AATCC Review

23 January 2026: Received
04 March 2026: Revised
05 April 2026: Accepted
14 April 2026: Available Online

https://aatcc.peerjournals.net/

Original Research Article

Open Access

Optimization and economic validation of year-round cropping sequences under naturally ventilated polyhouse in the northwestern Himalayas of India

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ABSTRACT

Protected cultivation of vegetables is a vital tool to cultivate vegetables even during weather extremities. . In the era of market-driven production system, suitable cropping sequence of high value vegetables is the most important aspect to get more benefit per unit of area. Moreover a viable cropping sequence by considering off seasonality and market demand will play significant role in making farming more profitable particularly for small and marginal farmers. The objective of this study was to evaluate the production efficiency and economic viability of six high-value vegetable cropping sequences (CS) to ensure round-the-year production in a naturally ventilated polyhouse in the mid-hill zone of Himachal Pradesh, India. The treatments were evaluated in a randomized complete block design with three replications. Cropping sequence CS1 was Cherry Tomato - Parthenocarpic Cucumber - Lettuce, which was compared against five other sequences (CS2 to CS6). Significant differences were observed for cumulative yield, production efficiency, and benefit: cost ratio among the tested sequences. Cherry tomato, tomato, lettuce, and cucumber were identified as the major determinants for yield, whereas broccoli and snow peas demonstrated minimum yield potential. Crop Sequence 1 (CS1) recorded the highest cumulative production (708.06) and production efficiency (2.36). Crucially, CS1 also yielded the highest Net Return (₹24,553.73/100 m^2) and a Benefit: Cost Ratio (B:C ratio) of 4.75. This was followed by CS4: Broccoli - Cherry Tomato - Parthenocarpic Cucumber (B:C ratio 4.14). The minimum profit and lowest B:C ratio (3.22) were recorded in CS2: Lettuce - Tomato - Parthenocarpic Cucumber. Based on superior performance across production and economic metrics, the cropping sequence CS1 is recommended as the most profitable system for continuous polyhouse production in the region.

Keywords: *Benefit: cost ratio, Cropping sequence, naturally ventilated, off season, polyhouse, profitability, vegetable crops.*

Introduction

Protected cultivation utilizing polyhouse technology has become a vital strategy for enhancing horticultural profitability and addressing market gaps in challenging environments, particularly in the mid-hill regions of the Indian Himalayas. These structures mitigate climatic stress, allowing for the year-round production of high-value, off-season vegetables.[1] However, the high initial capital investment for polyhouse construction and the subsequent operational costs mean that the cost of production can be up to five times higher than that of open-field cultivation.[1] This financial structure necessitates the adoption of optimized cropping sequences that maximize the utilization of the asset and generate a superior benefit: cost (B:C) ratio to ensure the long-term economic sustainability for growers.[1]

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DOI: https://doi.org/10.21276/AATCCReview.2026.14.02.54

Studying cropping sequences in polyhouse cultivation is essential for maximizing the biological, economic and resource-use efficiency of protected farming systems. Unlike open-field agriculture, polyhouses involve high initial investment, recurring operational costs and controlled environmental conditions; therefore, the choice and order of crops grown throughout the year directly determine profitability and sustainability. A well-planned cropping sequence ensures continuous utilization of the structure, reduces idle periods and allows farmers to harvest multiple high-value crops annually, thereby improving return on investment. From a productivity perspective, optimized sequences enable efficient use of space, light, temperature, and nutrient resources available within the protected environment. Different vegetable crops have varying growth durations, canopy structures and nutrient demands; arranging them strategically minimizes competition and enhances cumulative yield per unit area. Sequential cropping also helps maintain consistent market supply, especially during off-season periods when prices are higher, thus increasing gross and net returns.

