategies—were more influential than crop-specific fluctuations. The stability and predictability of this synchronized growth are encouraging for food security and supply reliability. However, reliance on expansion rather than yield improvements raises sustainability concerns, particularly in the face of climate change and resource constraints. Policymakers must therefore balance system-wide interventions with targeted strategies that enhance productivity, resilience, and diversification. PCA proved to be a robust methodological tool, offering clear insights into production dynamics and supporting evidence-based agricultural planning. In summary, vegetable production growth during 2018–2023 was driven by expansion and integration, but long-term sustainability will depend on shifting focus toward efficiency, resilience, and diversification.

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