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Research Article

Assessing Tomato Market Outlets Efficiency in Andhra Pradesh, India - Evidence from PCA-DEA Analysis

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Abstract

The study aims to evaluate and compare the marketing efficiency of five tomato marketing channels—local wholesalers, Rythu Bazars, processors, retail malls, and restaurants—in terms of net price realization for smallholder farmers in Andhra Pradesh. A two-stage sampling framework was employed, selecting Ananthapuramu district due to its prominence in tomato cultivation and further narrowing the focus to Kalyanadurgam and Settur mandals. A total of 300 smallholder tomato farmers (each with landholding ≤2 hectares) were selected, with 60 farmers representing each marketing channel. Data are collected through structured surveys and official secondary sources. Principal Component Analysis findings reveal distinct structural patterns across channels, with the number of significant principal components varying accordingly. Local wholesalers and processors exhibit ten principal components, capturing 70.66% and 70.95% of variance, respectively, indicating structured market behaviour. Rythu Bazars, characterized by direct producer-to-consumer transactions, demonstrate eleven principal components explaining 76.39% of variance, suggesting greater heterogeneity in pricing mechanisms and operational dynamics. Retail malls and restaurants, with ten principal components each, account for 71.09% and 70.56% of variance, respectively, reflecting structured market behaviour and dominant procurement strategies. Findings from Data Envelopment Analysis revealed significant efficiency disparities among the five marketing channels. Retail malls (Channel 4) emerge as the most efficient channel, with a mean Variable Returns to Scale Technical Efficiency score of 0.982, while local wholesalers (Channel 1) register the lowest efficiency (0.918) due to resource misallocation and intermediary costs. Scale efficiency analysis indicates that Channels 1 and 2 (local wholesalers and Rythu Bazars) exhibit increasing returns to scale, suggesting potential efficiency gains through capacity expansion. Overall, retail malls and Rythu Bazars demonstrate higher efficiency scores, ensuring better price transparency and reduced intermediary costs. The study underscores the need for enhanced infrastructure, digital market integration, producer cooperatives, and cold storage facilities to improve market access and efficiency.

Keywords

Smallholders, Market Channels, Factor Loadings, Scale Efficiency, Digital Inclusion, Price Realization

1. Introduction

Tomatoes remain a vital crop globally, playing an essential role in food security, enhancing nutritional value, and supporting rural economies. Grown extensively across various nations, including China, India, Turkey, United States, Egypt, Italy, and Mexico, tomatoes are integral to both domestic consumption and international trade. India, in particular,

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stands as the second-largest producer, producing over 20 million tonnes of tomatoes in TE 2023. India's tomato cultivation spanned an area of 0.85 million hectares with an average yield of 24.56 tonnes per hectare [1]. Within India, Madhya Pradesh emerges as the leading tomato producer, contributing 16.4 per cent to national production in 2023-24. Andhra Pradesh follows closely, securing second place with 11.4 per cent of India's total tomato output during the same period [2].

Market dynamics governing vegetable distribution are undergoing profound transformations worldwide, propelled by the emergence of innovative linkages connecting farmers with processors, retail establishments, and institutional buyers. In the United States, digital platforms are fundamentally altering conventional sales structures, fostering direct interactions between producers and consumers. Advanced technologies like big data analytics, blockchain applications and Internet of Things are improving supply chain efficiency, improving transparency and strengthening traceability mechanisms. Europe is witnessing a surge in digital integration within agricultural commerce, enabling producers to access sophisticated market systems. Accelerated adoption of digital platforms facilitates seamless supply chain optimization, fortifies market linkages, and augments competitive positioning. Meanwhile, China is experiencing an unprecedented expansion in e-commerce applications within vegetable trade, with online-to-offline food delivery models rapidly capturing market share. Increasing consumer inclination toward digital purchasing is amplifying demand for direct farm-to-household supply chains. Within Andhra Pradesh, India particularly in Ananthapuramu district, smallholder farmers are actively engaged with direct marketing avenues, circumventing conventional intermediaries. Processors, retail outlets, and restaurants are demonstrating heightened interest in procuring locally sourced produce, thereby diversifying sales opportunities for small-scale cultivators. Despite the momentum gained by modernized marketing strategies, traditional sales channels continue to dominate transactions, reflecting an ongoing coexistence between legacy distribution networks and contemporary commercial models.

Smallholders encounter formidable constraints when attempting to access remunerative markets, consequently restricting income potential and long-term economic viability. Substantial transaction costs—including expenses associated with transportation, buyer identification, and price negotiations—coupled with logistical inefficiencies and inadequate storage infrastructure, significantly diminish net earnings [3]. Limited asset endowments, characterized by constrained land holdings, insufficient irrigation facilities, and inadequate post-harvest management, further impede productivity and market competitiveness [4]. Infrastructural deficiencies exacerbate these challenges, exacerbating post-harvest losses and heightening dependency on intermediaries who frequently dictate unfavourable pricing structures [5]. Information asymmetry further weakens bargaining power, rendering producers vulnerable to income volatility. Consequently, market channel selection assumes strategic importance in ensuring profitability and resilience. Given the perishable nature of tomatoes, logistical considerations, fluctuating demand patterns, and prevailing pricing structures must be meticulously evaluated before determining optimal marketing avenues.

Local wholesale markets enable rapid disposal of produce, yet farmers often encounter exploitative pricing mechanisms imposed by intermediaries. Prices tend to be suppressed under presumptions of inferior quality, limiting profit margins and financial security. Although Rythu Bazars provide direct marketing avenues, several structural and operational constraints hinder their efficacy. Limited market infrastructure, inadequate storage facilities, and price fluctuations pose challenges, while logistical bottlenecks and inconsistent consumer footfall restrict sales volumes [6]. Additionally, farmers navigating these platforms often struggle with price volatility, lack of institutional support, and insufficient market intelligence, affecting decision-making and income stability. Within this evolving landscape, Farmer Producer Organizations (FPOs) emerge as pivotal institutions fostering collective empowerment, cost efficiencies, and enhanced price realization. By consolidating production and streamlining distribution, these entities enable smallholders to negotiate better terms, access modern value chains, and secure remunerative returns. Strengthened market positioning facilitates seamless integration with processors, retail malls, and restaurant chains, mitigating risks associated with dependence on singular distribution networks. Expanding engagement with contemporary marketing frameworks fosters broader economic participation, promoting financial viability and sectoral competitiveness. By leveraging institutional support, infrastructure enhancements, and digital market linkages, smallholder cultivators can transcend traditional constraints, unlocking pathways to sustainable growth and long-term economic prosperity.

Existing research had extensively explored factors influencing farmers' market channel choices, primarily focusing on socio-economic determinants, access to market information, and infrastructural constraints. Studies have predominantly examined parameters such as education levels, landholding size, institutional support, and transaction costs that influence selection patterns. However, these studies often overlook a critical dimension—marketing efficiency. A substantial research gap exists in evaluating the comparative marketing efficiency of different marketing channels in terms of price realization. Solely identifying determinants of market channels participation does not sufficiently inform strategies for maximizing profitability. Analyzing marketing efficiency across different marketing channels provides deeper insights and enables identification of optimal pathways that yield superior economic outcomes for producers. Given rising integration with modern retail systems, processors, and restaurants, comprehensive framework assessing marketing

efficiency is essential.

In this context, the present study was undertaken to conduct a comparative evaluation of marketing efficiency across various distribution channels, including local wholesalers, Rythu Bazars, processors, retail malls, and restaurants. The primary objective is to systematically assess the relative effectiveness of these channels in terms of net price realization of smallholder tomato farmers. Findings from this research will contribute to strategic interventions that enhance farmer participation in remunerative markets, promote sustainable commercialization, and strengthen supply chain efficiencies. Ultimately, the study aspires to guide stakeholders in fostering a more equitable, transparent, and economically viable marketing landscape for agricultural producers.

2. Review of Literature

Recent studies have provided in-depth insights into the efficiency of agricultural marketing channels, highlighting key determinants of farmer profitability, supply chain performance, and market integration. [7] conducted an empirical study on marketing efficiency in Kolar, India, across four major farming systems—Crop + Sheep, Crop + Dairy, Crop + Dairy + Horticulture, and Crop + Dairy + Sericulture—using Shepherd's and Acharya's methods. Their findings indicated that government procurement through Agricultural Produce Market Committees (APMCs) was the most efficient channel for selling finger millet, whereas direct farmer-to-consumer transactions played a dominant role in sheep marketing. The study also identified price fluctuations, inadequate market information, and high transportation costs as critical challenges, emphasizing the need for infrastructural improvements and intermediary reductions to enhance farmer profitability and income stability. Similarly, [8] examined institutional reforms in India's agricultural supply chains, focusing on the revisions to the APMC Act, including the Model APMC Act of 2003, which introduced private markets, direct purchase centers, contract farming, and public–private partnerships. The study demonstrated that these reforms significantly enhanced spatial efficiency in staple crop markets, particularly for rice and wheat, and recommended further infrastructural developments to improve market integration and supply chain performance. Expanding on marketing structures, [9] conducted a comparative analysis of organized retail collection centers versus traditional marketing channels for vegetable farmers in Ranga Reddy district, Telangana. The study revealed organized collection centers provided greater marketing efficiency, reinforcing the importance of improved post-harvest management strategies to enhance farmer income in contrast to traditional markets. Similarly, further exploring price variations across marketing channels, [10] analyzed the impact of different sales outlets on the prices received by farmers, utilizing farm-level data. The study found that selling through mandis allowed local crop producers to secure price premiums ranging from 13 per cent to 73 per cent compared to private traders. However, high-value crop producers received lower prices in mandis, illustrating need for differentiated marketing strategies rather than one-size-fits-all approach. Complementing these findings, [11] examined factors influencing farmers' selection of agricultural marketing channels, particularly among garden pea producers in India. The research identified household characteristics such as education, income, farming experience, access to storage facilities, and market information as significant determinants in marketing channel choices. The study also highlighted that direct marketing channels provided higher gross and net marketing margins for farmers, reinforcing their economic advantage over intermediary-heavy alternatives. Recognizing the complexity of agricultural marketing, [12] proposed an innovative methodology to assess marketing efficiency by incorporating all stakeholders within the marketing system. Using primary data from Delhi's agricultural markets, the study emphasized the necessity of a comprehensive evaluation framework that accounts for cooperative societies, intermediaries, processing units, and consumers. The results demonstrated the importance of an integrative approach in assessing and improving marketing channel efficiency.