In terms of soil and plant health, studying cropping sequences is crucial for reducing the buildup of pests, diseases and soil-borne pathogens that commonly occur under continuous mono-cropping in enclosed structures. Rotating crops with different botanical families and root characteristics helps break pest cycles, improves soil microbial balance, and maintains soil fertility. This contributes to reduced dependency on chemical pesticides and fertilizers, promoting environmentally sustainable production practices. Economically, cropping sequence research provides farmers with data-driven decision support regarding cost of cultivation, benefit–cost ratio and daily profitability. Since polyhouse cultivation often involves higher expenses for inputs such as hybrid seeds, fertigation, and climate control, selecting the right sequence of crops can significantly influence financial viability. Studies also help identify combinations of crops that balance high market value with stable yield potential, reducing economic risk. This is particularly important in hilly and temperate regions where climatic variability and limited landholdings necessitate intensive and efficient production systems. Overall, research on cropping sequences in polyhouses is fundamental for achieving year-round production, enhancing farm income, improving resource efficiency, and ensuring long-term sustainability of protected cultivation systems.

Previous studies in similar environments have highlighted that crops like tomato, bitter gourd, and cucumber are major determinants for both production and profitability.[2] Highly successful sequences in the mid-hills include King Chilli sole cropping (B:C 4.2) and the Tomato–Capsicum cropping sequence (B:C 3.5).[2] Conversely, cropping sequences incorporating low-value crops, such as Tomato–Cucumber–French bean–Coriander (B:C ratio 1.34), proved to be least profitable.[3] This indicates that economic success is highly dependent on both selecting high-value component crops and optimizing their sequence to achieve continuous production intensity. Furthermore, studies confirm that productivity under protected cultivation is, on average, 3.36 times greater than that achieved in open-field cultivation.[(4,6)]

The present study addresses the necessity for a rigorously evaluated, high-intensity, year-round rotation by comparing six distinct three-crop sequences.

Materials and Methods

The field studies were carried out inside the naturally ventilated polyhouses installed at the Experimental Farm of the Department of Vegetable Science, Dr YSP, UHF, Nauni, Solan, Himachal Pradesh, India during the year 2024 and 2025. The experimental Farm is located at an altitude of 1276 meters above mean sea level, lying between 30° 52' North latitude and 77° 11' East longitude. The area of the farm falls under sub-humid, sub-temperate and mid-hill zone of Himachal Pradesh, India. Treatments consisted of six cropping sequences (Table 1), which were evaluated in a randomized complete block design and replicated four times. Crop combinations were taken by considering their off seasonality and market price. The first crop of the cropping sequence was transplanted during December and all crops were grown with a complete package of nutrient and pest and disease management. Varieties selected for experimentation were Solan Lalima (tomato), Sweet Banana (capsicum), Snow pea (Meethi Phali), Solan Kriti (lettuce), Palam Vichitra (broccoli), and Kian (parthenocarpic cucumber). Vegetables were planted at recommended spacing inside polyhouse and in open field.

Table 1: Details of treatments

S.No.	Cropping sequence
	CS1: Cherry Tomato (Feb-June) - Parthenocarpic Cucumber (July-Oct) - Lettuce (Nov-Jan),
	CS2: Lettuce (Dec-April) - Tomato (May-August) - Parthenocarpic Cucumber (Sept-Nov),
	CS3: Snow peas (Dec-March) - Capsicum (April-August) - Lettuce (Sept-Nov),
	CS4: Broccoli (Dec-April)- Cherry tomato (April – July)- Parthenocarpic Cucumber (August – Nov),
	CS5: Capsicum (Feb-June)- Parthenocarpic Cucumber (July-Sept)- Lettuce (Oct-Jan),
	CS6: Lettuce (Jan-April)- Capsicum (May-Aug)- Snow peas (Sept-Dec)

No severe pests and diseases were observed during the crop growth; however, necessary plant-protection measures were taken on a need basis. For valid comparison between tested crop sequences, the yields of all crops were converted into total equivalent yield based on market price. Final crop yields were recorded and gross return (₹/ha) was calculated on the basis of the prevailing market price of the produce. Net return was calculated by subtracting the cost of cultivation from the gross value of the produce.

