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Agrarian Transformation and Smallholder Adaptation in Kerala's Vegetable Economy

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Abstract

Kerala's vegetable economy has undergone substantial agrarian transformation during the past three decades as technological innovation, institutional restructuring, climate adaptation and market integration have progressively reshaped smallholder agriculture. Existing scholarship has largely examined these dimensions independently, leaving limited understanding of how their interaction influences the restructuring of vegetable production and rural livelihoods. This study investigates agrarian transformation in Kerala's vegetable economy through an interdisciplinary documentary analysis that synthesises official statistics, Agricultural Census reports, Kerala State Planning Board publications, Department of Agriculture Development and Farmers' Welfare reports, Kerala Agricultural University publications, district agricultural contingency plans, Vegetable and Fruit Promotion Council Keralam (VFPCCK) documents and contemporary empirical research. Documentary evidence was comparatively analysed under five analytical dimensions: structural transformation, technological modernization, climate adaptation, institutional transformation and market integration. The findings show that Kerala's vegetable economy has shifted from dispersed homestead cultivation to a more organised production system supported by coordinated institutional intervention, scientific farming and decentralised agricultural governance. The predominance of small and marginal holdings has directed modernization towards intensive cultivation, protected agriculture, precision farming and resource-efficient production rather than large-scale mechanisation. Climate variability has accelerated the integration of adaptive farming practices with institutional support systems, while market restructuring through producer organisations, decentralised marketing networks and value-chain initiatives has strengthened the participation of smallholders in organised agricultural markets despite persistent disparities in infrastructure and regional implementation. The analysis demonstrates that agrarian transformation in Kerala is driven less by technological change alone than by the institutional integration of technology, ecological adaptation and market governance within a smallholder production system. By advancing an integrated analytical framework linking structural change, adaptive capacity and livelihood resilience, the study contributes to contemporary debates on sustainable agricultural transformation in environmentally vulnerable smallholder economies.

Keywords: Agrarian Transformation; Agricultural Modernization; Vegetable Farming; Climate Resilience; Institutional Transformation

1. INTRODUCTION

Agrarian transformation has become one of the defining features of contemporary rural development as agricultural systems respond to rapid technological change, environmental uncertainty, market restructuring and institutional reform [1]. Across much of the developing world, agriculture is no longer interpreted solely through the expansion of production or the adoption of improved technologies; rather, it is increasingly understood as a process through which changing production relations, resource use, public policy and rural livelihoods are continuously reconfigured [2]. These transformations have assumed particular significance in regions dominated by smallholder agriculture, where technological innovation, ecological constraints and institutional capacity collectively shape the sustainability of agricultural development [3]. Consequently, agricultural modernization is increasingly recognised as a

multidimensional process embedded within broader social, economic and environmental transformations rather than a simple transition towards technologically intensive farming.

This changing understanding has substantially influenced contemporary agrarian scholarship. Earlier modernization paradigms largely associated agricultural progress with mechanisation, improved seed varieties, irrigation expansion and increased use of external inputs [4]. But the recent studies emphasise that technological innovation produces highly differentiated outcomes depending upon institutional arrangements, ecological conditions, market structures and farmers' adaptive capacities [5]. Agricultural change is therefore interpreted as a negotiated process in which scientific innovation interacts with local knowledge, public institutions and environmental conditions to generate multiple pathways of rural transformation. This perspective has broadened the analytical focus of agrarian studies from production growth towards questions of resilience, sustainability, institutional governance and livelihood security.

These debates have particular relevance in India, where agriculture continues to support millions of rural households while simultaneously experiencing profound structural transformation. Although the Green Revolution substantially increased agricultural productivity through technological intensification, subsequent decades exposed important structural challenges associated with declining operational holdings, labour shortages, rising production costs, environmental degradation, groundwater depletion and increasing climatic variability [6]. In response, agricultural policy has progressively shifted towards climate-resilient farming, integrated nutrient management, precision agriculture, digital extension, natural farming and diversified production systems that seek to reconcile productivity with environmental sustainability and livelihood security [7]. This transition reflects a broader reorientation of agricultural development in which resilience and resource efficiency have become as important as production growth.

Kerala provides a particularly significant setting for examining these changes because its agricultural development differs markedly from that of many other Indian states [8]. Agriculture is characterised by fragmented operational holdings, diversified cropping systems, intensive homestead cultivation and relatively strong public institutional support [9,10]. Simultaneously, demographic transition, labour migration, urban expansion, changing food consumption patterns and increasing demand for fresh vegetables have accelerated diversification towards horticulture while exposing farming communities to greater climatic and market uncertainty [11]. Official policy has responded through sustained investments in protected cultivation, precision farming, micro-irrigation, integrated crop management, digital extension, organised farmer collectives and decentralised agricultural governance. Together, these interventions have reshaped the organisation of vegetable production across the state, although their adoption and outcomes remain uneven because of variations in agroecological conditions, institutional capacity and market accessibility.

Kerala's diverse agroecological settings—including the below-sea-level farming systems of Kuttanad, the coastal landscapes of Alappuzha, the homestead agriculture of the midlands and the commercial vegetable-producing regions of central and northern Kerala—illustrate that agricultural modernization follows regionally differentiated pathways shaped by ecological conditions, institutional capacity and market integration. Recurrent floods, rainfall variability, seasonal water stress and emerging pest dynamics have expanded the role of public institutions such as the Department of Agriculture Development and Farmers' Welfare, Kerala Agricultural University, the Vegetable and Fruit Promotion Council Kerala (VFPC), Krishi Bhavans, Farmer Producer Organisations and Kudumbashree in promoting technological innovation, climate adaptation and value-chain development. Yet, despite a substantial body of research on agricultural modernization, climate resilience, institutional development and rural transformation, these dimensions have largely been examined in isolation. Existing studies predominantly rely on farm-level surveys or technology-specific analyses, with limited attempts to integrate official statistics, policy documents, institutional reports and empirical evidence into a comprehensive explanation of how technological modernization, institutional transformation, environmental adaptation and market restructuring collectively shape agrarian transformation within Kerala's vegetable economy. This study addresses that gap through an interdisciplinary documentary analysis of these interconnected processes.

This study addresses these limitations through an interdisciplinary documentary analysis of agrarian transformation in Kerala's vegetable sector. Drawing upon official statistics, Agricultural Census reports,

Kerala State Planning Board publications, Department of Agriculture Development and Farmers' Welfare documents, Kerala Agricultural University research, Indian Council of Agricultural Research technical reports, district agricultural contingency plans, Vegetable and Fruit Promotion Council Kerala publications and peer-reviewed empirical studies, the study examines how technological innovation, institutional transformation, climate adaptation and market integration collectively shape contemporary agricultural change. By integrating perspectives from agrarian political economy, rural livelihood analysis, agricultural innovation systems, institutional theory and socio-ecological resilience, the article argues that agricultural modernization in Kerala is best understood as a multidimensional process in which technological progress derives its developmental significance through continuous interaction with public institutions, ecological adaptation and evolving rural markets. In doing so, it contributes to a more integrated understanding of agrarian transformation and provides an evidence-based framework for analysing sustainable agricultural development in smallholder farming systems.

