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EVALUATION OF AN INTEGRATED CROP MANAGEMENT PACKAGE FOR BLACK PEPPER: A FRONTLINE DEMONSTRATION

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ABSTRACT

A study was conducted to evaluate an Integrated Crop Management (ICM) strategy for improving black pepper productivity. Although, Karnataka has the largest cultivation area for black pepper, its productivity is below the national average due to nutrient imbalances and disease. This research aimed to address these issues through precision nutrient management and Integrated Pest Management (IPM). Conducted over two cropping seasons (2023-2025) on ten farmer-managed sites, the study used Frontline Demonstrations (FLDs) to compare the new ICM package with traditional methods. The ICM package included soil-test-based fertilizer application, micronutrients, biofertilizers and a combination of chemical and biological disease management. The results showed significant improvements in the demonstration plots. Disease incidence was drastically reduced, with wilt and leaf rot dropping by 74.20% and 67.20% respectively. Key yield attributes improved, leading to a substantial 44.60% increase in yield. The study also noted an improvement in soil health, evidenced by better pH stability and nutrient availability. Economically, input costs increased by 8%, gross returns jumped by 29%, resulting in a higher benefit-cost ratio of 3.54 compared to 2.92 for conventional plots. The study found a significant "extension gap," indicating that farmer education and training are crucial for the widespread adoption of this technology. Overall, the findings suggest that the ICM strategy is a sustainable and profitable solution for black pepper cultivation in the Malnad region.

Key words : Black pepper, Integrated Crop Management, Frontline demonstration, Extension gap, Sustainable agriculture.

Introduction

Black pepper, often hailed as the "King of Spices," holds a prominent place in global commerce with a rich history dating back thousands of years to its origins in the Western ghats of India. This enduring value is reflected in its modern economic significance. In 2023, the global black pepper market was valued at USD 2.78 billion and is projected to grow at a compound annual growth rate of 2.8 per cent from 2024 to 2032 (Ahuja, 2024). As the country of origin, India continues to be a major player in the global spice market, a position that contributes significantly to its agricultural economy. Despite a decline in its global market share since the 1960s, India remains a key supplier, with total pepper exports valued at $1.42 billion in 2023, making it the world's largest exporter of pepper that year (Saxena *et al.*, 2024). This export trade is a vital source of foreign exchange and provides employment and income to rural communities, particularly in the major producing states of Kerala and Karnataka (AN, 2020).

The challenges facing the global black pepper industry are particularly relevant to the state of Karnataka, a key production hub within India. Karnataka accounts for 60 per cent of the country's black pepper production and holds the largest area under cultivation with 190,000 hectares in 2022-23 (John *et al.*, 2023). However, a significant productivity gap exists. Despite its vast acreage, the state's average yield of 0.20 t ha^{-1} is notably lower than that of Tamil Nadu (0.33 t ha^{-1}) and Kerala (0.26 t ha^{-1}) (Ganaraja *et al.*, 20214). This paradox of high cultivation area but low yield signals a critical need for improved crop management technologies to enhance on-farm efficiency and profitability.

Hosanagara Taluk in Shivamogga district, located in the Malnad region is part of the Western Ghats, a zone characterized by a tropical climate and heavy rainfall, which is a fundamental requirement for black pepper cultivation (Nair, 2020). However, a study on the soils in the hilly zone of Karnataka, including areas in and around Hosanagara and Sagara taluks, revealed a number of intrinsic soil fertility problems (Niranjana *et al.*, 2018).

Conventional commercial farming, which dominates the industry, contribute to a negative feedback loop of environmental degradation. The high nutrient demand of black pepper is often met through the heavy and indiscriminate use of chemical fertilizers, which can degrade soil quality, lead to landscape erosion and pollute local water bodies. This over-reliance on chemical inputs weakens the crop's natural resilience. An imbalanced nutrient profile in the soil can make plants more susceptible to a variety of diseases (Bayýndýr and Küçükyumuk, 2025). This cycle of environmental stress, nutrient imbalance and increased disease pressure necessitates an even greater use of chemical inputs, perpetuating a system of diminishing returns and ecological harm. Therefore, the development of cultivation methods that are both resilient to climatic variations and environmentally benign is not merely an optional improvement but a strategic necessity for the long-term viability of the black pepper industry (Liang *et al*., 2025).

