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An Economic Analysis of Resource Efficiency, Growth and Sustainability of Vertical Farming in India

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ABSTRACT

Vertical farming, a form of Controlled Environment Agriculture (CEA) that cultivates crops in vertically stacked layers under regulated light, temperature and nutrient conditions, has emerged as a response to India's shrinking per-capita arable land, groundwater stress and rising urban demand for fresh, pesticide-free produce. This paper examines the productivity pattern of vertical farming in India using secondary data drawn from industry reports, government publications and peer-reviewed literature. It situates the phenomenon within the economic theories of production function, diminishing and increasing returns, land rent (Ricardian theory) and innovation diffusion, and analyses land productivity, water-use efficiency, capital intensity and market growth trends between 2020 and 2034. The analysis shows that vertical farms can achieve yields several times higher per unit area than open-field cultivation, while consuming a fraction of the water, even though high capital cost, energy dependence and limited crop diversity constrain the scale of adoption. The paper concludes that vertical farming exhibits a distinct productivity pattern in which land productivity rises sharply while capital productivity initially falls, gradually improving as technology costs decline and clusters of adoption emerge around metropolitan demand centres. Policy suggestions include capital subsidies, renewable-energy-linked incentives, cluster-based infrastructure and skill development to help vertical farming complement, rather than replace, conventional agriculture in India's food security strategy.

KEYWORDS

Vertical Farming, Productivity, Controlled Environment Agriculture, Land Productivity, Resource-Use Efficiency, Sustainable Agriculture, India, Agri-tech, Production Function, Diminishing Returns.

1. INTRODUCTION

Agriculture in India continues to be constrained by a fundamental arithmetic problem: the population that depends on farm output keeps rising while the land available to produce it keeps shrinking. Rapid urbanisation, the conversion of farmland for housing and industry, groundwater depletion, and increasingly erratic weather patterns linked to climate change have together placed enormous pressure on the productivity of India's traditional, horizontally organised cropping systems. Against this backdrop, vertical farming the practice of growing crops in vertically stacked layers, frequently indoors, using soil-less media such as coco-peat, perlite or nutrient-rich water in hydroponic, aeroponic or aquaponic systems has begun to attract attention from policymakers, entrepreneurs and investors as a complementary model of food production.

Unlike conventional farming, which is bound by the two-dimensional constraint of land area, vertical farming multiplies usable growing area by stacking layers, thereby altering the basic input-output relationship between land and output. It also substitutes capital, technology and energy for land and, to a large extent, for water, since closed-loop irrigation systems recycle a significant share of moisture that would otherwise be lost to evaporation or run-off in open fields. These structural differences make vertical farming an interesting case for examining productivity from an economic perspective, since it changes the relative scarcity of the factors of production that determine agricultural output.

This paper studies the productivity pattern of vertical farming in India that is how output responds to changes in land, capital, water, energy and labour inputs and locates this pattern within established economic theories of production. It also reviews the current market and policy landscape, and offers suggestions for improving the economic viability of vertical farming as part of India's broader agricultural strategy.

1.1 Statement of the Problem

While vertical farming is frequently described in popular and trade literature as being dramatically more "productive" than traditional agriculture, such claims are rarely grounded in a formal economic framework that accounts for the full basket of inputs like capital, energy and skilled labour that vertical systems require. There is, therefore, a need to examine whether the productivity gains of vertical farming in India represent genuine total-factor productivity improvement or merely a reallocation of scarcity from land to capital and energy.

1.2 Objectives of the Study

- To examine the concept and forms of vertical farming prevalent in India.
- To analyse the productivity pattern of vertical farming with respect to land, water and capital, in comparison with traditional agriculture.
- To relate the productivity pattern of vertical farming to relevant economic theories of production.
- To assess the growth trend and market size of the vertical farming sector in India.
- To identify constraints and suggest policy measures to improve the economic viability of vertical farming.

1.3 Significance of the Study

The study is significant for agricultural economists, policymakers and agri-entrepreneurs seeking to understand where vertical farming fits within India's food-security architecture. As India's National Institution for Transforming India and several state governments explore urban agriculture and controlled-environment agriculture as tools for nutritional security and farmer income enhancement, an economically grounded assessment of productivity patterns can help calibrate the extent and manner of policy support extended to this emerging sub-sector.