The Benefit: Cost ratio (B: C ratio) for different crop sequences was calculated by dividing the net returns by the cost of cultivation. Production efficiency was calculated by taking the total duration of crops in a sequence and dividing it by 365. Production-efficiency value was calculated by dividing the total equivalent yield (kg/ha) with the total duration of the crops (days) in a sequence. Economic efficiency value was calculated by dividing the total net return (₹/) with the total duration of the crops (days) in a sequence. The data on yield of crops and economics were recorded and subjected to statistical analysis as per Panse and Sukhatme (1985) [5] by using MS Excel and OP STAT.

Results and Discussion

Significant differences were observed among cropping sequences in cumulative yield, production efficiency and benefit: cost ratio during both the years. Higher production and production efficiency under different cropping sequences were recorded as compared to open field condition. The yield advantage under polyhouse condition may be attributed to the prevalence of congenial microclimate in terms of temperature and relative humidity [6]. CS1 (cherry tomato–cucumber–lettuce) recorded the highest total equivalent yield (708.06 kg/100 m^2/year), production efficiency (2.36 kg/100 m^2/day), and B:C ratio (4.75), followed by CS5 (capsicum–cucumber–lettuce). CS4 (broccoli–tomato–cucumber) recorded the lowest yield (440.90 kg/100 m^2/year). The superior performance of CS1 was due to efficient resource utilization and high market value crops like cherry tomato and lettuce. Economic analysis (Table 2) confirmed these trends, with CS1 giving the highest net return (₹24,553.73/100 m^2/year) and profitability (₹75.09/day).Cherry tomato, tomato, lettuce, and cucumber were the major determinants for yield, whereas broccoli and snow peas had the minimum yield potential.

The results definitively establish the superior economic performance of the Cherry Tomato – Parthenocarpic Cucumber – Lettuce sequence (CS1), which achieved a B:C ratio of 4.75 and a profitability of ₹75.09/100m^2 This outcome is superior to established high-return benchmarks identified in similar regions, such as King chilli sole cropping (B:C 4.2) and the high-density Tomato–Capsicum rotation (B:C 3.5).[1]

Table 2: Yield and production efficiency of vegetable-based cropping sequence under protected condition (Pooled data)

Cropping sequence	1st crop	2nd crop	3rd crop	Land-use efficiency (%)	1st crop	2nd crop	3rd crop	Production (kg/100m^2/year)	Production efficiency (kg/100m^2/day)
	Crop duration (days)	Crop duration (days)	Crop duration (days)		Mean yield (kg/100 m2)	Mean yield (kg/100 m2)	Mean yield (kg/100 m2)		
CS1	115	95	92	82.73	250.40	305.50	152.16	708.06	2.36
CS2	105	97	91	80.27	118.30	312.40	97.80	528.50	1.80
CS3	100	121	92	85.75	92.50	250.80	161.10	504.40	1.55
CS4	98	122	95	86.30	85.60	240.10	115.20	440.90	1.40
CS5	121	92	95	84.38	241.00	250.70	157.60	649.30	2.11
CS6	95	112	106	85.75	138.00	271.60	85.10	494.70	1.58
CD (P=0.05)	5.3	6.2	4.9	3.6	4.8	6.4	5.1	11.6	0.29

The high profitability of CS1 is directly attributable to two key factors: the inclusion of high-value crops with off-season price potential and the maximization of the asset's land-use efficiency. The study confirms that cherry tomato, tomato, lettuce, and cucumber are major determinants for profitability, a finding corroborated by general protected cultivation trends.[2] The strategic timing of these three crops (Table 2) ensured maximum output during periods of high market demand, thereby realizing a Gross Return of ₹29,724.23/100m^2 (Table 3). The use of parthenocarpic cucumber is also critical, as it eliminates reliance on natural pollinators and ensures reliable, high-volume fruit set, stabilizing the mid-season yield.