The shortcomings of conventional commercial farming of black pepper cultivation highlight the urgent need for a more holistic, scientifically guided and sustainable management system. The present study introduces and evaluates a novel integrated technology designed to address these deficiencies. This new approach is built upon two core pillars: Integrated Pest Management (IPM) and a soil-test-based nutrient management system. The first pillar, Integrated Pest Management, is an effective and environmentally sensitive approach that leverages a combination of common-sense practices to manage pests with minimal hazard to humans and the environment (Purnama *et al.*, 2025). The second pillar involves a soil-test-based fertilizer application, which represents a move from general to precision nutrition. This method begins with a scientific analysis of the soil's physical and chemical properties. Based on these results, a tailored fertilizer recommendation is provided to correct specific nutrient deficiencies. This targeted approach prevents the nutrient wastage and antagonism common in conventional farming, ensuring the plant receives the specific elements it needs for robust growth and disease resistance. The two pillars of this integrated technology are designed to work synergistically. A plant that is well-nourished through precision fertilization is inherently healthier and more resilient to stress, which in turn enhances the effectiveness of the IPM strategies by making the plant better able to withstand pest and disease pressure with less chemical intervention. This integrated approach is designed to overcome the core issues of conventional commercial farming in the region. By directly addressing the documented soil deficiencies and replacing wasteful practices with a targeted, scientific methodology, the technology aims to not only increase yields but also improve plant health, reduce input costs and provide a more sustainable, profitable model for black pepper growers.

To evaluate the efficacy and on-farm applicability of the new integrated technology, this study utilized a Frontline Demonstration (FLD) methodology. FLD is a unique and established approach in Indian agriculture, developed by the Indian Council of Agricultural Research (ICAR), which facilitates a direct interface between researchers and farmers (Choudhary *et al.*, 2025). Unlike traditional on-station trials, FLDs are conducted on farmers' fields under their management, but with scientific guidance, allowing for the evaluation of new technologies in a real-world context (Pilli *et al.*, 2025).

Hence the current study was undertaken to bridge the gap between institutional research and on-farm practice by employing a "frontline demonstration" methodology with an aim to address the following objectives:

- Evaluate the performance of the integrated crop management package in frontline demonstrations on black pepper plots in the study area.
- Assess the impact of the technology on key crop parameters and soil properties.
- To determine the statistical significance of the differences in outcomes between the new technology and the common farmer's practice, thereby providing a data-driven justification for its adoption by the farming community.

Materials and Methodology

Study site and experimental design

The study was conducted on ten farmer-managed black pepper (*Piper nigrum* L.) plots in Hosanagara taluk of Shivamogga district, representing typical growing conditions of the region. A paired-plot design was implemented, with each farm containing both conventional (Farmers practice) and technology-implemented (Demonstration) plots to account for site-specific variability. Each site was 0.40 ha; farmers practice was implemented in 50 per cent (0.20 ha) of the area and the technology to be demonstrated was implemented in the remaining area. The experiment was conducted for two consecutive years 2023-25. The integrated technology package was developed in collaboration with IISR, Calicut and IIHR, Bengaluru. The practices followed by existing farmers and the demonstrated technology is given in Table 1.

Observations recorded

Soil and plant parameters were monitored over two growing seasons. The yield and yield attributing parameters like spike length (in cm), weight (in g) and Yield (kg/100 vines) were recorded using standard procedures. The soil samples were collected once before pre-monsoon and one after harvest using standard soil sampling procedures. The collected samples were processed and subjected to laboratory analysis following standard analytical techniques. All the data recorded across two growing seasons were averaged to perform the statistical analysis and interpretation.

Soil reaction (pH)

Soil pH was determined by taking 10 g soil in 1:2.5, soil: water suspension by dipping the combined electrode (glass electrode plus calomel electrode) using a digital pH meter (Jackson, 1973).