2. REVIEW OF LITERATURE

Beacham, Vickers and Monaghan (2019) trace the evolution of vertical farming approaches from small community-scale operations to large commercial skyscraper farms and note that the term covers a wide spectrum of technological intensity, which complicates cross-study productivity comparisons.

Al-Kodmany (2018) examines the architectural and urban-planning dimensions of vertical farms and argues that integrating food production into the built environment can substantially raise the effective yield obtainable from a fixed urban footprint, although this comes at a high initial construction cost.

Studies reviewed in the Indian context (see, for instance, work compiled in the Acta Scientific Agriculture series and allied agri-extension journals) observe that Indian vertical farms report yields of leafy greens in the range of 40–50 kilograms per square metre annually, considerably above open-field benchmarks for the same crops, while requiring 70–90 per cent less water due to closed-loop recirculation.

A recurring theme in the literature reviewed for this paper is the tenfold-or-higher yield multiplier commonly cited for vertical systems relative to conventional agriculture, though authors caution that such multiples vary widely by crop type, by the sophistication of lighting and climate-control technology deployed, and by the yardstick used yield per square metre of growing area versus yield per square metre of total building footprint.

On the demand side, industry analyses (IMARC Group; Grand View Research; Polaris Market Research; Market Research Future; Ken Research; Research and Markets, various years) converge on the finding that India's vertical farming market is in an early but rapidly compounding growth phase, driven by urban demand concentrated in metropolitan centres such as Delhi, Mumbai and Bangalore, by the entry of agri-tech start-ups, and by rising consumer preference for pesticide-free, traceable produce.

Taken together, the literature suggests two broad gaps that this paper seeks to address: first, most productivity claims are stated in physical rather than economic terms, without reference to the capital and energy costs incurred to obtain them; and second, there is limited synthesis connecting Indian vertical farming data to formal economic theories of production, which this paper attempts to provide.

3. RELATED ECONOMIC THEORY

The productivity pattern of vertical farming can be understood through four complementary strands of economic theory.

3.1 Theory of Production and the Production Function

In neoclassical economics, output (Q) is expressed as a function of inputs such as land (L), capital (K), labour (Lb) and, in agriculture, water and energy: $Q = f(L, K, Lb, W, E)$. Vertical farming alters the relative input intensities embedded in this function: it dramatically reduces the marginal land requirement per unit of output while raising the marginal capital and energy requirement. This is best understood as a movement along an isoquant the same output level achieved via a different input combination rather than a pure outward shift of the production function, although efficiency gains from controlled conditions can additionally shift the function itself.

3.2 Law of Diminishing Marginal Returns and Increasing Returns to Scale

Traditional agriculture is a textbook illustration of diminishing marginal returns to land as a fixed factor: beyond a point, additional labour or fertiliser applied to a fixed plot yields progressively smaller increments of output. Vertical farming attempts to relax this constraint by treating land as an extensible factor through vertical stacking, so that within a building envelope, output can rise roughly in proportion to the number of growing layers added, exhibiting near-constant or even increasing returns to the capital invested in additional layers, up to the point where lighting, climate-control and structural costs begin to rise disproportionately.

3.3 Ricardian Theory of Land Rent

David Ricardo's theory of rent holds that rent arises from the differential productivity of land of varying fertility and location, with land nearest to markets or of higher fertility commanding higher rent. Vertical farming effectively decouples food production from locational and fertility constraints altogether: a vertical farm can be located inside a city, on land whose value is determined by real-estate rather than agricultural rent, and can therefore only be economically justified where the savings in transport, spoilage and land-rent differentials are large enough to offset the higher capital cost a modern extension of the Ricardian logic to urban agricultural rent.

3.4 Theory of Innovation Diffusion

Everett Rogers' theory of the diffusion of innovations characterizes the adoption of a new technology as an S-shaped curve moving through innovators, early adopters, early and late majority, and laggards. The current Indian vertical farming market, dominated by a small number of agri-tech start-ups and pilot projects concentrated in metropolitan regions, corresponds to the early-adopter phase of this curve; the double-digit compound annual growth rates projected by industry sources for the 2025-2034 period are consistent with the steep, early part of an S-curve of diffusion.

4. METHODOLOGY

4.1 Research Design

The study adopts a descriptive and analytical research design based entirely on secondary data.