2. AGRARIAN TRANSFORMATION AND AGRICULTURAL MODERNIZATION: REVIEW OF LITERATURE

Agrarian transformation has occupied a central place in rural scholarship because it provides the principal analytical framework for understanding how technological change, institutional restructuring, market expansion and ecological processes reshape agricultural production and rural society. Classical agrarian studies interpreted modernization largely as a structural transition characterised by changes in land tenure, labour organisation, commercialisation and capital accumulation, assuming that technological progress would progressively replace traditional farming systems. Subsequent scholarship has questioned this deterministic interpretation by demonstrating that agrarian change is neither linear nor uniform but evolves through historically contingent interactions among ecological conditions, institutional arrangements, public policy and farmers' adaptive responses. Rather than representing a universal pathway towards industrialised agriculture, modernization increasingly appears as a differentiated process in which multiple forms of production coexist, adapt and evolve within changing rural economies.

This reconceptualisation is particularly evident in studies of rural livelihoods and peasant adaptation. Scoones [12], through the Sustainable Rural Livelihood Framework, shifted analytical attention from agricultural production alone towards the assets and capabilities that enable rural households to respond to economic and environmental uncertainty. Ellis [13] further demonstrated that rural livelihoods increasingly depend upon diversified income strategies in which agriculture functions alongside non-farm employment, migration and local enterprise, making livelihood security inseparable from broader processes of rural transformation. Building upon these perspectives, van der Ploeg [14] rejected the assumption that modernization inevitably eliminates peasant agriculture, arguing instead that contemporary farming systems emerge through continuous negotiation between market forces, technological innovation and local autonomy. Bernstein [15] likewise emphasised that agrarian transformation is fundamentally political, reflecting unequal access to land, labour, capital, markets and institutions. Collectively, these studies reposition agrarian change as a dynamic process shaped simultaneously by structural conditions and local agency, providing a broader conceptual foundation for analysing agricultural modernization beyond technological determinism.

This shift in agrarian thinking has significantly influenced the study of agricultural innovation. Early diffusion research conceptualised technological adoption primarily as an individual decision based upon perceptions of relative advantage and compatibility. Rogers' Diffusion of Innovations [16] remains influential in explaining how communication, social networks and innovation characteristics influence adoption behaviour. However, empirical studies increasingly demonstrated that adoption decisions cannot be understood independently of structural conditions. Feder et al. [17] showed that farm size, access to credit, extension services, education and institutional support frequently determine technological uptake more strongly than the technical characteristics of innovations themselves. Extending this perspective, Hall et al. [18] proposed the Agricultural Innovation Systems (AIS) framework, arguing that innovation emerges through interactions among research institutions, extension agencies, governments, markets, private enterprises and farming communities rather than through the linear transfer of scientific knowledge. Agricultural modernization is therefore increasingly interpreted

as an institutional process in which knowledge generation, dissemination and adaptation occur through collaborative networks rather than isolated technological interventions.

Growing concern over the ecological consequences of input-intensive agriculture has further transformed debates on agricultural modernization. Early evaluations of agricultural success were largely confined to productivity and economic growth, but contemporary scholarship increasingly incorporates environmental sustainability, social equity and long-term resource conservation into assessments of agricultural performance. Andreoli and Tellarini [19] argued that agricultural sustainability should be evaluated through integrated economic, environmental and social indicators rather than production alone. Similar conclusions emerged from Singh et al. [20], Gómez-Limón and Sánchez-Fernández [21] and Dantsis et al. [22], all of whom demonstrated that multidimensional sustainability indicators provide more robust assessments of agricultural systems than conventional productivity measures. Pretty [23] likewise argued that sustainable agricultural intensification depends upon improving ecological functions while maintaining productive capacity, whereas Magdoff [24] emphasised that long-term agricultural resilience requires ecological management rather than continued dependence on external inputs. Together, these studies redefined modernization as a process that must reconcile productivity with environmental integrity and social sustainability.

These debates have generated extensive empirical research comparing conventional, organic and natural farming systems. Eyhorn et al. [25] demonstrated that organic cotton cultivation in India can remain economically viable when supported by institutional arrangements, certification systems and favourable market conditions. Ramesh et al. [26] similarly concluded that organic agriculture possesses considerable potential for improving soil quality, biodiversity conservation and environmental sustainability, although productivity outcomes vary across agroecological settings. Comparative studies undertaken by Patil et al. [27] revealed that neither conventional nor organic systems are inherently superior; rather, sustainability depends upon local ecological conditions, management practices and institutional support. Rao [28] highlighted the expanding policy significance of organic farming while identifying certification, market access and extension services as persistent barriers to wider adoption. Garibaldi et al. [29] further demonstrated that diversified farming systems simultaneously enhance biodiversity, food security and rural livelihoods, strengthening resilience under environmental stress. More recent research has extended this discussion towards institutional innovation and behavioural change. Khadse et al. [30] interpreted agroecological transitions in India as collective social movements rather than purely technological innovations, while Kumar et al. [31] emphasised that adoption of natural farming depends upon extension support, knowledge dissemination and institutional capacity. Recent contributions by Malhan and Ram [32], Koner et al. [33] and Muthana et al. [34] similarly indicate that farmers' perceptions, social enterprises, policy incentives and post-pandemic institutional reforms increasingly shape the trajectory of sustainable agricultural modernization.

Within Kerala, scholarship has documented substantial changes in agricultural production arising from land fragmentation, labour scarcity, demographic transition, climate variability and the diversification of cropping systems. Publications of the Kerala State Planning Board, Kerala Agricultural University, the Department of Agriculture Development and Farmers' Welfare and the Vegetable and Fruit Promotion Council Kerala consistently demonstrate that vegetable cultivation has become an increasingly important component of the state's agricultural strategy through the expansion of protected cultivation, precision farming, integrated nutrient management, micro-irrigation, organised farmer collectives and decentralised extension systems. Technical studies undertaken by Kerala Agricultural University further report that location-specific production technologies, scientific water management and integrated crop protection have improved production stability under highly diverse agroecological conditions. Parallel evidence from district agricultural contingency plans illustrates considerable spatial variation in climate risks, resource availability and adaptive strategies, reinforcing the importance of region-specific institutional responses to agricultural modernization. Collectively, these studies suggest that Kerala's vegetable economy is being transformed through the simultaneous interaction of technological innovation, institutional coordination and climate adaptation rather than through technological diffusion alone.