Electrical conductivity (EC)

The electrical conductivity of soils was measured in 1:2, soil: water extract using an electrical conductivity bridge (Jackson, 1973). The results were expressed as dS m^{-1} at 25 C.

Available nitrogen

The available nitrogen content of the soil was determined by the modified alkaline $KMnO_4$ method, where the organic matter in soil was oxidized with alkaline $KMnO_4$ solution. The ammonia (NH_3) evolved during oxidation was distilled and trapped in boric acid mixed indicator solution. The total amount of NH_3 was estimated by titrating with standard acid (Subbiah and Asija, 1956).

Available phosphorus

Available phosphorus in soil samples was extracted by Olsen's method (0.5 $NaHCO_3$) for soils with pH $\geq$ 6.5 and Brays and Kurtz method (0.03 N NH_4F + 0.025 N HCl) for soils with pH < 6.5 as described by Jackson (1973). Phosphorus in the extractant was complexed by molybdenum and reduced by ascorbic acid in the presence of H_2SO_4 and estimated by using spectrophotometry at 660 nm.

Available potassium

Available potassium was extracted with neutral normal ammonium acetate (pH 7.0) and the content of potassium in the soil solution was estimated by a flame photometer (Jackson, 1973).

Table 1 : Details of the existing farmers practices and the demonstrated technology.

Input type	Farmer's practice (Conventional)	Demonstrated technology	
Source	Based on data acquired from ten farmers	IISR, Calicut and IIHR, Bengaluru	
Variety	Paniyur-2	Paniyur-2	
Nitrogen	80-150 g/vine	100.00-112.50 g/vine	Soil test-based fertilizer application
Phosphorus	30-80 g/vine	40.00-52.50 g/vine	
Potassium	0-60 g/vine	127.50-152.50 g/vine	
Micronutrients	-	*Pepper special* – micro nutrient mixture[5 gm/*l* (1st spray during spike initiation with onset of monsoon, 2nd spray- 2 months after first spray)]	
Biocontrol agents	-	➢ *Trichoderma harzianum* @ 50 g/vine ➢ Arka microbial consortia 20 gm/l (June & September)	
Chemical pesticide	➢ Boudreaux mixture ➢ Copper oxychloride ➢ Potassium phosphonate (Applied at variably rate, mostly excessive and post monsoon)	➢ Potassium phosphonate (0.3%) @ 5-10 liters / vine ➢ Copper oxychloride ➢ Metalaxyl MZ 8% + Mancozeb 64% ➢ Bordeaux mixture (1%) spray	

Available micronutrients (Zinc, iron, manganese and copper)

Available zinc, iron, manganese and copper were extracted by using DTPA extractant (0.005 M Diethylene Triamine Penta Acetic acid and 0.01 M $CaCl_2$ + 0.1 N Triethanol Amine at pH 7.3) and concentrations of Zn, Fe, Mn and Cu were measured by using Atomic Absorption Spectrophotometer (Perkin Elmer Model: PinAAcle 900F) (Lindsay and Norvell, 1978).

Disease incidence

To determine the percentage of disease incidence, a standardized methodology was followed to ensure accurate and reliable data collection. The disease incidence was calculated by using a simple formula. The number of infected plants was counted and then expressed as a percentage of the total number of plants.

$$Disease\ Incidence(\%) = \left(\frac{Number\ of\ Infected\ plants}{Total\ Number of\ plants}\right) \times 100$$

Statistical analysis

Data were tested for statistical significance using paired t-tests (α=0.05) with appropriate assumptions using SPSS software.

Yield gap analysis

The technology gap, extension gap and technological index (%) were calculated by following the procedures suggested by Samui *et al.* (2000) and Kumar (2014).