Beyond India, [13] highlighted about optimizing production and distribution of fresh food that presents a complex challenge due to its perishability and numerous factors influencing efficiency. This study examines 15 prefecture-level cities in China from 2008 to 2020, compiling data on rural economic development and agricultural ecological recovery. Findings indicate a pattern of linear economic growth with regional disparities, as evidenced by the rural economy's composite index, which ranges from 0.422 to 0.622. A mixed-integer programming model is proposed to integrate various constraints, demonstrating that the collaborative planning framework can improve farmers' distribution revenues by 7.98 per cent compared to independent decision-making. Based on multiple decision scenarios, strategic recommendations are provided, emphasizing the need for careful product sorting and bundling, partnerships with reliable logistics services, and timely deliveries. [14] analyzed the distribution channels used by small farms in Eastern Europe, particularly in Moldova, Romania, and Serbia. The study found that smallholder farmers faced considerable marketing constraints due to limited infrastructure and policy support, which significantly impacted market efficiency. The comparative analysis revealed that access to well-integrated supply chains was a crucial determinant of profitability and sustainability for small farms. [15] extended this research by examining pressures on agricultural distribution channels in Europe, identifying a growing shift toward direct sales models. Their study estimated that approximately 15 per cent of European farms now sell over half of their produce through short distribution channels, reflecting a growing producer preference for minimizing intermediary involvement to maximize efficiency and revenue. [16] provided a historical perspective on

transformative role of digital technologies in agricultural marketing. Their research, focusing on West Africa and India, analyzed how mobile phone coverage and e-commerce platforms enhanced producer market access, reduced market failures, and lowered transaction costs by improving price transparency and weakening the monopsony power of traders. The study underscored the revolutionary impact of digital agriculture in enhancing marketing efficiency and farmer profitability.

Collectively, these studies underscore the critical role of institutional reforms, infrastructure enhancement, direct-sales models, and digital integration in improving agricultural marketing efficiency. They emphasize the necessity for targeted policy interventions that consider regional disparities, crop-specific market dynamics, and the transformative influence of technology in agricultural trade. However, despite extensive research on agricultural marketing efficiency, no study has specifically employed the Principal Component Analysis-Data Envelopment Analysis (PCA-DEA) approach to systematically evaluate and compare efficiency levels across diverse marketing channels. Given the complexity and heterogeneity of agricultural markets, a robust methodological framework that integrates dimensionality reduction with efficiency measurement is essential for drawing precise and actionable insights. In this context, the present study fills a critical research gap by leveraging PCA-DEA to assess marketing efficiency across selected channels, offering a more comprehensive and data-driven perspective on performance variations and optimization strategies within the agricultural marketing landscape.

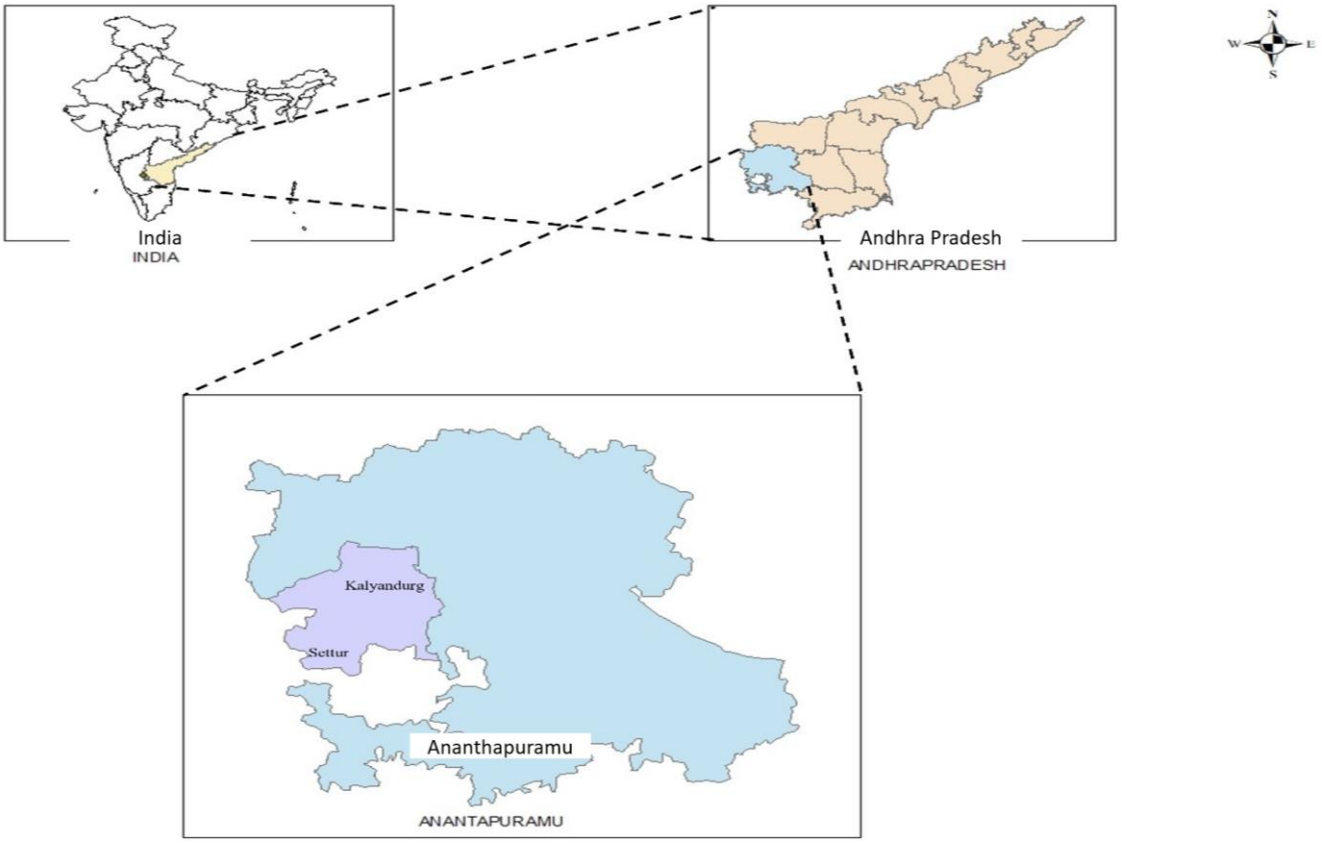

Figure 1. *Location Map of selected mandals in Ananthapuramu, Andhra Pradesh*

3. Methodology

Andhra Pradesh exhibits exceptional potential in tomato cultivation, with several districts maintaining a strong presence in both cultivated area and output. Among the leading regions, Ananthapuramu, Annamayya, and Sri Satya Sai have emerged as significant contributors, particularly following the administrative reorganization and formation of new districts in 2022. Collectively, these districts contribute significantly to market supply, ensuring steady availability while supporting economic sustainability in horticultural development.