Despite these advances, important analytical limitations remain. Existing research has generally examined technological adoption, protected cultivation, organic farming, climate adaptation, institutional support or agricultural marketing as separate themes, while relatively few studies have investigated how

these processes interact to reshape agrarian structures within Kerala's vegetable economy. Equally, most empirical investigations rely on farm-level surveys, technology assessments or programme evaluations, with limited attempts to synthesise official statistics, policy documents, institutional reports and empirical research into a comprehensive explanation of agrarian transformation. Consequently, the cumulative relationships among technological modernization, institutional change, environmental adaptation and market restructuring remain insufficiently integrated within existing scholarship. The present study addresses this gap through an interdisciplinary documentary analysis that brings together official datasets, policy evidence and empirical research to explain how these interconnected processes collectively shape agrarian transformation and rural livelihood resilience in Kerala's evolving vegetable sector.

3. THEORETICAL AND CONCEPTUAL FRAMEWORK

Agricultural modernization among smallholder farmers is a multidimensional process shaped by economic structures, technological innovation, institutional arrangements and environmental change. Understanding this complexity requires an integrated theoretical framework that explains how farmers respond to changing production environments while maintaining sustainable livelihoods. Accordingly, this study draws upon complementary perspectives from agrarian political economy, rural livelihood studies, agricultural innovation systems, diffusion of innovation, adaptive capacity, socio-ecological resilience and institutional theory to develop a comprehensive analytical framework.

Agrarian political economy provides the broad structural perspective for examining how technological modernization is embedded within wider processes of agrarian transformation, market integration and changing rural production relations. Rather than treating technological change as an autonomous process, this perspective emphasises the influence of landholding patterns, market forces, state intervention and resource access on farmers' production decisions. Complementing this structural approach, the Rural Livelihood Framework conceptualises farming households as combining multiple assets, capabilities and livelihood strategies to cope with economic and environmental uncertainties. Livelihood outcomes therefore depend not only on productive resources but also on institutional support, knowledge networks and the capacity to respond to external shocks.

The Agricultural Innovation Systems perspective further extends this understanding by recognising innovation as an interactive process involving research institutions, extension agencies, government departments, farmer organisations, markets and local communities. Technological change is therefore viewed as the outcome of collaboration and knowledge exchange rather than the simple transfer of technologies. Similarly, Diffusion of Innovation Theory explains variations in farmers' adoption of improved seeds, protected cultivation, precision farming, micro-irrigation, integrated nutrient management and digital advisory services, highlighting the importance of perceived benefits, compatibility with existing practices, institutional communication and social networks in influencing adoption behaviour.

The framework also incorporates Adaptive Capacity Theory and the concept of socio-ecological resilience to explain farmers' responses to climate variability, floods, droughts, pest outbreaks and market fluctuations. These perspectives recognise adaptation as a continuous process through which farming households reorganise production systems, utilise indigenous knowledge and adopt new technologies to maintain livelihood security under changing environmental conditions. Institutional Theory complements these approaches by emphasising the role of formal organisations, extension systems, government programmes, farmer collectives and policy interventions in shaping agricultural decision-making and facilitating technological transformation.

Drawing upon these theoretical perspectives, the study conceptualises agricultural modernization as an integrated process in which institutional support, technological innovation, climate adaptation, farm management practices and market integration collectively strengthen farmers' adaptive capacity. Enhanced adaptive capacity is expected to improve farm performance through increased productivity, resource-use efficiency and risk management, which in turn contributes to more resilient and sustainable rural livelihoods. The conceptual framework therefore positions adaptive capacity as the central mechanism linking modernization processes with long-term livelihood resilience, providing the analytical foundation for examining smallholder vegetable farming across Kerala.

4. MATERIALS AND METHODS

This study adopts an interdisciplinary documentary research design based on the systematic analysis and synthesis of secondary data to examine the processes of agrarian transformation and agricultural modernization in Kerala's vegetable sector. The research is positioned within the tradition of documentary social research, where official statistics, institutional reports, policy documents and published empirical studies constitute the primary evidence for analysing long-term structural change. This approach is appropriate because the study seeks to explain statewide agrarian transformation across multiple institutional, ecological and temporal contexts rather than evaluate a single programme or farm-level intervention.

The analysis focuses on Kerala, with particular attention to the principal vegetable-producing districts of Thiruvananthapuram, Kollam, Alappuzha, Kottayam, Ernakulam, Palakkad, Kozhikode and Kasaragod, which collectively represent the state's major coastal, midland and highland agroecological regions. Alappuzha receives additional analytical emphasis because its below-sea-level Kuttanad farming system, recurrent flooding, coastal agriculture and integrated water-management practices provide an important context for examining climate adaptation and institutional responses within ecologically vulnerable agricultural landscapes.

Document identification was undertaken through a systematic search of official institutional repositories, government statistical publications, policy reports, organisational databases and academic literature. Searches employed combinations of keywords including *Kerala vegetable cultivation*, *vegetable production Kerala*, *horticulture*, *agricultural modernization*, *agrarian transformation*, *climate adaptation*, *protected cultivation*, *farmer producer organisations*, *value chains*, *agricultural policy Kerala*, *horticultural statistics*, and *vegetable marketing*. Documentary evidence was retrieved from the websites and digital repositories of the Kerala State Planning Board, Department of Agriculture Development and Farmers' Welfare, Kerala Agricultural University, Indian Council of Agricultural Research, Directorate of Economics and Statistics, Agricultural Census, Vegetable and Fruit Promotion Council Kerala, National Horticulture Mission, FAO, World Bank, and peer-reviewed databases including Scopus, Web of Science and Google Scholar.

Document selection followed three operational criteria. First, documents were included when they directly addressed vegetable production, agricultural modernization, institutional interventions, climate adaptation, marketing systems or rural transformation in Kerala. Second, priority was given to documents produced by recognised public institutions, international organisations and peer-reviewed academic publications to ensure source credibility. Third, documents were selected primarily from the period 2000–2025 to capture contemporary agricultural transformation, while earlier publications were retained where they provided essential historical or policy context. Documents were excluded when they contained duplicated information, lacked methodological transparency, focused exclusively on crops unrelated to vegetable cultivation, or addressed geographical contexts outside Kerala without comparative relevance.

The final documentary corpus consisted of official statistical publications, agricultural census reports, state economic reviews, horticultural statistics, policy documents, departmental reports, institutional project reports, district agricultural contingency plans, technical manuals, international development reports and peer-reviewed journal articles. A complete inventory of analysed documents, together with the search strategy and document selection procedure, is provided in Appendix A.

The analytical procedure combined descriptive statistical analysis with qualitative documentary analysis. Quantitative datasets were organised to examine temporal and regional changes in cultivated area, production, productivity, irrigation, institutional interventions and district-level variation. Qualitative content analysis was undertaken using a structured coding framework in which documents were examined for recurring evidence relating to six analytical themes: (i) agrarian transformation; (ii) technological modernization; (iii) climate adaptation and environmental resilience; (iv) institutional support and governance; (v) market restructuring and value chains; and (vi) farmer adaptation and livelihood outcomes. Codes were developed deductively from the study objectives and refined iteratively as additional documentary evidence was reviewed.