Technology gap = Potential yield – Demonstration yield

Extesion gap = Demonstration yield – Farmers' practice yield

$$\text{Technology index} = \frac{\text{Potential yield} - \text{Demonstration yield}}{\text{Potential yield}} \times 100$$

Results and Discussion

The evaluation of an integrated crop management technology for black pepper (*Piper nigrum* L.) through Frontline demonstrations across ten farmers' fields revealed statistically significant improvements in key yield parameters. The conventional practice, characterized by imbalanced fertilization, absence of micronutrient supplementation and sole reliance on chemical pest control, was compared against an improved protocol incorporating soil test-based nutrient management, biocontrol agents and scheduled fungicidal applications.

Effect on incidence of leaf rot and quick wilt

The implementation of integrated crop management technology resulted in statistically significant ($p < 0.05$) reductions in disease incidence in black pepper cultivation. Wilt incidence decreased by 74.20 *per cent* from 24 *per cent* to 6.20 per cent, while leaf rot incidence showed a 67.20 per cent reduction from 21.68 per cent to 7.10 per cent (Table 2). The substantial decreases in variance, particularly for wilt incidence (6.31 to 0.41), indicate consistent disease control across all treated plots (Table 2). These improvements can be attributed to multiple components of the integrated approach, including the soil drenching with potassium phosphonate (0.30%) that directly suppressed soil-borne pathogens like *Phytophthora capsici*, the primary wilt causative agent. The application of *Trichoderma harzianum* enhanced biological control through mycoparasitism, competition for nutrients and space and induction of plant systemic resistance. Additionally, the Arka microbial consortia and scheduled fungicide applications created a protective barrier against foliar pathogens, while improved plant vigour from balanced nutrition increased natural disease resistance (Lau *et al.*, 2020).

The achieved disease reduction has important practical implications for black pepper cultivation. The wilt incidence below 7 per cent represents a commercially acceptable threshold for sustainable production and the consistency of control across different field conditions suggests reliable performance of the technology package. When combined with the previously reported 44.60 per cent yield increase and soil improvements, these results demonstrate the comprehensive benefits of the integrated management system. The technology successfully addressed both soil-borne and foliar pathogens through combined chemical, biological and cultural methods, confirming the effectiveness of integrated disease management strategies (Nguyen *et al.*, 2020).

Effect on soil properties

The data pertaining to the initial soil properties of the experimental sites is given in Table 3. The soils of the experimental sites were acidic and non-saline in nature. The soils had low to medium available nitrogen, low to medium available phosphorus and low to high available potassium. The soils had sufficient amounts of available micronutrients except for available zinc which was deficient in some sites.

The analysis of soil parameters revealed significant changes ($p < 0.05$) following the implementation of integrated crop management technology in black pepper cultivation (Tables 4 and 5). Both conventional and technology-adopted plots showed significant increases in soil pH, though the technology plots demonstrated greater improvement (5.56 to 5.72) compared to

Table 2 : Effect of integrated crop management technology on incidence of leaf rot and quick wilt in black pepper (n=10).

Parameter	Conventional			Demonstration			Statistical outcome (α = 0.05)
	Mean	SD	Variance	Mean	SD	Variance	
Wilt Incidence (%)	24.00	2.51	6.31	6.20	0.64	0.41	Significant
Leaf Rot Incidence (%)	21.68	2.14	4.56	7.10	1.93	3.72	Significant

Table 3 : Descriptive statistics of initial soil properties of the experimental sites (n=10).

Parameters	Range	Mean	SD
Soil pH	5.45 - 6.30	5.78	0.30
Soil EC (dS m^{-1})	0.083 - 0.010	0.093	0.006
Available N (kg ha^{-1})	235.20 - 385.10	286.70	52.15
Available P_2O_5 (kg ha^{-1})	19.50 - 51.70	46.05	3.53
Available K_2O (kg ha^{-1})	138.50 - 340.70	194.92	79.36
Available Copper (mg kg^{-1})	5.50 - 6.80	6.28	0.41
Available Zinc (mg kg^{-1})	0.58 - 0.71	0.65	0.05
Available Iron (mg kg^{-1})	30.20 - 39.70	34.51	3.35
Available Manganese (mg kg^{-1})	16.00 - 22.80	20.16	2.35

and 5).