3.1. Selection of Sample

Ananthapuramu emerges as a dominant contributor, covering an extensive 0.17 lakh ha hectares in the 2023-24 season, surpassing its five-year average of 0.11 lakh hectares [17]. This district also leads in production, achieving an impressive

output of 7.33 lakh tonnes. Annamayya follows closely, cultivating 0.09 lakh hectares during the same period, a figure slightly below its five-year average of 0.13 lakh hectares. Nevertheless, its production remains substantial, reaching 5.13 lakh tonnes. Sri Satya Sai district, occupying 0.08 lakh hectares, records a total output of 4.39 lakh tonnes, reflecting significant agricultural activity. These three districts, long established as pivotal centers of tomato production, highlight the substantial economic significance of this crop. Historical data further highlights Chittoor's past prominence, maintaining an average cultivation of 0.06 lakh hectares over five years. To ensure a methodologically robust and representative selection of smallholder tomato farmers, a two-stage sampling framework was employed. In the initial phase, Ananthapuramu was purposefully selected for the study considering its prominence in tomato cultivation. Within this district, Kalyanadurgam and Settur mandals, exhibiting the most extensive cultivation areas, were identified as focal study sites. Further refinement led to the selection of two villages per mandal—Palavoy and Kodipalli from Kalyanadurgam, alongside Chintarlapalli and Ayyagarlapalli from Settur (Figure 1). The subsequent stage involved compiling a comprehensive registry of smallholder tomato farmers, specifically those with a landholding size of two hectares or less, derived from official records maintained by the Department of Horticulture in the designated villages. Extensive consultations with local Horticulture Officers indicated that 3,740 smallholder farmers were actively engaged in tomato cultivation and marketing across these locations in 2024. To determine an optimal sample size, [18] formula was applied as follows:

$$n = \frac{N}{1+N(e)^2}$$

where n = sample size, N = target population (3740) and e = margin of error (7%)

$$n = \frac{3740}{1+3740(0.07)^2} = 259$$

Accordingly, a representative sample size of 300 was established, rounded to the nearest hundred for methodological rigor. Tomato cultivation remains instrumental in rural development, fostering employment generation and ensuring a stable income for farming households. However, multiple constraints persist, including escalating transaction costs, volatile pricing dynamics, infrastructural inadequacies, inefficient storage systems, and restricted access to timely and accurate market intelligence, collectively undermining profitability and sustainability [4]. Identifying marketing channels with optimal efficiency becomes imperative to mitigate these challenges and enhance farmer resilience within competitive agricultural markets. In this context, five predominant distribution channels have been identified to analyze smallholder tomato farmers' participation in diverse marketing networks. First, local wholesalers function as intermediaries, procure produce directly from farmers at farm gates, transact in Madanapalle market (Asia's largest tomato market) and Bangalore and ensuring immediate liquidity but often yielding lower margins due to intermediary costs. Second, Rythu Bazars, serve as government-facilitated marketplaces, eliminate middlemen, fostering direct transactions between producers and consumers while enhancing price transparency and ensuring competitive rates. Third, processors (located in Ananthapuramu and Bangalore) represent another critical avenue, converting fresh tomatoes into value-added products such as puree, sauces, and dehydrated goods, stabilizing demand and mitigating post-harvest losses through structured procurement systems. Fourth, retail malls provide an organized marketing framework where farmers establish direct supply relationships with supermarket chains, benefiting from premium pricing and assured procurement while meeting stringent quality and grading standards. Lastly, restaurants offer a direct market through collaborations with farmer collectives, facilitating bulk sales and enhancing traceability—an increasingly valued aspect within hospitality sectors [19, 20]. Sixty farmers from each channel are randomly selected to prioritize efficient channels in transacting tomato [21]. However, due to variations across multiple parameters, these marketing channels require a standardized set of criteria for meaningful comparison. Based on preliminary discussions with local horticultural farmers, 23 common indicators have been identified (Table 1). Each channel is assessed according to these predefined criteria, incorporating both quantitative and qualitative variables. Qualitative variables are ranked on a scale from 0 to 1, where a higher value signifies greater intensity of the respective attribute. These assigned values serve as foundational inputs for evaluating the proposed methodology.

Table 1. *Names and definitions of selected variables.*

Factor	Abbreviation	Description	Unit of measurement
Net Price Received	NPR	Net Price Received by the farmer in transacting produce	Rs/qtl
Land Holding Size	LHS	Land holding under tomato cultivation	Acreage

Factor	Abbreviation	Description	Unit of measurement
Distance	DIST	Physical distance from farm to transaction point	Kilometers
Marketable Surplus	MBLS	Actual quantity sold in the market by the farmer	Quintals
Cold Storage Cost	CSC	Cost incurred for storing tomatoes in cold storage facilities	Rs/qtl
Transaction Cost	TC	Expenses related to selling, such as transportation, handling, loading and unloading etc	Rs/qtl
Quality & Grading of Produce	QP	Extent of sorting, grading, and quality control measures applied before sale	0 – 1 scale*
Market Linkages & Contract Farming	ML	Farmer's access to organized market channels and contract farming agreements	0 – 1 scale
Access to Market Information	AMI	Availability and utilization of market-related data for pricing and demand trends	0 – 1 scale
Prompt Payment of Sales Proceeds	PPSP	Timeliness of payments received from buyers after selling produce	0 – 1 scale
Storage Facility	SF	Availability and adequacy of on-farm or off-farm storage structures	0 – 1 scale
FPO Membership	FPOM	Farmer’s membership in a FPO for collective benefits	0 – 1 scale
Delivery Time	DT	Time taken from harvesting to final delivery at the market or buyer	0 – 1 scale
Consumer Preferences for Organic Food	CP	Influence of consumer demand for organic tomatoes on farmer’s sales	0 – 1 scale
Price Volatility	PV	Degree of fluctuation in market prices affecting farmer earnings	0 – 1 scale
Inventory Costs	IC	Costs associated with holding unsold stock, including wastage	0 – 1 scale
Quantity Loss	QL	Loss of tomatoes due to spoilage, mishandling, or delayed sales	0 – 1 scale
Quality of Roads Infrastructure	RI	Condition and accessibility of roads affecting transportation efficiency	0 – 1 scale
Bargaining Power	BP	Farmer’s ability to negotiate better prices and terms with buyers	0 – 1 scale
Digital Integration	DI	Use of digital platforms and mobile applications for trading and market access	0 – 1 scale
Market Financing	MF	Availability of credit, loans, and financial support for production and marketing	0 – 1 scale
Intermediary Influence	II	Extent of dependence on middlemen in the supply chain and their impact on profits	0 – 1 scale
Climate-Resilient Practices	CRP	Adoption of techniques that enhance resilience to climate variability and risks	0 – 1 scale
Changing Retail Structures	CR	Impact of evolving retail trends, such as supermarkets and e-commerce, on sales	0 – 1 scale

Note: - *values represent scores for each channel according each indicators (parameters) on 0-1 scale

3.2. Data

This research relied on both primary and secondary data sources. Primary data collection involved administering a pre-tested survey schedule through face-to-face interviews with smallholder tomato farmers across selected locations. To ensure relevance, validity, and reliability, an initial pilot survey was conducted with 30 respondents in Settur mandal of Ananthapuramu. Insights derived from this preliminary exercise facilitated necessary refinements, enhancing the overall effectiveness of the structured schedule. Secondary data was sourced from official records, including publications from Directorate of Economics and Statistics of Andhra Pradesh, and statistical handbooks specific to Ananthapuramu.

3.3. Analytical Framework

3.3.1. Descriptive Statistics

These were utilized to summarize and elucidate the characteristics of household attributes marketing facilities and services. Key indicators included percentages, means and Coefficient of Variation (CV).

3.3.2. Principal Component Analysis (PCA)

This was employed to mitigate multicollinearity among determinants shaping smallholder farmers' selection of tomato marketing channels. Multiple variables under consideration are consolidated into a reduced set of principal components, capturing essential patterns while enhancing analytical precision. Let $X = (X_1, X_2, \dots, X_p)'$ represent variables under discussion, while $F = (F_1, F_2, \dots, F_m)'$ denote extracted primary components or factors, $\varepsilon = (\varepsilon_1, \varepsilon_2, \dots, \varepsilon_p)'$ signifies residual items. The factor loading matrix, denoted as A, where a_{ij} represents individual factor loads, establishes the connection between observed variables and underlying factors. This relationship can be formally expressed through Equation (1), providing a structured representation of how factors influence variables of interest:

$$\begin{cases} X_1 = a_{11}F_1 + a_{12}F_2 + \cdots + a_{1m}F_m + \varepsilon_1 \\ X_2 = a_{21}F_1 + a_{22}F_2 + \cdots + a_{2m}F_m + \varepsilon_2 \\ \cdots\ \cdots \\ X_p = a_{p1}F_1 + a_{p2}F_2 \dots + + a_{pm}F_m + \varepsilon_p \end{cases}, A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1m} \\ a_{21} & a_{22} & \dots & a_{2m} \\ \cdots & \dots & \ddots & \dots \\ a_{p1} & a_{p2} & \dots & a_{pm} \end{bmatrix} \quad (1)$$

Through PCA, the 23 variables listed in Table 1 are transformed into a smaller set of Principal Components (PCs), each capturing distinct dimensions of influence. These components are categorized as different factors reflecting key determinants in DEA to ascertain marketing efficiency in terms of NPR by sample farmers across different marketing channels. PCs represent uncorrelated linear combinations, ordered by variance in descending magnitude. [22] introduced additional constraints, ensuring that weight assigned to PC_1 is no less than that of PC_2, weight of PC_2 is no less than that of PC_3, and so forth [23, 24].