4.2 Sources of Data

Data have been compiled from industry market-research reports (IMARC Group, Grand View Research/Horizon Databook, Coherent Market Insights, Market Research Future, Ken Research, Research and Markets, The Report Cubes), peer-reviewed and extension-journal articles on vertical farming productivity, and agri-business advisory publications. No primary survey or field data collection was undertaken; consequently, the findings represent a synthesis of secondary estimates rather than field-verified measurements.

4.3 Period of Study

The analysis draws on market and productivity estimates published for the period 2020 to 2035, with the base analytical year taken as 2025-26.

4.4 Tools of Analysis

Simple comparative and tabular analysis, percentage and compound annual growth rate (CAGR) interpretation, and conceptual mapping to production-theory constructs have been used. No inferential statistical testing was performed, given the descriptive, secondary-data nature of the study.

4.5 Limitations

- Market-size estimates vary considerably across research agencies owing to differing definitions and methodologies; this paper reports the range rather than treating any single estimate as definitive.
- Yield and resource-efficiency figures are drawn from secondary, often industry-sourced literature and have not been independently verified through field trials.
- The analysis is descriptive; it does not estimate a formal econometric production function due to the absence of firm-level panel data on Indian vertical farms.

5. ANALYSIS

5.1 Market Size and Growth Trend

Independent market-research estimates of the size and growth of India's vertical farming market differ in absolute value because of varying scope definitions (equipment-only versus equipment-plus-produce, for instance) but are unanimous in projecting a sustained double-digit compound annual growth rate through the next decade. Table 1 summarizes estimates from five independent sources.

Table 1: Comparative Market Size Projections for Vertical Farming in India

Source	Base Year Value (USD million)	Target Year	Projected Value (USD million)	CAGR (%)
IMARC Group	100.46 (2025)	2034	699.35	20.64
Grand View Research (Horizon)	358.6 (2025)	2033	1,926.1	23.5
Market Research Future	790 (2025)	2035	4,270	18.58
Research and Markets	62.21 (2024)	2030	200.14	21.50
The Report Cubes	514.48 (2025)	2034	3,604.87	24.15

Despite the divergence in absolute figures a natural consequence of differing scope and forecasting methodology every source projects a CAGR between roughly 18 and 24 per cent, indicating strong consensus on the direction and pace of growth even where the base is measured differently. India's share of the global vertical farming market is estimated at around 3.7 per cent as of 2025, with South India cited as a leading region owing to its agri-tech ecosystem and early adoption of technology.

5.2 Land Productivity: Vertical versus Traditional Farming

The central productivity claim in the literature concerns yield per unit of land area. Table 2 presents illustrative comparisons compiled from the reviewed sources.

Table 2: Indicative Productivity Comparison — Traditional vs Vertical Farming (compiled from secondary sources)

Parameter	**Traditional (Open-Field) Farming**	**Vertical Farming (Hydroponic/Aeroponic)**
Yield per sq. m. (leafy greens, indicative)	Baseline (1x)	Up to 10x–40x, reported as high as 50–100x for some crops/technologies
Water use	Baseline (1x)	70%–90% lower, due to closed-loop recirculation
Cropping cycles per year	1–3 (season-dependent)	Up to 10–12 (year-round, climate-independent)
Land footprint dependency	High — output tied directly to acreage	Low — output scalable via additional vertical layers
Pesticide/herbicide use	Standard usage	Minimal to none, due to controlled indoor environment

The wide range in the reported yield multiplier (10x to 100x) reflects the heterogeneity of vertical farming technologies and crop choices discussed in Section 2, and should be read as an order-of-magnitude indication of land-productivity gain rather than a precise, universally applicable figure. The consistent pattern across all sources, however, is that land productivity rises sharply while water intensity per unit of output falls sharply a productivity pattern that is the inverse of that seen in most traditional intensive-agriculture strategies, where higher yields are typically obtained by using more water and chemical inputs rather than less.

5.3 Capital and Component Structure of Vertical Farms

Because vertical farming substitutes capital and energy for land, the composition of capital expenditure is a useful indicator of where productivity gains are "purchased" from. Industry segment data indicate that lighting (LED grow-light systems) is consistently the largest component category, commanding close to 29 per cent of component revenue in 2025 estimates, followed by climate-control, irrigation and sensor systems. By growth mechanism, hydroponics holds the largest share of the market (around 53 per cent in 2026 estimates) owing to superior water-use efficiency relative to aeroponic and aquaponic alternatives, while aeroponics is frequently identified as the fastest-growing mechanism due to even lower water and nutrient requirements.