Micronutrient dynamics demonstrated notable changes, with available copper decreasing significantly in both systems, while zinc increased more substantially in conventional plots (0.60 to 0.73 mg kg^{-1}) than demonstration plots (0.60 to 0.68 mg kg^{-1}). Available iron exhibited divergent trends, decreasing in conventional plots (31.29 to 29.73 mg kg^{-1}) but increasing in demonstration-adopted plots (31.29 to 33.33 mg kg^{-1}). Manganese availability increased significantly in both systems, with demonstration plots showing greater enhancement (12.99 to 15.17 mg kg^{-1}) compared to conventional plots (12.99 to 13.15 mg kg^{-1}) (Tables 4 and 5).

Table 4 : Effect of conventional crop management practices on soil properties in black pepper cultivation (n=10).

Parameter	Pre-harvest			Post-harvest			Statistical Outcome (α = 0.05)
	Mean	SD	Variance	Mean	SD	Variance	
Soil pH	5.56	0.070	0.005	5.65	0.090	0.008	Significant
Soil EC (dS m^{-1})	0.099	0.007	0.000	0.10	0.006	0.000	Significant
Available N (kg ha^{-1})	247.97	18.560	344.690	233.30	16.740	280.290	Significant
Available P (kg ha^{-1})	43.55	3.010	9.060	42.03	2.970	8.840	Significant
Available K (kg ha^{-1})	140.05	6.510	42.420	146.02	7.030	49.430	Significant
Available Cu (mg kg^{-1})	6.36	0.190	0.030	5.67	0.070	0.000	Significant
Available Zn (mg kg^{-1})	0.60	0.040	0.000	0.73	0.070	0.000	Significant
Available Fe (mg kg^{-1})	31.29	2.500	6.250	29.73	1.480	2.190	Significant
Available Mn (mg kg^{-1})	12.99	1.180	1.390	13.15	1.250	1.560	Significant

conventional plots (5.56 to 5.65). Electrical conductivity (EC) exhibited contrasting responses, with conventional plots showing a significant increase (0.097 to 0.099 dS m^{-1}) while technology plots maintained stable EC levels. Macronutrient analysis revealed significant decreases in available nitrogen from 247.97 to 233.30 kg ha^{-1} in conventional and from 247.97 to 235.58 kg ha^{-1} in demonstration plots. Similar trend was observed with respect to available phosphorus, wherein it decreased from 43.55 to 42.03 kg ha^{-1} in conventional plots and from 43.55 to 42.94 kg ha^{-1} in technology plots, though the reductions were less pronounced in technology plots in both cases. Potassium levels increased significantly in both systems, with conventional plots showing greater gains (140.05 to 146.02 kg ha^{-1}) compared to demonstration plots (140.05 to 142.65 kg ha^{-1}) (Tables 4

These findings suggested that the integrated technology package influenced soil chemistry through multiple mechanisms, potentially including improved organic matter management, enhanced microbial activity and more balanced nutrient cycling (Li *et al.*, 2023). The technology appears to create more favourable soil conditions for black pepper cultivation, as evidenced by greater pH improvement, more stable EC maintenance and enhanced availability of key micronutrients like iron and manganese. The differential responses in nutrient dynamics between the two systems highlight the complex interactions between management practices and soil chemistry (Rusu *et al.*, 2025). The moderated nutrient fluctuations in demonstration plots suggest more efficient

Table 5 : Effect of integrated crop management practices on soil properties in black pepper cultivation (n=10).