Comparative thematic analysis was subsequently employed to synthesise findings across different document categories by identifying areas of convergence, divergence and continuity between official statistics, policy documents, institutional reports and empirical studies. Rather than relying on a single

source of evidence, analytical triangulation was applied by systematically comparing quantitative trends with institutional interpretations and independent scholarly findings. For example, changes in vegetable cultivation area and productivity reported in official statistical publications were compared with policy documents describing agricultural interventions and subsequently evaluated against empirical studies assessing their implementation and outcomes. This process enabled the identification of both consistencies and discrepancies across documentary evidence, thereby strengthening interpretative reliability while reducing dependence on any single source. A worked example of this triangulation procedure is presented in Appendix A.

Although the study does not generate primary field data, the systematic integration of multiple documentary sources provides a comprehensive evidence base for examining statewide agrarian transformation across institutional, ecological and temporal dimensions. Nevertheless, documentary analysis cannot directly verify farm-level behavioural responses or livelihood outcomes. Consequently, the findings should be interpreted as evidence of structural and institutional transformation, while future research incorporating farm surveys, stakeholder interviews and field observations could further validate the relationships identified in this study.

5. RESULTS AND DISCUSSION

The results synthesise evidence from official statistics, policy documents and published empirical studies to explain the changing trajectory of agrarian transformation in Kerala's vegetable sector. The analysis is organised around the interrelated dimensions of structural change, technological modernization, institutional development, climate adaptation and market integration that collectively shape contemporary rural transformation.

5.1. Structural Transformation of Kerala's Vegetable Economy

Kerala's vegetable economy has undergone a marked structural transition during the past three decades, reflecting broader changes in the organisation of agriculture rather than a simple expansion of horticultural production. Vegetable cultivation, once largely confined to homestead gardens and mixed farming systems, has become an increasingly important component of state agricultural policy in response to growing urban demand, concerns over food security, declining food-grain cultivation and heavy dependence on interstate supplies. Public investment gradually shifted from promoting agricultural production in general to strengthening local vegetable production through decentralised planning, protected cultivation, farmer organisations and value-chain development. The result has been a reorientation of vegetable cultivation from a subsistence activity towards a commercially organised, institutionally supported and climate-responsive production system.

This transformation unfolded within one of India's most fragmented agrarian structures. Agricultural Census reports indicate that more than 96 per cent of Kerala's operational holdings belong to the small and marginal category, with average operational holdings remaining well below one hectare. Such structural conditions limited the scope for large-scale mechanised farming while encouraging intensive cultivation, crop diversification and multiple cropping systems capable of generating higher returns from limited land resources. Vegetable cultivation became particularly suited to this agrarian setting because it could be integrated with coconut gardens, homestead farming and mixed cropping without major changes in land ownership or farm organisation. Rather than replacing existing farming systems, vegetable production increasingly diversified them.

Official statistics further demonstrate the scale of this restructuring. The area under vegetable cultivation expanded from about 46,500 ha in 2015–16 to more than 102,000 ha in 2020–21, while production increased from approximately 0.63 million tonnes to 1.57 million tonnes during the same period through state-supported vegetable self-sufficiency programmes, improved planting materials, protected cultivation and scientific crop management [35,36]. Growth therefore reflected improvements in production intensity and institutional support as much as expansion of cultivated area.

Table 1. Structural Transformation of Kerala's Vegetable Economy

Period	Structural Characteristics	Major Institutional Interventions	Agrarian Outcome

Before 2000	Homestead production; mixed farming; limited commercial cultivation	Conventional extension and input distribution	Household consumption-oriented production
2000–2015	Crop diversification; growing urban demand; organised vegetable promotion	KAU technologies, Krishi Bhavans, VFPC expansion, precision farming	Expansion of commercial vegetable cultivation
2015 - 2025	Climate-resilient production; protected cultivation; digital extension; organised marketing	Vegetable self-sufficiency programmes, FPOs, local governments, KERA and value-chain initiatives	Integrated production systems combining technology, markets and institutional support

Structural transformation has not proceeded uniformly across Kerala. Palakkad remains the principal commercial vegetable-producing district because relatively larger holdings, irrigation infrastructure and market connectivity support specialised cultivation. Highland districts, particularly Idukki and Wayanad, concentrate on temperate vegetables adapted to cooler environments, whereas coastal and midland districts increasingly depend on homestead cultivation, integrated farming and protected agriculture. These regional differences demonstrate that modernization has followed distinct agroecological pathways shaped by land availability, climatic conditions, irrigation facilities and institutional capacity rather than a uniform technological model. Kerala's exceptional agrobiodiversity—more than 450 cultivated crop species, including 73 vegetable crops—has further enabled this diversification by allowing vegetable production to be integrated within existing mixed farming systems instead of displacing them [37].

Alappuzha illustrates this differentiated trajectory particularly well. The Kuttanad below-sea-level farming system, extensive canal networks and flood-prone wetlands have historically favoured paddy cultivation, yet recurrent flooding, saline intrusion and hydrological instability have encouraged diversification towards vegetables, coconut-based mixed farming and homestead production. Adaptation has depended less on expanding cultivated area than on improved drainage, regulated water management, raised-bed cultivation, flood-tolerant production practices and institutional support through Krishi Bhavans, Kerala Agricultural University and district contingency planning. In this setting, ecological constraints have acted as a stimulus for institutional innovation, making Alappuzha an important illustration of how agrarian restructuring emerges through continuous interaction between environmental change and public intervention.

The restructuring of Kerala's vegetable economy therefore reflects a reorganisation of agricultural priorities rather than a sectoral shift alone. Land fragmentation, diversification, public investment, decentralised planning and changing food systems have collectively reshaped production structures while reinforcing the strategic role of vegetable cultivation in rural livelihoods and state food security. From the perspective of Agrarian Political Economy, these changes represent a reconfiguration of smallholder agriculture through institutional and market restructuring rather than through land consolidation or large-scale capital-intensive farming.

5.2. Technological Modernization and Innovation in Kerala's Vegetable Sector

Technological modernization has reshaped Kerala's vegetable economy by enabling agricultural growth within an agrarian structure characterised by fragmented holdings, labour shortages and increasing environmental uncertainty. Unlike the Green Revolution regions, where technological change was associated with large-scale mechanisation and intensive input use, Kerala's experience has centred on improving productivity, production stability and resource efficiency within smallholder farming systems. Scientific innovation has therefore functioned less as a substitute for existing production practices than as a means of reorganising them through location-specific technologies suited to diversified farming and limited operational holdings.

The expansion of this technological transition has depended upon sustained institutional investment. During the past decade, programmes implemented through the Department of Agriculture Development and Farmers' Welfare, Kerala Agricultural University (KAU), the Vegetable and Fruit Promotion Council Keralam (VFPC), Krishi Bhavans and local self-government institutions have progressively shifted agricultural extension from conventional input supply towards integrated technology support.