3.3.3. Data Envelopment Analysis (DEA)

The component scores obtained from PCA (market channel-wise) are considered as inputs in DEA model to analyze and prioritize marketing channels based on marketing (technical) efficiency (TE) scores. So, PCA - DEA model for Decision-Making Unit (DMU_a) has the following form [25]:

$$\max_{U_{IC}, V_{NC}} U_{PC} Y_{PC}^{a} \quad (2)$$

Subject to:

$$V_{PC} X_{PC}^{a} = 1 \quad (3)$$

$$V_{PC} X_{PC} - U_{PC} Y_{PC} \geq 0 \quad (4)$$

$$V_{PC_i} - V_{PC_{i+1}} \geq 0, \text{ for } i = 1, \dots m-1, \text{ where } mPCs \text{ are analyzed} \quad (5)$$

$$U_{PC_i} - U_{PC_{i+1}} \geq 0, \text{ for } i = 1, \dots m-1, \text{ where } mPCs \text{ are analyzed} \quad (6)$$

$$V_{PC}^{t} L_x \geq 0 \quad (7)$$

$$U_{PC}^{t} L_y \geq 0 \quad (8)$$

$$V_{PC}, U_{PC} \quad (9)$$

V_{PC} and U_{PC} are vector of weights assigned to inputs and outputs PCs, X_{PC} and Y_{pC} indicate input and output matrix, while L_x and L_y relate to matrix of PCA linear coefficients of input and output data [22, 26].

4. Results and Discussion

4.1. Descriptive Statistics

The marketing of tomatoes across various distribution channels—Local Wholesales, Rythu Bazar, Processors, Retail Malls, and Restaurants—exhibits notable differences due to

variations in infrastructure, transaction costs, storage facilities, and market structures (Table 2). The NPR is highest in Channel 4 (Rs. 5022.50) and Channel 5 (Rs. 4400.83), indicating better price realization, while Channel 1 (Rs. 3088.33) has the lowest due to intermediary costs. CV is lowest for Channel 5 (0.08) and Channel 4 (0.13), reflecting stable pricing, whereas Channel 1 (3.19) shows high price volatility. This suggests that structured and direct marketing channels offer higher and more stable returns to farmers compared to local wholesalers. Local wholesale markets primarily serve as intermediaries between farmers and bulk buyers, handling large volumes of produce. However, farmers operating in this channel often experience lower bargaining power and are susceptible to price fluctuations dictated by middlemen. Additionally, lack of organized storage and direct consumer access increases inventory costs and potential losses due to spoilage. In contrast, Rythu Bazar offers farmers a direct-to-consumer platform, reducing intermediary influence and ensuring relatively lower transaction costs. Farmers benefit from immediate payments and greater control over pricing, but demand fluctuations and perishable nature of tomatoes contribute to higher price volatility, requiring efficient inventory management [27, 28]. Processors, who require a steady and high-quality supply, mitigate market fluctuations by engaging in contract farming and offering stable prices. This provides farmers with a sense of security, though they must meet stringent quality and grading standards. Cold storage costs are high in this channel, given the need to maintain quality during transportation and processing. Delivery time also becomes a critical factor, as delays could impact the quality of tomatoes used in processed products. Retail malls and restaurants, catering to urban consumers, emphasize superior quality, consistency, and extended shelf life. Consequently, these channels incur higher transaction and inventory costs due to stricter grading requirements, storage facilities, and logistical challenges. However, they compensate farmers with premium pricing and reliable payments. Access to market information plays a crucial role in all channels, with structured markets such as processors, malls, and restaurants providing better price predictability. Digital integration is increasingly transforming urban markets, offering farmers direct linkages with buyers through online platforms, thereby reducing intermediary influence. The availability of storage facilities and FPO membership enhances farmers' ability to manage supply fluctuations, particularly in organized markets where large-scale operations demand consistent supply. Consumer preferences for organic food are significantly shaping retail and restaurant demand, prompting farmers to adopt better quality control measures. Price volatility remains a persistent challenge, particularly in small, unstructured markets like local wholesales and Rythu Bazar, where seasonal oversupply can lead to drastic price drops. Conversely, processors and retail malls experience relatively stable pricing due to longer-term contracts and structured procurement. Inventory costs and quantity loss further highlight inefficiencies in supply chains, with better infrastructure in structured markets helping minimize post-harvest losses. Transportation efficiency, influenced by road infrastructure quality, plays a key role in determining delivery time and product freshness. Bargaining power varies across channels, with farmers in direct-selling markets like Rythu Bazar exercising more control over prices, whereas those in traditional wholesale markets often face unfavorable pricing due to middlemen's dominance. Market financing, including access to credit and investment opportunities, impacts farmers' ability to scale operations, with organized channels offering better financial support. Climate-resilient practices and evolving retail structures, such as supermarkets and e-commerce, are shaping long-term trends by offering structured pricing, reduced wastage, and direct farm-to-consumer linkages. Thus, while structured channels like processors, retail malls, and restaurants provide stability and higher returns, direct-selling markets such as Rythu Bazar and Local Wholesales remain vital for small farmers despite challenges related to price volatility, infrastructure constraints, and market power dynamics.

Table 2. *Descriptive statistics of variables among selected marketing channels.*

Variables	Channel 1		Channel 2		Channel 3		Channel 4		Channel 5	
	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
NPR	3088.33	3.19	3937.50	1.33	4540.83	0.21	5022.50	0.13	4600.83	0.08
DIST	17.47	0.47	3.80	0.23	40.33	0.67	51.18	0.39	30.68	0.12
LHS	1.71	0.58	2.16	0.47	3.55	0.48	3.76	0.50	3.98	0.50
MBLS	25120.92	0.57	29106.18	0.47	35029.00	0.50	39637.61	0.51	38170.60	0.51
CSC	4.64	0.57	6.65	0.33	12.67	0.38	15.03	0.44	9.06	0.27
TC	19.72	0.27	11.23	0.26	9.10	0.17	61.88	0.12	73.04	0.30
QP	0.25	0.43	0.58	0.21	0.89	0.21	0.84	0.18	0.81	0.24

Variables	Channel 1		Channel 2		Channel 3		Channel 4		Channel 5	
	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
ML	0.22	0.48	0.29	0.28	0.68	0.19	0.78	0.20	0.75	0.26
AMI	0.24	0.47	0.30	0.26	0.67	0.20	0.77	0.21	0.74	0.27
PPSP	0.37	0.45	0.93	0.28	0.84	0.19	0.91	0.19	0.88	0.28
SF	0.35	0.54	0.20	0.43	0.69	0.22	0.71	0.19	0.64	0.27
FPOM	0.39	0.43	0.20	0.41	0.73	0.21	0.77	0.20	0.76	0.26
DT	0.38	0.44	0.46	0.26	0.77	0.20	0.83	0.21	0.86	0.40
CP	0.27	0.43	0.31	0.25	0.72	0.18	0.77	0.22	0.81	0.21
PV	0.64	1.56	0.74	1.45	0.48	0.27	0.53	0.29	0.50	0.29
IC	0.30	0.47	0.44	0.38	0.56	0.27	0.65	0.27	0.69	0.25
QL	0.30	0.48	0.54	0.30	0.35	0.34	0.45	0.29	0.34	0.30
RI	0.28	0.54	0.48	0.31	0.64	0.27	0.65	0.25	0.51	0.25
BP	0.30	0.48	0.24	0.46	0.62	0.27	0.71	0.26	0.74	0.26
DI	0.29	0.49	0.57	0.32	0.66	0.27	0.65	0.26	0.70	0.24
MF	0.30	0.46	0.35	0.32	0.55	0.33	0.65	0.43	0.81	0.41
II	0.70	0.21	0.11	0.45	0.35	0.30	0.25	0.47	0.20	0.43
CRP	0.27	0.40	0.19	0.40	0.77	0.22	0.81	0.17	0.85	0.13
CR	0.23	0.53	0.20	0.43	0.19	0.40	0.83	0.18	0.25	0.42

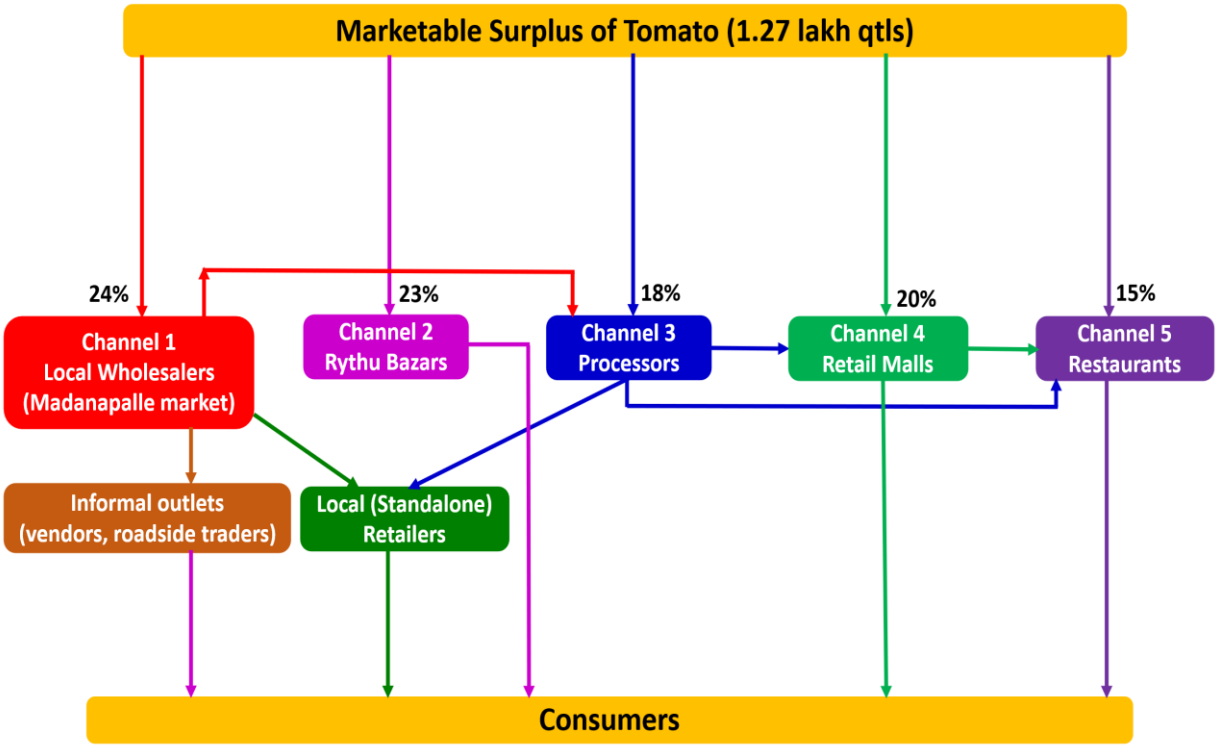

Figure 2. Market channel choices for transacting tomato in Chittoor.