5.4 Structural and Crop-Mix Pattern

Table 3: Structural Composition of the Indian Vertical Farming Sector

Segment	**Leading Category (Recent Estimates)**	**Reason**
Structure type	Shipping-container-based (largest current share); building-based (fastest growing)	Lower upfront cost for containers; better scalability and proximity to urban centres for building-based farms
Growth mechanism	Hydroponics (largest); Aeroponics (fastest	Water efficiency and nutrient-

Segment	Leading Category (Recent Estimates)	Reason
	growing)	delivery precision
Crop type	Leafy greens and tomatoes dominate	Short growth cycles, high urban consumer demand, price premium for freshness
End-use/demand centres	Delhi, Mumbai, Bangalore, and South Indian agri-tech clusters	High population density, limited peri-urban farmland, strong agri-tech ecosystem

5.5 Constraints Identified in the Data

- High initial capital investment for building-based and technologically advanced systems.
- Continuous energy dependence for lighting and climate control, which raises the operating-cost base and, indirectly, the carbon footprint unless renewable energy is used.
- Restricted crop range vertical farming remains economically viable mainly for high-value, short-cycle crops such as leafy greens, herbs and select fruiting vegetables, rather than staples such as wheat and rice.
- Requirement for technical expertise in system operation and maintenance, which raises the effective skilled-labour intensity of the model relative to traditional farming.

5.6 Synthesis: The Productivity Pattern

Read together, Tables 1 to 3 point to a distinctive productivity pattern: land productivity and water-use efficiency rise very sharply, cropping frequency multiplies through year-round, climate-independent production, but capital productivity is initially compressed by high fixed investment and energy costs. As the theory of innovation diffusion would predict, unit capital costs for lighting and climate-control components are expected to fall as adoption spreads beyond the current early-adopter phase, which should gradually improve capital productivity even as land and water productivity remain structurally higher than in traditional agriculture. This pattern is consistent with a rightward and outward shift along an isoquant described in Section 3.1, rather than a uniform improvement in the productivity of every input simultaneously.

6. SUGGESTIONS

- Capital-cost support: Provide targeted capital subsidies or concessional credit for LED lighting, climate-control and hydroponic/aeroponic infrastructure, since these components account for the largest share of vertical-farm capital cost.
- Renewable-energy linkage: Encourage co-location of vertical farms with solar or other renewable energy sources through net-metering or dedicated green-energy tariffs, to address the energy-intensity constraint identified in the analysis.
- Cluster development: Promote vertical-farming clusters near metropolitan demand centres (as already visible around Delhi, Mumbai and Bangalore) with shared cold-chain, logistics and market-linkage infrastructure to reduce per-unit fixed costs.

- Crop-diversification research: Support research into extending vertical-farming viability beyond leafy greens and herbs to a wider range of nutritionally important crops, to broaden the sector's contribution to food security.
- Skill development: Introduce vocational and agricultural-university curricula on controlled-environment agriculture to build the technical workforce vertical farming requires.
- Data and standards: Establish a national data-reporting standard for vertical-farm yield and resource-use metrics, to reduce the wide variation currently seen across industry estimates and enable more rigorous productivity benchmarking.
- Complementary, not substitutive, policy framing: Position vertical farming as a complement to, rather than a replacement for, staple-crop agriculture, given its current comparative advantage in high-value, short-cycle, urban-demand crops.

7. CONCLUSION

Vertical farming in India is transitioning from a niche, early-adopter activity into a rapidly growing agri-tech sub-sector, with market-size projections across independent sources converging on compound annual growth rates in the range of 18 to 24 per cent over the coming decade. Its productivity pattern departs markedly from that of traditional agriculture; it dramatically raises output per unit of land and per unit of water, and enables year-round production independent of season, but it does so by substituting capital, energy and technical skill for land a substitution that current data suggest still carries a capital-productivity cost during this early phase of diffusion. Viewed through the lens of production theory, Ricardian land-rent theory and innovation-diffusion theory, vertical farming does not so much abolish the constraints of traditional agricultural economics as relocate them from land scarcity to capital and energy scarcity. Its long-run contribution to Indian agriculture will likely depend on how quickly policy support, technological improvement and cluster-based infrastructure can lower this capital and energy cost, allowing vertical farming to complement conventional cultivation in strengthening India's urban food security.

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