Demonstration farms, farmer field schools, certified planting materials, digital advisory services and continuous technical supervision have become central components of production planning, allowing scientific recommendations to be incorporated into routine farm management rather than remaining confined to experimental stations. The rapid increase in vegetable cultivation after 2015 coincided with this institutional transition, indicating that technological diffusion has largely been organised through public agricultural systems instead of autonomous market expansion.

Protected cultivation has become the most visible expression of this transformation. Successive state programmes have promoted polyhouses, shade-net houses and rain shelters to reduce the effects of excessive rainfall, pest incidence and seasonal production instability. By 2023, Kerala had expanded protected cultivation to more than 3,500 ha, with vegetable crops accounting for the largest share of the covered area under subsidy-supported cultivation. Precision farming initiatives, fertigation technologies and scientific crop scheduling have further improved input-use efficiency while extending the production season beyond conventional cultivation cycles. Rather than functioning simply as yield-enhancing technologies, these interventions have altered production calendars, reduced climatic risk and enabled more stable market supply.

Table 2. Major Technological Interventions in Kerala's Vegetable Sector

Technological intervention	Principal objective	Institutional support	Agrarian outcome
Protected cultivation (polyhouses, shade-net houses, rain shelters)	Reduce climatic risk and extend production	Department of Agriculture, KAU, VFPC	Year-round cultivation and higher production stability
Precision farming	Improve input efficiency	KAU, Krishi Bhavans	Higher productivity with lower resource use
Drip and micro-irrigation	Efficient water management	PMKSY, Department of Agriculture	Reduced water use and improved irrigation efficiency
Hybrid and improved vegetable varieties	Increase productivity and disease resistance	KAU, ICAR	Improved yields and crop adaptability
Digital advisory services	Real-time production guidance	KAU, Krishi Bhavans, mobile platforms	Faster technology dissemination and informed farm decisions

Resource management has evolved alongside these production technologies. Expansion of drip irrigation, micro-irrigation, integrated nutrient management and ecological pest management reflects a gradual movement away from input-intensive cultivation towards precision-based production systems capable of maintaining productivity while reducing pressure on land and water resources. Scientific irrigation scheduling, balanced nutrient application and biological pest management are increasingly promoted as complementary practices rather than independent interventions, reflecting a broader shift towards resource optimisation under conditions of climatic variability. The emphasis on efficient resource use has acquired particular importance in districts where seasonal water stress and declining soil quality increasingly influence production decisions.

Alappuzha provides an instructive example of how technological innovation has been adapted to local ecological conditions. Vegetable cultivation within the Kuttanad region cannot depend upon standard production technologies because recurrent flooding, fluctuating water levels and saline intrusion impose distinct environmental constraints. Raised-bed cultivation, regulated drainage, protected structures, short-duration vegetable varieties and locally adapted irrigation practices have consequently become integral components of technological modernization in the district. Here, innovation has emerged through the modification of technologies to suit wetland agriculture rather than through the transfer of uniform production models, illustrating the close relationship between scientific research, local ecological knowledge and institutional support.

Technological modernization has also expanded through digital agriculture. Mobile-based advisory platforms, weather forecasting services, pest surveillance systems and online market information have strengthened communication between research institutions and farmers, reducing the time required for

responding to climatic events, pest outbreaks and market fluctuations. Adoption nevertheless remains uneven. Farmers integrated into producer organisations, extension networks and institutional programmes generally exhibit higher levels of technological adoption than isolated smallholders, indicating that access to knowledge and institutional support continues to influence the pace of modernization as much as financial capacity or farm size.

The pattern observed across Kerala demonstrates that technological change has not been an autonomous process of innovation but an institutional process of knowledge mobilisation. Productivity gains have depended upon the capacity of research organisations, extension agencies and local governments to adapt scientific technologies to diverse agroecological settings and smallholder production systems. This closely reflects the Agricultural Innovation Systems perspective, where innovation emerges through sustained interaction among research institutions, extension services, public agencies and farming communities rather than through technology diffusion alone.

5.3. Climate Change, Institutional Transformation and Adaptive Agricultural Practices

Climate variability has become one of the principal forces shaping Kerala's contemporary vegetable economy, altering both production systems and institutional priorities. Agrarian transformation is no longer interpreted solely through technological modernization or market expansion; it is equally conditioned by the capacity of farming systems to absorb climatic shocks while maintaining productive stability. Successive episodes of erratic monsoons, high-intensity rainfall, prolonged dry spells, rising summer temperatures, saline intrusion in coastal regions and changing pest incidence have reshaped cultivation decisions across the state. The 2018 flood marked a decisive turning point in this transition. Official post-disaster assessments estimated that 236,650 ha of agricultural land (about 11% of Kerala's cultivated area) were affected, including 10,850 ha under vegetable cultivation, while total agricultural losses exceeded ₹18,500 crore. More than 1.08 million agricultural households experienced direct livelihood disruptions, demonstrating that climatic shocks have become structural determinants of agricultural performance rather than isolated environmental events.

The spatial distribution of these risks reveals marked regional differences that have influenced the trajectory of adaptation. The low-lying agroecosystems of Kuttanad and Alappuzha remain highly vulnerable to recurrent flooding, prolonged water stagnation and saline intrusion, whereas districts such as Palakkad, Wayanad and parts of the central midlands increasingly encounter rainfall variability, moisture stress and higher summer temperatures. More than 50 per cent of Alappuzha district lies within flood-prone zones, with Kuttanad experiencing repeated inundation that has progressively weakened its traditional below-sea-level farming system. Following the 2018 floods, over 53,700 families in Kuttanad were affected, and flooding continued during subsequent years, demonstrating that recovery has become a recurring rather than episodic process. These conditions have compelled agricultural planning to shift from post-disaster compensation towards anticipatory climate-risk management through landscape-specific interventions. The persistence of Kuttanad's internationally recognised below-sea-level cultivation system simultaneously illustrates both the ecological vulnerability and adaptive potential of Kerala's agrarian landscape.

Farm-level adaptation reflects a gradual reorganisation of production practices rather than a simple substitution of traditional methods with modern technologies. Vegetable cultivation is increasingly integrated with coconut, banana, tubers and other horticultural crops to diversify income sources and reduce production risks associated with climatic uncertainty. Adjustments in sowing calendars, wider adoption of short-duration and stress-tolerant varieties, crop rotation and improved soil management have become common responses to shifting rainfall regimes. Scientific water management has assumed equal importance. Drip irrigation, rainwater harvesting, precision irrigation scheduling and improved field drainage are now adopted alongside traditional water conservation practices. In Alappuzha, particularly within the Kuttanad wetland ecosystem, the rehabilitation of canals, polders and protective bunds has become indispensable for sustaining vegetable cultivation because field-level technological interventions alone cannot offset recurrent hydrological disturbances. Adaptation therefore operates simultaneously at the farm, landscape and institutional levels, linking ecological restoration with production management rather than treating them as separate domains.