Figure 2 encapsulates the intricate network of market channels facilitating tomato transactions in Ananthapuramu, delineating the allocation of 1.27 lakh quintals of marketable surplus across various intermediaries. Multiple interconnected pathways define the transition of produce from cultivators to end consumers, each exhibiting distinct roles and proportional contributions. Local wholesalers absorb a substantial 24 percent share, serving as pivotal intermediaries by redistributing produce to processors and informal vendors, including roadside traders. Rythu Bazaars account for 23 percent, offering a direct interface between farmers and consumers, thereby fostering accessibility and price efficiency. Processors handle 18 percent of the supply, channelling output towards retail malls and retailers, ensuring further distribution within the market. Retail malls, commanding 20 percent of the total supply, cater to both consumers and restaurants, the latter independently securing 15 percent to maintain a steady influx of high-quality produce. Informal vendors, operating as crucial conduits, enhance consumer accessibility, enabling the last-mile reach of fresh produce. Thus, marketable surplus traverses multiple pathways, illustrating strategic sales optimization by farmers who navigate price differentials, established trade relationships, and shifting demand dynamics. Transactions with processors, retail malls and restaurants reflect efforts to maximize revenue, leveraging price fluctuations and supply chain efficiencies. Procurement by these three agencies directly from producers ensures consistency in quality, volume, and cost-effectiveness. These well-entrenched linkages, reinforced by mutual trust, underpin seamless transactions, timely payments, and an uninterrupted supply chain. Logistical efficiency, storage infrastructure, and processing imperatives significantly shape channel selection, contributing to a flexible and adaptive market framework. The co-existence of formal and informal actors underscores the dynamic nature of tomato marketing, where multiple stakeholders collaboratively optimize distribution while catering to diverse consumer preferences. This inter-connected structure reflects the evolving complexity of market mechanisms, balancing producer interests with consumer demand through strategic trade engagements and well-established supply networks.

4.2. PCA

A comprehensive examination of Appendices 1 and 2 uncovers substantial correlations among selected independent variables, accompanied by elevated Uncentered Variance Inflation Factor (VIF) and Centered VIF values for specific predictors, indicating a pronounced degree of multicollinearity. This statistical challenge necessitated the application of PCA to transform highly collinear variables into a set of orthogonal components while retaining critical informational attributes (Table 3). So, PCA was implemented to generate a factor loading matrix, ensuring that the underlying patterns within the data remain preserved despite the reduction in dimensionality. By leveraging covariance characteristic roots, market channel-wise factors were systematically extracted (Tables 4 to 8), capturing essential structural variations within each distribution channel. This methodological approach enhances interpretability and mitigates distortions arising from multicollinearity, thereby reinforcing the reliability of subsequent econometric modelling and inferential analysis [29].

Table 3. *Channel-wise Number of Significant Components and Variance Explained.*

Market channel	No of Components with Eigen value > 1	Cumulative proportion of Variance explained (%)
Local Wholesaler	10	70.66
Rythu Bazar	11	76.39
Processor	10	70.95
Retail mall	10	71.09
Restaurant	10	70.56

Table 3 highlight the number of significant principal components—those with eigenvalues exceeding unity—identified for each market channel, along with the cumulative proportion of variance they account for in the respective datasets. These findings indicate that the number of significant components varies across different market channels, with eigenvalues surpassing the conventional threshold of one. Local wholesalers exhibit ten principal components, cumulatively capturing 70.66 per cent of total variance, thereby suggesting that a substantial portion of data variability is explained by these extracted dimensions [30, 31]. Similarly, the processor channel also registers ten principal components, explaining 70.95 per cent of variance, reinforcing the effectiveness of dimensionality reduction in capturing influential data patterns within this segment. Rythu Bazar, a distinct marketplace characterized by direct

producer-to-consumer transactions, demonstrates the presence of eleven principal components, cumulatively explaining 76.39 per cent of total variance. This relatively higher proportion suggests that a broader range of latent factors significantly influences structural variations within this channel, possibly due to greater heterogeneity in operational dynamics, pricing mechanisms, and producer-consumer interactions. Retail malls, integral to modern supply chains, manifest ten principal components, explaining 71.09 per cent of variance. The relatively high explanatory power of extracted components within this channel suggests a structured and streamlined market behaviour, where fewer latent dimensions encapsulate complex interrelationships between economic variables. Restaurants, another key market outlet, exhibit a similar pattern, with ten principal components collectively accounting for 70.56 per cent of variance, indicating the presence of dominant factors influencing procurement strategies, cost structures, and consumer preferences within food service operations. The cumulative variance explained across market channels underscores the effectiveness of PCA in transforming multidimensional datasets into interpretable structures while preserving substantial informational content. By systematically reducing data dimensionality while retaining core informational attributes, the extracted components serve as valuable inputs for further empirical investigation and decision-making frameworks across distinct market structures [31].

Marketing Channel I (Farmer-to-Local Wholesaler) operates through distinct structural patterns shaping producer-market interactions (Table 4). Factor analysis highlights the influence of farm scale and market transition, strongly correlated with DIST, LHS, and CR, emphasizing spatial and operational dynamics in market linkages. Consumer choice, aligned with CP, reflects buyer preference-driven demand variations. Supply chain mediation, represented by II, ensures seamless procurement logistics, while inventory and quality control, captured by QP and IC, reinforce product standards. Collective action, indicated by FPOM and BP, strengthens producer bargaining power, while market access and negotiation disparities, correlated with ML, influence price-setting power. Climate-smart adaptation, reflected in CRP, highlights resilience strategies against environmental uncertainties. Supply chain stability, shaped by SF and PV, ensures market continuity, whereas market readiness and post-harvest financial efficiency, signified by PPOS and MBLS, reinforce commercialization preparedness and fiscal prudence [32].

Marketing Channel II (Farmer-to-Rythu Bazar) exhibits structural dimensions centered on farm scale and market supply, with strong correlations to LHS, MBLS, and II, indicating the influence of farm size, marketable surplus, and intermediary mediation (Table 5). Market accessibility and trade efficiency, represented by AMI, INFRA, and RISK, highlight the role of market information, infrastructure constraints, and risk perceptions. Post-harvest losses, shaped by FPOM and CP, emphasize the impact of producer organizations and consumer preferences. Information asymmetry and trade costs, signified by TC, reflect barriers in price transparency and transaction inefficiencies. Sustainable market linkages, structured by PV and CR, underscore resilience amid price volatility. Market dynamics, captured by DI, showcase digital integration's role in improving efficiency, while market reach and inventory costs, linked to DIST and IC, highlight spatial logistics and cost implications. Financial leverage, represented by MF and BP, indicates disparities in access to financing and bargaining power. Storage infrastructure, reflected by SF and CSC, mitigates perishability risks, and trade facilitation, symbolized by ML, strengthens structured market linkages. Revenue generation, signified by PPOS, sustains farmer incomes through prompt sales proceeds [33].