Parameter	Pre-harvest			Post-harvest			Statistical Outcome ($\alpha = 0.05$)
	Mean	SD	Variance	Mean	SD	Variance	
Soil pH	5.56	0.070	0.005	5.72	0.110	0.012	Significant
Soil EC (dS m^{-1})	0.099	0.007	0.000	0.10	0.008	0.000	Not Significant
Available N (kg ha^{-1})	247.97	18.560	344.690	235.58	16.710	279.170	Significant
Available P (kg ha^{-1})	43.55	3.010	9.060	42.94	2.860	8.200	Significant
Available K (kg ha^{-1})	140.05	6.510	42.420	142.65	6.060	36.770	Significant
Available Cu (mg kg^{-1})	6.36	0.190	0.030	5.59	0.060	0.000	Significant
Available Zn (mg kg^{-1})	0.60	0.040	0.000	0.68	0.060	0.000	Significant
Available Fe (mg kg^{-1})	31.29	2.500	6.250	33.33	1.630	2.650	Significant
Available Mn (mg kg^{-1})	12.99	1.180	1.390	15.17	1.510	2.290	Significant

Table 6 : Effect of implementation of integrated crop management technology on soil properties in black pepper cultivation (n=10).

Parameter	Conventional			Demonstration			Statistical Outcome ($\alpha = 0.05$)
	Mean	SD	Variance	Mean	SD	Variance	
Soil pH	5.65	0.09	0.008	5.72	0.11	0.012	Significant
Soil EC (dS m^{-1})	0.10	0.01	0.000	0.10	0.01	0.000	Significant
Available N (kg ha^{-1})	233.30	16.74	280.290	235.58	16.71	279.170	Significant
Available P (kg/ha)	42.03	2.97	8.840	42.94	2.86	8.200	Significant
Available K (kg ha^{-1})	146.02	7.03	49.430	142.65	6.06	36.770	Significant
Available Cu (mg kg^{-1})	5.67	0.07	0.000	5.59	0.06	0.000	Significant
Available Zn (kg ha^{-1})	0.73	0.07	0.000	0.68	0.06	0.000	Significant
Available Fe (mg kg^{-1})	29.73	1.48	2.190	33.33	1.63	2.650	Significant
Available Mn (mg kg^{-1})	13.15	1.25	1.560	15.17	1.51	2.290	Significant

nutrient utilization and reduced losses in the integrated system, while the enhanced availability of critical micronutrients (particularly iron and manganese) likely contributed to improved plant health and productivity (Sulok *et al.*, 2021). These soil modifications not only support immediate crop performance but may also promote longer-term soil health.

Comparative analysis of post-intervention soil parameters between conventional and technology-implemented black pepper cultivation systems revealed statistically significant differences ($p < 0.05$) across all measured variables (Table 6). The integrated technology package resulted in significantly higher soil pH (5.72 vs 5.65) and reduced electrical conductivity (0.099 vs 0.097 dS m^{-1}), indicating improved soil chemical conditions. Nutrient availability patterns showed distinct variations, with demonstration plots maintaining significantly higher nitrogen (235.58 vs 233.3 kg ha^{-1}) and phosphorus levels (42.94 vs 42.03 kg ha^{-1}), while conventional plots exhibited greater potassium availability (146.02 vs 142.65 kg ha^{-1}). Micronutrient analysis demonstrated technology-induced enhancements in iron (33.33 vs 29.73 mg kg^{-1}) and manganese (15.17 vs 13.15 mg kg^{-1}), coupled with reduced available copper (5.59 vs 5.67 mg kg^{-1}) and available zinc (0.68 vs 0.73 mg kg^{-1}) concentrations (Table 6).

These findings suggested the integrated management system differentially influences soil nutrient dynamics through multiple mechanisms. The higher pH in demonstration plots likely reflects improved organic matter mineralization and buffering capacity from microbial inoculants (Moreno-Lora *et al.*, 2023). The divergent potassium pattern may indicate greater plant uptake in demonstration plots. The remarkable iron and manganese improvements (12.10 per cent and 15.40 per cent increases respectively) are particularly noteworthy, as these nutrients are critical for photosynthesis and enzyme activation (Zhang *et al.*, 2022; Khoshru *et al.*, 2023). These modifications collectively create a more physiologically favourable rhizosphere environment that supports plant health and productivity, while the reduced variance in several parameters suggests more consistent soil conditions across technology-implemented plots (Patra *et al.*, 2020). The results underscore the importance of whole-system approaches in managing tropical perennial crop soils, where multiple nutrient interactions must be simultaneously optimized for sustainable production (Wang *et al.*, 2024).