The increasing use of protected cultivation demonstrates how climate adaptation has become embedded within Kerala's broader programme of technological modernization. Vegetable Development

Programmes implemented since 2015 expanded rain shelters, polyhouses, terrace cultivation, grow-bag cultivation, irrigation support and hybrid seed promotion as integrated components of state horticultural policy rather than isolated technological interventions. Technical evaluations indicate that programme efficiency improved even during the flood years of 2018–2019 and the COVID-19 period, suggesting that institutional support for protected cultivation contributed to maintaining household vegetable production under adverse conditions. Rain shelters reduce crop losses caused by intense monsoon rainfall, while shade-net structures moderate high temperatures and improve productivity in crops such as tomato, capsicum and French bean. Digital weather advisories, pest surveillance systems and mobile-based extension services have further strengthened farmers' capacity to adjust irrigation, planting and harvesting decisions according to short-term climatic variability. These developments illustrate that productive resilience increasingly depends upon the integration of climate information, agronomic knowledge and technological innovation rather than upon higher external input use alone.

Institutional change has been equally significant in reshaping climate adaptation. Agricultural governance has expanded beyond conventional extension services to function through interconnected networks involving the Department of Agriculture Development and Farmers' Welfare, Kerala Agricultural University, the Vegetable and Fruit Promotion Council Keralam (VFPCCK), Krishi Bhavans, Kudumbashree, Farmer Producer Organisations and local self-government institutions. Their activities increasingly combine climate-resilient seed distribution, protected cultivation subsidies, precision farming, farmer training, weather advisories and decentralised planning within a common implementation framework. This institutional convergence is particularly visible in Alappuzha, where climate-resilient farming initiatives are coordinated with wetland conservation, below-sea-level farming research and local adaptation planning. At the same time, recent studies of Kerala's smallholders show that access to extension services, climate information, formal credit and community organisations substantially improves farmers' willingness to adopt adaptive technologies, whereas limited financial resources continue to constrain investment among marginal producers. Institutional effectiveness therefore depends not merely on technology dissemination but on sustained interaction among research organisations, extension agencies, local governments and farming communities.

Kerala's experience indicates that climate resilience has become a defining component of agrarian transformation rather than an additional environmental objective attached to agricultural development. The state's annual vegetable production now exceeds 1.5 million tonnes, yet this still satisfies only part of domestic demand, making stable local production strategically important for food security and reducing dependence on interstate supplies. Climatic disturbances therefore influence not only farm incomes but also market availability, consumer prices and institutional planning. The interaction between technological innovation, ecological management and decentralised governance has progressively redefined agricultural modernization as a process of continuous adaptation to environmental uncertainty. This pattern reinforces the socio-ecological resilience perspective by demonstrating that adaptive capacity emerges through the interaction of ecological processes, technological innovation and institutional support. The institutional and technological adjustments discussed here also created the conditions through which market integration and value-chain transformation have evolved, which forms the focus of the following section.

5.4. Market Integration, Institutional Transformation and Rural Livelihoods

The expansion of vegetable cultivation in Kerala has been accompanied by a parallel reorganisation of agricultural markets that has altered the relationship between production, institutions and rural livelihoods. Earlier marketing systems were dominated by local traders, fragmented supply chains and highly localised exchanges in which smallholders negotiated individually under conditions of limited bargaining power and considerable price uncertainty. As vegetable cultivation assumed greater importance within the state's food security strategy, agricultural policy progressively shifted beyond production support to include aggregation, post-harvest management, logistics, market intelligence and value-chain development. This transition reflects a broader restructuring of Kerala's agrarian economy in which commercialization is increasingly mediated through public institutions and collective organisations rather than through conventional market intermediaries alone. Vegetable production expanded rapidly during the last decade, yet this growth also exposed the need for stronger institutional

mechanisms capable of connecting dispersed producers with expanding urban demand and reducing the state's continuing dependence on vegetables imported from neighbouring states.

The documentary evidence shows that production growth has been substantial, although structural constraints continue to shape market outcomes. The area under vegetable cultivation increased from approximately 46,500 ha in 2015-16 to more than 102,000 ha by 2020-21, while production rose from nearly 6.3 lakh metric tonnes to about 15.7 lakh metric tonnes during the same period under the combined influence of the Vegetable Development Programme, protected cultivation, homestead farming and institutional support. Despite this expansion, Kerala still remains structurally dependent on external markets for a significant share of its vegetable requirement. Programme evaluations estimate that annual demand exceeds domestic production by more than 40 per cent, requiring continuous procurement from neighbouring states to maintain market supplies. Production growth has therefore intensified rather than reduced the importance of efficient aggregation, storage, transport and coordinated marketing systems, particularly during periods of seasonal fluctuation and climate-induced production instability.

Institutional innovation has emerged largely as a response to these structural conditions. Instead of relying exclusively on conventional wholesale markets, Kerala has gradually developed a decentralised marketing architecture in which the Vegetable and Fruit Promotion Council Keralam (VFPCCK), Farmer Producer Organisations (FPOs), Krishi Bhavans, Kudumbashree, local self-government institutions and agricultural cooperatives collectively perform functions traditionally undertaken by private intermediaries. Producer groups facilitate input procurement, crop planning, quality control, aggregation, market intelligence and direct marketing, enabling smallholders to participate in value chains that would otherwise remain inaccessible to individual producers. In districts such as Alappuzha, where landholdings are small and production is geographically dispersed, collective marketing has reduced transaction costs while strengthening farmers' bargaining capacity through aggregation centres and institutional procurement networks. The expansion of these organisations has gradually shifted market participation from an individual commercial activity towards a coordinated institutional process in which production, extension, logistics and marketing operate as mutually reinforcing components of rural development.

The strengthening of institutional networks has nevertheless not eliminated long-standing structural weaknesses within Kerala's vegetable economy. Small operational holdings, fragmented production landscapes, inadequate storage facilities, limited cold-chain infrastructure, high transportation costs and uneven regional market connectivity continue to reduce farm profitability despite improvements in productivity. Planning documents consistently identify post-harvest losses, insufficient value addition, weak digital market integration and inadequate aggregation infrastructure as persistent constraints preventing higher production from translating into proportionate increases in farm income. These limitations become particularly visible during periods of climatic disruption, when interruptions in transport, localised flooding and supply fluctuations expose the vulnerability of decentralised production systems. The experience of Alappuzha illustrates this relationship clearly. Climatic disturbances affect not only production but also collection, transportation and marketing, demonstrating that market resilience depends as much on institutional coordination and physical infrastructure as on agricultural output itself.