Table 4. *Factor analysis results of variables of Marketing Channel I (Farmer to Local Wholesalers).*

	Factors									
Variables	**Farm Scale & Market Transition**	**Consumer Choice**	**Supply Chain Mediation**	**Inventory & Quality Control**	**Collective Action**	**Market Access & Negotiations**	**Climate Smart Adaptation**	**Supply Chain Stability**	**Market Readiness**	**Post-Harvest Financial Efficiency**
DIST	0.6514									
LHS	0.6502									
MBLS									-0.4213	
CSC										-0.4661
QP				0.6259						
ML						-0.4724				

Variables	Factors									
	Farm Scale & Market Transition	Consumer Choice	Supply Chain Mediation	Inventory & Quality Control	Collective Action	Market Access & Negotiations	Climate Smart Adaptation	Supply Chain Stability	Market Readiness	Post-Harvest Financial Efficiency
PPOS										0.7165
SF								0.5805		
FPOM					-0.6698					
CP		-0.6600								
PV								-0.5218		
IC				0.5453						
BP						0.6562				
II			0.6440							
CRP							0.6919			
CR	0.6514									

Table 5. *Factor analysis results of variables of Marketing Channel II (Farmer to Rythu Bazar).*

Variables	Factors										
	Farm Scale & Market Supply	Market Accessibility & Trade Mediation	Post-Harvest Losses	Information Asymmetry & Trade Costs	Sustainable Market Linkages	Market Dynamics	Market Reach & Inventory Overheads	Financial Leverage	Storage	Trade Facilitation	Revenue
DIST							0.4204				
LHS	0.6603										
MBLS	0.6634										
CSC									0.8076		
TC				-0.5305							
ML										0.4412	
AMI				0.6602							
PPOS											0.837
SF										0.8743	
FPOM					0.4970						
CP					-0.7041						
PV						-0.5547					
IC							0.7937				
RISK			0.8311								
INFRA		-0.5106									

Variables	Factors										
	Farm Scale & Market Supply	Market Accessibility & Trade Mediation	Post-Harvest Losses	Information Asymmetry & Trade Costs	Sustainable Market Linkages	Market Dynamics	Market Reach & Inventory Overheads	Financial Leverage	Storage	Trade Facilitation	Revenue
BP								0.6647			
DI						0.5531					
MF								-0.5079			
II		0.6951									
CR						0.4730					

Table 6. *Factor analysis results of variables of Marketing Channel III (Farmer to Processors).*

Variables	Factors									
	Farm Scale & Market Supply	Eco-Driven Distribution	Information-Driven Bargaining	Cash-Flow Efficiency	FPO-Driven Linkages	Quality	Delivery	Logistics & Warehousing	Risk & Smart Supply Chain	Market Adaptability
DIST		0.5461								
LHS	0.6240									
MBLS	0.6310									
CSC								0.5973		
TC								0.4042		
QP						0.6418				
ML					-0.4834					
AMI			0.5869							
PPOS				0.5763						
SF		0.4426						-0.4309		
FPOM					0.6906					
DT							0.6492			
CP		0.4933								
PV										0.7075
IC				0.4997						
RISK									0.6654	
BP			0.5574							
DI									0.4154	
CR										0.4759

Table 7. Factor analysis results of variables of Marketing Channel IV (Farmer to Retail malls).

Variables	Factors									
	Farm Scale & Market Supply	Eco-Driven Inventory Dynamics	Climate Adaptive Cold Chain	Institutional Financial Access	Market Access	Transport Efficiency	Cash Flow Sensitivity	Retail Logistics & Dynamics	Trade Efficiency	Quality Storage & Management
DIST									-0.4766	
LHS	0.6229									
MBLS	0.6277									
CSC			-0.5523							
TC									0.5993	
QP										0.5251
ML					0.6962					
AMI									0.4494	
PPOS							0.6938			
FPOM				0.5940						
DT								-0.4054		
CP		0.5909								
PV							0.5217			
IC		-0.5411								
RISK										0.5713
INFRA						0.6769				
MF				-0.5875						
CRP			0.6488							
CR								0.7030		

Table 8. Factor analysis results of variables of Marketing Channel V (Farmer to Restaurants).

Variables	Factors									
	Farm Scale & Market Supply	Eco-Market Trade	Transactions Overhead	Financial & Quality Assurance	Digital Retail Dynamics	Collective Climate Resilience	Transport Efficiency	Logistics Efficiency	Storage Infrastructure	Market Accessibility
DIST										0.7520
LHS	0.6546									

Variables	Factors									
	Farm Scale & Market Supply	Eco-Market Trade	Transactions Overhead	Financial & Quality Assurance	Digital Retail Dynamics	Collective Climate Resilience	Transport Efficiency	Logistics Efficiency	Storage Infrastructure	Market Accessibility
MBLS	0.6566									
CSC									-0.5737	
TC			0.6652							
QP				0.4004						
PPOS				0.6234						
SF									0.6503	
FPOM						0.5457				
DT								0.7475		
CP		-0.4393								
IC		0.5051								
INFRA							0.7065			
BP		0.5115								
DI					0.4042					
MF				0.5049						
CRP						0.6342				
CR					0.6864					

Marketing Channel III (Farmer-to-Processor) is shaped by farm scale and market supply, with strong associations to LHS, MBLS, and CP, emphasizing farm size, surplus, and consumer-driven production (Table 6). Eco-driven distribution, structured by AMI, BP, and DIST, underscores market accessibility and producer-buyer relationships. Information-driven bargaining, represented by IC, PPOS, and FPOM, highlights trade optimization through price negotiation and producer organizations. Cash-flow efficiency, signified by ML and DT, ensures financial fluidity in farmer-processor linkages. FPO-driven linkages, captured by QP and FPOM, reinforce collective action in market stability. Quality control, shaped by CSC and TC, emphasizes adherence to processing standards, while delivery logistics, represented by SF, addresses storage challenges and perishability concerns. Logistics and warehousing, correlated with PV and CR, optimize procurement and supply chain management. Risk mitigation and smart supply chain adaptation, indicated by RISK, enhance resilience against market uncertainties, while market adaptability, captured by DI, highlights digital integration in responding to demand shifts [34-37].

Marketing Channel IV (Farmer-to-Retail Malls) reflects structural patterns where farm scale and market supply, signified by LHS, MBLS, and CP, align farm outputs with retail demand (Table 7). Eco-driven inventory dynamics, structured by CRP and CSC, emphasize climate-adaptive procurement and storage strategies. Cold chain infrastructure resilience, captured by INFRA, minimizes wastage and ensures supply chain efficiency. Institutional financial access, represented by MF and FPOM, facilitates stable trade engagements with retail malls, while market access, shaped by ML, supports direct farmer integration into organized retail chains. Transport efficiency, indicated by DIST and DT, influences supply chain continuity and delivery timelines. Cash flow sensitivity, reflected by PPOS and PV, ensures liquidity and smooth financial management. Retail logistics, captured by CR, coordinates procurement, inventory, and product replenishment, while trade efficiency, indicated by TC, minimizes transaction costs. Quality storage and management, represented by QP and RISK, reinforce product quality and market stability through robust storage solutions and risk mitigation strategies [33, 38, 39].

Marketing Channel V (Farmer-to-Restaurants) exhibits structural dimensions where farm scale and market supply, strongly associated with LHS and MBLS, sustain stable supply arrangements (Table 8). Eco-market trade, represented by TC, highlights sustainable procurement and environmentally conscious trade practices. Transaction overhead, captured by

PPOS and QP, reflects price negotiations, order fulfilment, and quality compliance. Financial and quality assurance, signified by FPOM and CR, ensure trade stability and adherence to quality standards. Digital retail dynamics, structured by MF and DI, enhance transparency, direct transactions, and supply chain efficiency. Collective climate resilience, captured by CRP, mitigates climate-induced disruptions, ensuring consistent produce availability. Transport efficiency, represented by DT, addresses logistical constraints in delivery cycles, while logistics efficiency, indicated by SF and DIST, ensures uninterrupted supply. Storage infrastructure, reflected by INFRA, maintains freshness and minimizes food wastage. Market accessibility, captured by CSC, highlights procurement challenges, regulatory constraints, and urban market penetration strategies in restaurant supply chains [40-42].

Thus, the structural components shaping each marketing channel underscore key factors influencing farmer-market linkages, trade efficiency, and market resilience [32, 43-45]. In the Farmer-to-Local wholesaler channel, farm scale, market transition, and consumer choice play a crucial role, with strong correlations to spatial and operational dynamics (DIST, LHS, CR) and demand variations (CP). Supply chain mediation (II), inventory control (QP, IC), and collective action (FPOM, BP) enhance producer leverage, while market access disparities (ML) and climate adaptation (CRP) shape price-setting power and resilience [27, 28, 30]. The Farmer-to-Rythu Bazar channel emphasizes farm scale and marketable surplus (LHS, MBLS, II), with accessibility (AMI, INFRA) and risk perceptions (RISK) affecting trade efficiency. Post-harvest losses (FPOM, CP), trade costs (TC), and sustainable linkages (PV, CR) highlight challenges in transparent pricing, while digital integration (DI) and financial leverage (MF, BP) support revenue stability. The Farmer-to-Processor channel focuses on structured supply arrangements, emphasizing consumer-driven production (LHS, MBLS, CP), eco-driven distribution (AMI, BP, DIST), and bargaining power (IC, PPOS, FPOM). Quality control (CSC, TC), logistics efficiency (SF, PV, CR), and risk adaptation (RISK) ensure market continuity, while financial flows (ML, DT) sustain cash flow efficiency. The Farmer-to-Retail Malls channel highlights climate-adaptive procurement (CRP, CSC), cold chain resilience (INFRA), and financial access (MF, FPOM) in facilitating structured trade. Market access (ML), transport efficiency (DIST, DT), and liquidity management (PPOS, PV) ensure smooth financial transactions, while storage solutions (QP, RISK) support quality assurance. The Farmer-to-Restaurants channel emphasizes marketable surplus (LHS, MBLS), eco-market trade (TC), and transaction overheads (PPOS, QP), with financial stability (FPOM, CR) and digital platforms (MF, DI) streamlining trade. Climate resilience (CRP), logistics coordination (SF, DIST), and storage infrastructure (INFRA) ensure supply reliability, while accessibility constraints (CSC) impact procurement policies. Comparing these channels, Farmer-to-Local Wholesaler and Farmer-to-Rythu Bazar focus more on direct trade and collective bargaining, while Farmer-to-Processor and Farmer-to-Retail Malls emphasize quality compliance, structured financing, and logistics. Farmer-to-Restaurants, though market-driven, integrates digital efficiency and eco-friendly trade [28].