The analysis of the cost of cultivation (COC) confirmed that the economic profile of protected cultivation is dominated by fixed infrastructure costs, aligning with regional studies confirming that these costs exceed 50%.[1] Furthermore, studies have shown that optimal nutrient management alone can push cucumber profitability close to the 3.42 B:C ratio mark, highlighting the importance of precision management within high-value crop cycles.[7]

Table 3: Cost of cultivation, gross return, net return, benefit: cost ratio and profitability inside polyhouse (Pooled data)

Cropping sequence	Cost of cultivation (₹/100m2/year)	Gross return* (₹/100m2/year)	Net return (₹/100m^2/year)	BCR	Profitability (₹/100m2/day)
CS1	5170.50	29724.23	24553.73	4.75	75.09
CS2	3809.50	16060.15	12250.65	3.22	41.81
CS3	4516.50	21101.42	16584.92	3.67	52.99
CS4	5046.00	25959.02	20913.02	4.14	66.39
CS5	4183.10	20958.77	16775.67	4.01	54.47
CS6	4285.00	20639.56	16354.56	3.82	52.25
CD(P=0.05)	76.4	82.5	854.6	0.21	1.8

**Local market price (₹/q): Lettuce ₹4000, capsicum ₹4000, cherry tomato ₹7000, cucumber ₹2000, broccoli ₹8000, tomato ₹3000, and snow pea ₹5000.*

In comparison to other regional findings, the performance of CS1, generating a Net Return of ₹24,553.73/100 m^2 (equivalent to Rs. 2,45,537.3 per 1000 m^{2}area), indicates that the optimized three-crop sequence provides substantially higher economic benefits per unit area.

The relative poor performance of sequences containing lower-yielding components, like CS2 and CS3, and the lowest productivity of CS4, further underscores the importance of crop choice. Although CS4: Broccoli - Cherry Tomato - Parthenocarpic Cucumber yielded a competitive B:C ratio (4.14) due to the high price of broccoli (₹8000/q), the overall cumulative yield (440.90) and production efficiency (1.40) were substantially lower than CS1. This validates the finding that crops with minimum yield potential, such as snow peas and broccoli, though they may fetch a high price, can ultimately compromise overall production efficiency metrics. This mirrors earlier findings where incorporating low-value crops into a rotation severely compromises the overall economic returns of the capital-intensive polyhouse structure, as seen with the Tomato–Cucumber–French bean–Coriander sequence (B:C 1.34).[3]

The high profitability per day (₹75.09/100m^2) of CS1 is the cumulative result of its robust cropping intensity and high-value components, confirming it as the optimal strategy for maximizing return on investment in the protected environment. Future policy interventions should focus on encouraging Farmer Producer Organizations (FPOs) and Self-Help Groups (SHGs) to facilitate direct marketing, which can reduce middlemen's commissions and increase the effective B:C ratio realized by the farmers.[8]

Future prospectus

Polyhouses provide a controlled environment that enables intensive multi-cropping and year-round production, allowing growers to adopt multiple crop cycles annually and ensure continuous supply of high-value crops. Crop sequencing in polyhouse systems is highly promising, driven by the need to enhance productivity, profitability and sustainability under protected cultivation. Future crop sequencing will emphasize sustainability through efficient use of water and nutrients, recycling of growing media and integration of biological pest management practices. Market-driven sequencing based on demand forecasting and price trends will help farmers maximize returns and reduce risks associated with market fluctuations. Furthermore, increased policy support, research initiatives and capacity-building programs will promote the adoption of scientifically designed crop sequences. Overall, the integration of advanced technologies, improved crop varieties, sustainable practices and market intelligence will make crop sequencing in polyhouse systems a key component of modern, high-efficiency horticulture.

Conclusion

During the present investigation, the cropping sequence CS1: Cherry Tomato - Parthenocarpic Cucumber – Lettuce performed well over all other cropping sequences. It demonstrated statistically superior cumulative yield (708.06 kg/100 m^2/year), production efficiency (2.36 kg/ m^2/day), and the highest benefit: cost ratio (4.75), which significantly exceeds established regional benchmarks. This high profitability is a result of effective year-round utilization of the polyhouse asset through three high-value crops, selected and timed to capitalize on off-season market prices.

Acknowledgments
The authors gratefully acknowledge the financial support received from the National Horticulture Board, Ministry of Agriculture and Farmers Welfare, Government of India to conduct this study.

Conflict of Interest
The authors declared that there are no conflicts of interest.

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