Table 3. Market Integration and Institutional Transformation in Kerala's Vegetable Sector

Dimension	Documentary Evidence	Institutional Response	Agrarian Implication
Production Expansion	Vegetable area increased from 46,500 ha (2015–16) to >102,000 ha (2020–21)	Vegetable Development Programme, protected cultivation, homestead farming	Greater production required organised market integration
Market Dependence	Domestic production still insufficient to meet total demand; continued interstate procurement	Promotion of local production and aggregation	Improved food security and reduced external dependence

Institutional Marketing	Expansion of VFPCCK, FPOs, Krishi Bhavans, Kudumbashree and cooperatives	Collective marketing, aggregation centres, market intelligence	Increased bargaining power of smallholders
Structural Constraints	Fragmented holdings, inadequate storage, weak cold-chain and logistics	Investments in post-harvest infrastructure and value-chain development	Improved income realisation remains the principal challenge
Livelihood Transformation	Greater integration of production, marketing and climate adaptation	Climate-resilient value chains and local value addition	Commercialization increasingly linked with livelihood resilience

Recent policy initiatives increasingly recognise that commercialization, climate resilience and livelihood security cannot be pursued independently. Programmes promoting Farmer Producer Organisations, agri-enterprises, protected cultivation, local value addition and climate-resilient value chains are redefining agricultural modernization around integrated market systems capable of sustaining both production and rural incomes. Market integration has consequently evolved beyond the expansion of commercial exchange to become a mechanism for strengthening institutional coordination, improving price realisation, reducing transaction costs and expanding livelihood opportunities across the vegetable economy. The effectiveness of this transformation ultimately depends on the extent to which smallholders remain connected to organised institutional networks that combine production support, climate adaptation, value addition and market access within a single development framework. These findings are consistent with the agrarian political economy perspective, which interprets market participation as an institutional process shaped by governance structures, collective organisation and unequal access to resources rather than by commercial exchange alone. The institutional consolidation of Kerala's vegetable economy also provides the context for evaluating the broader implications of agrarian transformation discussed in the following section.

5.5. Agrarian Transformation, Adaptive Capacity and Rural Livelihood Resilience

The evidence presented across the preceding sections demonstrates that Kerala's vegetable economy has undergone a multidimensional agrarian transformation in which structural change, technological modernization, climate adaptation and market integration have evolved as interconnected processes. The substantial expansion of vegetable cultivation and production reflects not merely increased agricultural output but the broader reorganisation of the agrarian economy through public investment, scientific agriculture, decentralised governance and institutional coordination. Vegetable cultivation has consequently evolved from dispersed homestead production into an increasingly organised component of Kerala's food security and rural development strategy. At the same time, agricultural modernization has shifted from a narrow emphasis on productivity enhancement towards building resilience under climatic uncertainty. Technologies such as protected cultivation, precision farming, drip irrigation and digital extension services derive their effectiveness from the institutional arrangements that facilitate their dissemination, financing and local adaptation. The experience of ecologically vulnerable districts such as Alappuzha illustrates that technological interventions achieve sustainable outcomes only when supported by context-specific ecological management and coordinated institutional action.

These findings support the Agricultural Innovation Systems perspective by demonstrating that agrarian transformation is driven by interaction among research institutions, extension agencies, local governments, producer organisations and farming communities rather than by technological transfer alone. Institutions such as Kerala Agricultural University, the Department of Agriculture Development and Farmers' Welfare, VFPCCK, Krishi Bhavans, Farmer Producer Organisations, Kudumbashree and local self-government institutions collectively strengthen technology dissemination, market coordination, climate adaptation and institutional learning. Nevertheless, the evidence also indicates that policy outcomes remain uneven across regions owing to differences in agroecological conditions, infrastructure and institutional capacity. Flood-prone districts require adaptation centred on resilient wetland management, whereas interior regions increasingly depend on water conservation and efficient irrigation. Persistent constraints, including fragmented landholdings, uneven cold-chain infrastructure, post-harvest losses and regional disparities in institutional effectiveness, further indicate that agrarian transformation remains an evolving process rather than a completed transition. Overall, Kerala's experience illustrates

that sustainable smallholder development emerges through the continuous interaction of technological innovation, institutional governance and ecological adaptation, consistent with both the Agricultural Innovation Systems and Socio-Ecological Resilience perspectives.

6. DISCUSSION

The findings demonstrate that agrarian transformation in Kerala's vegetable sector has been shaped by the interaction of technological modernization, institutional interventions and changing agricultural resource conditions. Although government programmes have expanded technology dissemination, extension services, protected cultivation and market-oriented initiatives, the outcomes have not been uniformly realised across the state. Structural constraints remain evident in the continued decline of net sown area despite modest improvements in cropping intensity, indicating that productivity-enhancing interventions have only partially compensated for the long-term reduction of agricultural land resulting from competing land-use pressures. Likewise, the predominance of smallholder agriculture, with the overwhelming majority of operational holdings remaining below one hectare, reinforces the importance of institutional support while simultaneously limiting economies of scale and the independent adoption of capital-intensive technologies.

The documentary evidence further reveals considerable regional disparities that influence the effectiveness of agricultural modernization. District-level differences in irrigation availability, operational landholdings and production systems indicate that statewide programmes have been implemented under highly diverse agroecological and institutional conditions. Consequently, districts possessing relatively stronger infrastructure and institutional capacity have generally been better positioned to adopt technological innovations, whereas areas constrained by limited irrigation, fragmented holdings or ecological vulnerabilities have experienced slower or more uneven progress. These patterns suggest that the effectiveness of agricultural policies depends not only on programme design but also on the capacity of local institutions to translate policy objectives into sustained agricultural practice.

The results also indicate that policy outcomes have been uneven across different components of the agricultural sector. While improvements in productivity and technological adoption are evident for several crops, reductions in cultivated area for others demonstrate that modernization has not produced uniformly positive outcomes. These contrasting trends highlight that technological advancement alone is insufficient to drive agricultural transformation. Market conditions, environmental risks, institutional effectiveness and regional resource availability collectively influence farmer responses and the long-term sustainability of agricultural change. The documentary evidence therefore suggests that Kerala's agrarian transformation represents a process of differentiated adaptation rather than a uniform transition, with institutional interventions contributing substantially to modernization while remaining constrained by persistent structural and regional inequalities.

7. LIMITATIONS

This study is based exclusively on documentary evidence and does not incorporate primary empirical data such as farm surveys, stakeholder interviews or field observations. Consequently, while the analysis provides a robust understanding of long-term institutional and structural transformation in Kerala's vegetable sector, it cannot directly verify farm-level behavioural responses, technology adoption decisions or livelihood outcomes. Future research integrating documentary analysis with primary field investigations would provide a more comprehensive understanding of how institutional interventions are experienced and adapted by farmers across diverse agroecological and socio-economic contexts.

8. CONCLUSION

This study demonstrates that agrarian transformation in Kerala's vegetable sector is fundamentally an institutional and systemic process rather than a linear outcome of technological modernization. The evidence indicates that changes in production systems have been shaped through the interaction of public policy, institutional support, scientific innovation, market restructuring and ecological adaptation, producing a dynamic framework within which agricultural development is continuously negotiated.