4.3. DEA

In the second phase of DEA, efficiency assessment of marketing channels relies on component scores obtained from first phase of PCA as inputs, with NPR serving as the output [29]. However, certain predicted component scores derived through PCA exhibit negative values across selected channels, complicating direct DEA implementation. Since DEA estimation necessitates covariates that maintain both interpretability and non-negativity, a Min-Max normalization approach—specifically, the Shifting by Absolute Minimum method—is employed to address this challenge. This transformation reconfigures component scores within a standardized range, enhancing coherence and analytical stability. By preserving relative variations inherent in PCA-derived scores while eliminating negative values, this approach ensures their compatibility with DEA, thereby facilitating robust efficiency estimation across marketing channels [46].

Findings from DEA (Table 9) underscore substantial disparities in efficiency across marketing channels, revealing variations in both technical and scale efficiency [47, 48]. Among the evaluated channels, Channel 4 emerges as the most efficient, exhibiting the highest mean Variable Returns to Scale – Technical Efficiency (VRS-TE) score (0.982), which signifies optimal utilization of available resources to generate maximum output. Conversely, Channel 1 records the lowest mean efficiency score (0.918), indicating suboptimal performance in resource allocation and operational execution. Scale efficiency trends align closely with these results, with Channel 4 maintaining superior performance, while Channel 1 demonstrates inefficiencies in scaling operations effectively. Disparities in efficiency levels stem from several underlying structural and operational factors unique to each marketing channel. Channels 1 and 2 exhibit a predominant presence of increasing returns to scale (IRS), suggesting that expanding operational capacity could lead to enhanced efficiency by leveraging economies of scale. This trend suggests that these channels currently operate below their optimal scale and could benefit from further growth to maximize efficiency. In contrast, Channels 3, 4, and 5 display significant instances of decreasing returns to scale (DRS), implying inefficiencies arising from excessive scaling, which may result in diminishing marginal returns due to rising operational complexities, coordination challenges, or resource misallocation. Furthermore, efficiency variations may also be attributed to differences in marketing strategies, infrastructure availability, supply chain integration, and transaction costs. Channels with higher efficiency scores likely benefit from well-structured distribution networks, streamlined logistical frameworks, and

cost-effective transaction mechanisms, whereas those with lower efficiency may experience bottlenecks such as fragmented supply chains, inadequate infrastructure, or higher operational expenditures. These distinctions highlight the necessity of customized strategic interventions tailored to each channel's specific inefficiencies. For channels exhibiting IRS, targeted investments in capacity expansion and technological advancements could enhance efficiency, whereas for those with DRS, refining operational processes, optimizing scale, and minimizing excess capacity could yield better outcomes. By understanding these efficiency patterns, decision-makers can implement precise policy measures and structural reforms to enhance overall marketing channel performance [49, 50].

Table 9. *Scale and Efficiency measures across selected marketing channels.*

Efficiency Scores	Channel 1		Channel 2		Channel 3		Channel 4		Channel 5	
	VRS-TE	Scale	VRS-TE	Scale	VRS-TE	Scale	VRS-TE	Scale	VRS-TE	Scale
1.000	49	26	48	39	48	44	48	45	47	36
0.999 - 0.900	1	14	3	16	3	8	7	11	3	16
0.899 - 0.800	--	9	2	2	4	7	5	3	6	4
0.799 - 0.700	1	2	--	2	2	1	--	1	1	4
0.699 - 0.600	1	4	3	1	3	--	--	--	3	--
0.599 - 0.500	4	3	4	--	--	--	--	--	--	--
0.499 - 0.400	1	2	--	--	--	--	--	--	--	--
0.399 - 0.300	3	--	--	--	--	--	--	--	--	--
Mean	0.918	0.893	0.943	0.973	0.963	0.974	0.982	0.979	0.963	0.967
Constant Returns to Scale (CRS)		26		39		44		45		36
IRS		27		15		5		2		13
DRS		7		6		11		13		11

5. Summary and Conclusions

This study conducted a comparative evaluation of marketing efficiency across five distinct tomato marketing channels—local wholesalers, Rythu Bazars, processors, retail malls, and restaurants—to assess their effectiveness in terms of net price realization for smallholder farmers in Ananthapuramu district, Andhra Pradesh. This research aimed to bridge gap in existing literature to focus on determinants of market channel choices rather than their relative marketing efficiency. A two-stage sampling framework was employed, selecting Ananthapuramu district based on its prominence in tomato cultivation and further narrowing the focus to Kalyanadurgam and Settur mandals. A sample of 300 smallholder tomato farmers (each with landholding ≤2 hectares) was selected, with 60 farmers representing each marketing channel. Both primary and secondary data are employed in this study.

PCA identifies key determinants influencing market efficiency, with the number of significant principal components varying across channels, reflecting distinct structural patterns. Local wholesalers and processors exhibit ten principal components, capturing 70.66 per cent and 70.95 per cent of variance, respectively, indicating substantial data variability. Rythu Bazars, characterized by direct producer-to-consumer transactions, demonstrate eleven components, explaining 76.39 per cent of variance, suggesting greater heterogeneity in pricing mechanisms and operational dynamics. Retail malls and restaurants, with ten principal components each, account for 71.09 per cent and 70.56 per cent of variance, respectively, reflecting structured market behavior and dominant procurement strategies.

Findings from DEA revealed significant efficiency disparities, with Channel 4 (retail malls) emerging as the most efficient (mean VRS-TE score: 0.982), while Channel 1 (local wholesalers) records the lowest efficiency (0.918), highlighting resource misallocation and operational constraints. Scale efficiency trends align closely, with Channels 1 and 2 exhibiting increasing returns to scale (IRS), suggesting efficiency gains through capacity expansion, while Channels 3, 4, and 5 display decreasing

returns to scale (DRS), indicating inefficiencies due to excessive scaling and coordination challenges. These findings underscore the need for tailored interventions—capacity expansion and technological investments for IRS channels, and process optimization for DRS channels—to enhance marketing efficiency. The study confirms that marketing efficiency varies significantly across channels, with some offering better price realization and reduced transaction costs. Among the five channels, retail malls and Rythu Bazars exhibited higher efficiency scores, ensuring better price transparency and minimal intermediary costs. Processors and restaurants provided relatively stable pricing, though stringent quality requirements acted as a barrier to farmer participation. Local wholesalers, despite ensuring liquidity, yielded the lowest margins due to intermediary costs and price-setting asymmetries.

So, farmers aiming to maximize profitability should prioritize direct marketing channels such as Rythu Bazars and retail malls, which offer competitive pricing and direct consumer access. Strengthening linkages with processors and restaurants can further enhance market stability, provided farmers meet the necessary quality standards. These findings highlight the need for enhanced infrastructure, digital market integration, and producer cooperatives to improve market access and efficiency. Expanding cold storage facilities, transparent pricing mechanisms, and farmer training programs will further enable smallholder farmers to participate in high-value markets.

While this study provides valuable insights into price realization across different tomato marketing channels, it has certain limitations that warrant further investigation. First, the analysis primarily focuses on efficiency and price realization without considering the impact of seasonality and price volatility, which significantly influence market performance and farmer earnings. Second, the study does not account for farmers' bargaining power, TCs, and institutional constraints, all of which exert a significant influence on profitability dynamics. Third, the findings are based on data from a specific geographic region (Ananthapuramu district), limiting their generalizability to other markets with different structural and operational characteristics. Additionally, while the study employs PCA and DEA to assess market efficiency, it does not integrate qualitative factors such as farmer perceptions, consumer demand shifts, or policy interventions that might affect market outcomes. Future research could address these gaps by incorporating dynamic pricing models, assessing supply chain resilience, and analyzing the role of digital market platforms in enhancing efficiency. Examining contractual agreements with organized retail players and the impact of sustainability and climate risks on marketing efficiency would further enrich the understanding of market stability and farmer resilience. Ultimately, the study underscores the critical role of marketing efficiency in enhancing farmer incomes and promoting sustainable commercialization, offering a roadmap for policymakers and agribusiness stakeholders to optimize tomato marketing channels.

Abbreviations

APMCs	Agricultural Produce Market Committees
CRS	Constant Returns to Scale
CV	Coefficient of Variation
DEA	Data Envelopment Analysis
DMU	Decision-Making Unit
DRS	Decreasing Returns to Scale
FPOs	Farmer Producer Organizations
IRS	Increasing Returns to Scale
PCA	Principal Component Analysis
PCs	Principal Components
TE	Technical Efficiency
VIF	Variance Inflation Factor
VRS-TE	Variable Returns to Scale – Technical Efficiency

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Author Contributions

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Public Interest Statement

This study evaluates the efficiency of different tomato marketing channels in Ananthapuramu district, Andhra Pradesh, focusing on their impact on smallholder farmers' earnings. It highlights how direct-to-consumer platforms like Rythu Bazars and retail malls offer better price realization and transparency compared to traditional wholesale markets. Using advanced analytical methods, the research identifies efficiency gaps and areas for improvement in marketing structures. Findings suggest that farmers can boost profitability by engaging with high-efficiency channels while strengthening ties with processors and restaurants for price stability. The study also emphasizes the need for better infrastructure, digital market integration, and cold storage facilities to minimize losses and improve access. These findings provide valuable guidance for improving farmer incomes and optimizing tomato market operations. Policymakers and agribusiness stakeholders can use these insights to design more efficient and farmer-friendly market systems. Future research could explore supply chain resilience and innovative pricing strategies to strengthen agricultural marketing.

Data Availability Statement

The data for the study is available upon request

Conflicts of Interest

No potential conflict of interest was reported by the author(s).

Appendix

Appendix I: Uncentered VIF

Channel 1: Local Wholesalers			Channel 2: Rythu Bazars			Channel 3: Processors			Channel 4: Retail malls			Channel 5: Restaurants		
Variable	**VIF**	**1/VIF**	**Variable**	**VIF**	**1/VIF**	**Variable**	**VIF**	**1/VIF**	**Variable**	**VIF**	**1/VIF**	**Variable**	**VIF**	**1/VIF**
MBLS	1192.52	0.0008	LHS	3660.37	0.0003	DIST	547.38	0.0018	DIST	559.69	0.0018	LHS	452.88	0.0022
LHS	1167.15	0.0009	MBLS	3596.52	0.0003	MBLS	426.19	0.0023	LHS	369.40	0.0027	MBLS	442.17	0.0023
DIST	299.42	0.0033	DIST	561.34	0.0018	LHS	417.36	0.0024	MBLS	364.60	0.0027	DIST	370.04	0.0027
II	40.75	0.0245	PV	85.70	0.0117	TC	53.14	0.0188	TC	114.37	0.0087	CRP	77.58	0.0129
PV	29.09	0.0344	QP	39.58	0.0253	AMI	52.84	0.0189	CRP	56.99	0.0175	CP	39.70	0.0252
TC	20.96	0.0477	TC	32.47	0.0308	PPSP	49.85	0.0201	CR	55.30	0.0181	IC	35.06	0.0285
CRP	12.67	0.0789	CP	29.71	0.0337	CP	43.01	0.0232	SF	51.38	0.0195	BP	28.72	0.0348
CP	12.14	0.0824	DT	29.46	0.0339	QP	41.61	0.0240	PPSP	45.22	0.0221	QP	28.61	0.0350
FPOM	10.73	0.0932	AMI	25.87	0.0386	FPOM	41.11	0.0243	QP	42.30	0.0236	RI	27.93	0.0358
DT	10.06	0.0994	RI	21.11	0.0474	ML	40.28	0.0248	ML	42.04	0.0238	DI	27.09	0.0369
PPSP	9.48	0.1055	PPSP	20.50	0.0488	SF	39.75	0.0252	FPOM	41.60	0.0240	FPOM	26.79	0.0373
IC	8.88	0.1126	QL	19.76	0.0506	DT	38.80	0.0258	DT	40.95	0.0244	SF	23.83	0.0420
QL	8.42	0.1188	ML	18.83	0.0531	CRP	34.44	0.0290	CP	35.80	0.0279	QL	23.15	0.0432
QP	8.40	0.1190	CRP	16.33	0.0612	BP	27.76	0.0360	AMI	31.73	0.0315	AMI	21.81	0.0458
ML	8.32	0.1201	MF	16.24	0.0616	IC	24.72	0.0405	RI	24.10	0.0415	PPSP	21.11	0.0474
MF	8.14	0.1229	CSC	15.50	0.0645	DI	23.71	0.0422	PV	23.38	0.0428	TC	20.70	0.0483
DI	8.13	0.1230	DI	14.48	0.0691	II	22.27	0.0449	BP	23.33	0.0429	CSC	20.41	0.0490
AMI	7.86	0.1272	IC	12.28	0.0814	RI	21.28	0.0470	IC	23.00	0.0435	PV	18.59	0.0538
CR	7.77	0.1287	FPOM	12.08	0.0828	PV	19.16	0.0522	DI	22.73	0.0440	ML	18.27	0.0547
BP	7.34	0.1362	BP	10.67	0.0938	MF	15.48	0.0646	QL	18.32	0.0546	DT	12.06	0.0829
CSC	7.22	0.1386	II	10.49	0.0953	QL	13.22	0.0756	CSC	10.67	0.0938	MF	10.91	0.0917
RI	5.85	0.1709	CR	10.10	0.0990	CSC	12.44	0.0804	MF	8.93	0.1120	II	10.26	0.0975
sf	4.99	0.2003	SF	8.29	0.1206	CR	10.65	0.0939	II	8.16	0.1225	CR	9.90	0.1010
Mean VIF	125.93		Mean VIF	359.46		Mean VIF	87.67		Mean VIF	87.56		Mean VIF	76.85	

Appendix II: Centered VIF

Channel 1: Local Wholesalers			Channel 2: Rythu Bazars			Channel 3: Processors			Channel 4: Retail malls			Channel 5: Restaurants		
Variable	**VIF**	**1/VIF**	**Variable**	**VIF**	**1/VIF**	**Variable**	**VIF**	**1/VIF**	**Variable**	**VIF**	**1/VIF**	**Variable**	**VIF**	**1/VIF**
MBLS	290.69	0.0034	LHS	655.77	0.0015	MBLS	82.84	0.0121	MBLS	75.14	0.0133	LHS	90.72	0.0110
LHS	286.97	0.0035	MBLS	652.67	0.0015	LHS	77.77	0.0129	LHS	73.19	0.0137	MBLS	89.58	0.0112
PV	1.85	0.5405	CRP	2.24	0.4464	AMI	2.03	0.4926	SF	1.82	0.5495	IC	1.99	0.5025
CP	1.85	0.5405	TC	2.02	0.4950	II	1.84	0.5435	PV	1.8	0.5556	QL	1.89	0.5291
CSC	1.76	0.5682	RI	1.87	0.5348	BP	1.84	0.5435	CSC	1.71	0.5848	BP	1.81	0.5525
II	1.73	0.5780	DT	1.83	0.5464	PPSP	1.79	0.5587	DT	1.67	0.5988	FPOM	1.72	0.5814
CRP	1.73	0.5780	BP	1.83	0.5464	SF	1.78	0.5618	ML	1.67	0.5988	TC	1.68	0.5952
FPOM	1.66	0.6024	PV	1.79	0.5587	QP	1.75	0.5714	DIST	1.67	0.5988	RI	1.67	0.5988
CR	1.66	0.6024	II	1.75	0.5714	FPOM	1.68	0.5952	CR	1.65	0.6061	DT	1.63	0.6135
DT	1.61	0.6211	FPOM	1.74	0.5747	CRP	1.63	0.6135	CP	1.63	0.6135	SF	1.61	0.6211
IC	1.59	0.6289	CP	1.7	0.5882	DI	1.63	0.6135	CRP	1.55	0.6452	CP	1.6	0.6250
PPSP	1.56	0.6410	AMI	1.66	0.6024	DIST	1.63	0.6135	TC	1.55	0.6452	MF	1.57	0.6369
QL	1.56	0.6410	QP	1.57	0.6369	IC	1.62	0.6173	FPOM	1.54	0.6494	QP	1.57	0.6369
DIST	1.56	0.6410	QL	1.56	0.6410	CSC	1.57	0.6369	IC	1.53	0.6536	II	1.56	0.6410
DI	1.56	0.6410	CR	1.53	0.6536	MF	1.49	0.6711	PPSP	1.5	0.6667	PPSP	1.5	0.6667
ML	1.54	0.6494	CSC	1.53	0.6536	TC	1.46	0.6849	II	1.44	0.6944	AMI	1.48	0.6757
TC	1.43	0.6993	IC	1.53	0.6536	CR	1.45	0.6897	DI	1.43	0.6993	DI	1.47	0.6803
AMI	1.42	0.7042	DIST	1.53	0.6536	ML	1.45	0.6897	BP	1.42	0.7042	CR	1.45	0.6897
MF	1.4	0.7143	PPSP	1.49	0.6711	RI	1.45	0.6897	QL	1.38	0.7246	PV	1.4	0.7143
BP	1.38	0.7246	MF	1.45	0.6897	DT	1.43	0.6993	RI	1.37	0.7299	CRP	1.36	0.7353
QP	1.31	0.7634	DI	1.36	0.7353	QL	1.36	0.7353	MF	1.36	0.7353	DIST	1.36	0.7353
RI	1.31	0.7634	ML	1.35	0.7407	CP	1.33	0.7519	AMI	1.32	0.7576	CSC	1.34	0.7463
SF	1.12	0.8929	SF	1.3	0.7692	PV	1.28	0.7813	QP	1.28	0.7813	ML	1.14	0.8772
Mean VIF	26.53		Mean VIF	58.39		Mean VIF	8.44		Mean VIF	7.85		Mean VIF	9.27	

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