Rather than representing a simple transition towards higher productivity, Kerala's vegetable economy illustrates how technological change acquires transformative significance only when supported by institutional arrangements capable of facilitating knowledge exchange, coordinated governance and adaptive decision-making across diverse agroecological contexts.

The study contributes to the literature by integrating official statistics, policy documents, institutional reports and empirical scholarship within a unified documentary analytical framework, thereby providing a comprehensive explanation of agrarian transformation that extends beyond technology-centred or policy-specific interpretations. In doing so, it demonstrates that the resilience and sustainability of smallholder agriculture depend on the interaction between institutional capacity, environmental conditions and market systems, rather than on isolated technological interventions. The persistence of fragmented landholdings, uneven infrastructure and regional differences in institutional effectiveness further indicates that agrarian transformation remains an evolving process whose outcomes are conditioned by local contexts and implementation capacities.

These findings have broader implications for agricultural policy in regions characterised by ecological diversity and smallholder-dominated farming systems. Future strategies should therefore prioritise region-specific planning, strengthen institutional coordination, expand climate-resilient infrastructure, improve post-harvest and market systems, and reinforce collective farmer institutions to ensure more equitable agricultural development. While the documentary approach provides robust insights into long-term structural change, future research integrating longitudinal farm-level surveys, stakeholder interviews and field observations would further illuminate how institutional participation, technological adoption and adaptive behaviour interact across different agroecological settings. Such evidence would contribute to a more nuanced understanding of sustainable agrarian transformation under conditions of climatic uncertainty, changing markets and evolving rural livelihoods.

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Ethics Statement: This study is based entirely on documentary analysis of publicly available official documents, policy reports, and secondary data and does not involve human participants, animals, personal data, interviews, surveys, or clinical materials. Accordingly, institutional ethical approval and informed consent were not required under applicable research ethics guidelines.

Supplementary Materials:

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APPENDIX A: DOCUMENTARY RESEARCH PROTOCOL AND ANALYTICAL FRAMEWORK

This study employed a systematic documentary research protocol to ensure the transparency, consistency and replicability of document identification, selection and analysis. Documentary evidence was collected between January and May 2026 from official institutional repositories, government statistical publications, international development agencies and peer-reviewed academic databases. Searches combined keywords including *Kerala vegetable cultivation, vegetable production, horticulture, agrarian transformation, agricultural modernization, climate adaptation, protected cultivation, precision farming, farmer producer organisations, value chains, horticultural statistics, and agricultural policy Kerala*. Multiple keyword combinations were used iteratively to maximise retrieval of relevant documentary evidence.

Documents were evaluated according to predefined inclusion and exclusion criteria before being incorporated into the analytical corpus (Table A1). Only documents directly relevant to Kerala's vegetable sector and published by recognised public institutions, international organisations or peer-reviewed academic sources were retained. Earlier publications were included where they provided historical or policy context necessary for interpreting long-term agrarian transformation.

Table A1. Document selection criteria

Inclusion criteria	Exclusion criteria
Documents addressing vegetable production, horticulture, agricultural modernization, institutional interventions, climate adaptation or agrarian transformation in Kerala	Documents unrelated to Kerala or vegetable agriculture
Official publications, international agency reports and peer-reviewed research	Opinion pieces or documents lacking identifiable institutional authorship
Statistical publications containing state- or district-level agricultural data	Duplicate publications or documents containing substantially identical information
Publications contributing historical or contemporary evidence relevant to the study objectives	Documents without sufficient methodological or evidential basis

The final documentary corpus integrated complementary forms of evidence representing statistical, institutional and scholarly perspectives on Kerala's vegetable economy (Table A2). Combining multiple document categories enabled the analysis of agrarian transformation from policy, institutional, technological and empirical perspectives rather than relying on a single source of evidence.

Table A2. Documentary corpus used in the study

Document category	Principal contribution to analysis
Official statistical publications	Trends in cultivated area, production, productivity and district-level variation
Agricultural Census reports	Structural characteristics of agricultural holdings
Kerala Economic Reviews	Agricultural policy and sectoral performance
Horticultural Statistics	Vegetable crop production statistics
Government policy documents and departmental reports	Institutional interventions and programme implementation
Kerala Agricultural University and ICAR publications	Technological innovation and extension
District Agricultural Contingency Plans	Climate vulnerability and adaptation strategies
VFPC publications	Farmer institutions, value chains and market integration

FAO and World Bank publications	Comparative policy perspectives and agricultural development frameworks
Peer-reviewed journal articles	Independent empirical evidence and critical interpretation

Documentary analysis followed a structured coding framework aligned with the objectives of the study (Table A3). Initial codes were developed deductively from the research questions and subsequently refined through iterative reading of the documentary material. Coding focused on identifying recurring patterns, institutional relationships, technological developments and explanatory themes across diverse documentary sources.

Table A3. Analytical coding framework

Code	Analytical domain	Illustrative analytical focus
AT	Agrarian transformation	Land-use change, production structure, cropping patterns
TM	Technological modernization	Protected cultivation, mechanisation, precision farming, improved varieties
CA	Climate adaptation	Flood management, resilient production systems, environmental adaptation
IS	Institutional support	Government programmes, extension services, subsidies, farmer organisations
MV	Market restructuring	Value chains, marketing systems, supply-chain integration
FA	Farmer adaptation	Adoption behaviour, diversification and livelihood responses

Analytical triangulation was undertaken by systematically comparing three complementary forms of evidence: official statistical datasets, institutional policy and technical documents, and peer-reviewed empirical research. Statistical publications established quantitative trends, institutional documents provided policy and implementation perspectives, while scholarly studies offered independent empirical evaluation. Conclusions were derived only after examining convergence or divergence across these evidence streams, thereby reducing dependence on any individual source and strengthening interpretative reliability.

An illustration of the triangulation procedure is presented in Table A4.

Table A4. Example of analytical triangulation

Research theme	Statistical evidence	Institutional evidence	Scholarly evidence	Integrated interpretation
Expansion of protected cultivation	Horticultural statistics indicate a steady increase in protected cultivation area across Kerala.	Departmental reports attribute expansion to subsidy schemes, extension support and protected cultivation programmes.	Empirical studies report increased adoption but identify uneven uptake resulting from investment costs, maintenance requirements and differences in institutional support.	Protected cultivation expanded through sustained institutional intervention; however, adoption remained spatially uneven because technological diffusion depended on local economic and institutional conditions.

The documentary research protocol adopted in this study enhances methodological transparency by explicitly documenting the search strategy, document selection criteria, analytical coding framework and triangulation procedure. Although the approach provides a robust basis for analysing long-term structural transformation at the state level, it does not directly capture farm-level perceptions or behavioural responses. Consequently, the findings should be interpreted as evidence of institutional and structural change, while future research incorporating household surveys, stakeholder interviews and field-based observation would complement the present documentary analysis.