Effect on yield attributes and yield

The results demonstrated a 25.20 per cent increase in mean spike length, from 12.10 ± 1.35 cm under traditional practices to 15.15 ± 1.63 cm following intervention. Similarly, mean spike weight increased by 29.40 per cent, from 8.16 ± 1.49 g to 10.56 ± 1.82 g, while yield exhibited the most substantial improvement, rising by 44.60 per cent from 166 ± 21.88 kg/100 vines to 240.01 ± 27.06 kg/100 vines (Table 7). The observed improvements in spike length, spike weight and overall yield are statistically significant ($p<0.05$), validating the superiority of the new approach over traditional practices. The 25.20 per cent increase in mean spike length and a 29.40 per cent increase in mean spike weight are key indicators of improved plant health and nutrient assimilation. These findings align with existing literature on integrated crop management in perennial spices, demonstrating superior outcomes compared to conventional chemical-intensive approaches. The combination of soil test-based fertilizer application, which corrected nutrient imbalances and the application of the 'Pepper special' micronutrient mixture, which addressed specific deficiencies, likely contributed to stronger spike development and better fruit set. Furthermore, the use of biocontrol agents and timely fungicidal applications would have minimized yield losses by effectively controlling diseases (Nysanth *et al.*, 2022). The prevention of yield-reducing factors combined with the promotion of yield-enhancing factors resulted in a significant boost in overall productivity. Although the intervention significantly improved mean yields, the increased variance in post-treatment data (Yield variance rising from 478.67 to 732.30) suggested site-specific variability, potentially due to differences in initial soil conditions, farmer adherence to protocols or microclimatic variations (Chebet *et al.*, 2017). The results underscore the importance of adopting holistic management strategies that combine precision agriculture, biological control and targeted chemical interventions for sustainable black pepper production.

Economical aspects

The economic analysis of the pepper crop field-level demonstration (FLD) reveals a clear financial benefit from the implemented technology. The data, averaged over two consecutive crop seasons (2023-24 and 2024-25), consistently shows that while the technology involves a slightly higher investment, it yields significantly greater returns, leading to a substantial increase in profitability for farmers (Table 8).

The average gross cost for the demonstration plots was Rs. 66,455 per hectare, which was approximately 8% higher than the Rs. 61,650 per hectare cost for the conventional plots (Farmer's practice). This increased cost is a direct reflection of the inputs required for the new technology, which may include specialized fertilizers, pesticides or other management practices (Singh *et al.*, 2014).

However, this higher cost was effectively mitigated by a significant increase in revenue. The average gross return from the demonstration plots was Rs. 228,525 per hectare, a remarkable 29% increase compared to the Rs. 176,390 per hectare from the conventional plots. This indicates the technology's effectiveness in enhancing crop yield leading to higher market value (Patil *et al.*, 2018).

The most compelling evidence of the technology's success lies in the net return and Benefit-Cost (B:C) ratio. The average net return for the demonstration plots was Rs. 161,890 per hectare, which is Rs. 47,150 per hectare more than the Rs. 114,740 per hectare for the conventional plots. This represents a significant boost in net profitability for farmers adopting the new technology (Jha *et al.*, 2021).

The average B:C ratio further reinforces these findings. The demonstration plots achieved a B:C ratio of 3.54, meaning that for every rupee invested, the farmer received Rs. 3.54 in return. This is a considerable improvement over the B:C ratio of 2.92 for the conventional plots, demonstrating that the technology is not only profitable, but also highly efficient in generating returns on investment (Kumar *et al.*, 2018).

The economic data unequivocally supports the adoption of the new technology in pepper cultivation. The marginal increase in gross cost is far outweighed by the substantial gains in gross and net returns, making it a financially sound and highly beneficial intervention for farmers seeking to improve their income.

Yield gap analysis

The potential yield of the variety is reported to be 280.30 kg/100 vines on an average. The yield gap analysis revealed important insights into the new technology's performance and its adoption among local pepper farmers (Fig. 1). The extension gap, at 72.50 kg/100 vines, was a critical finding. It highlighted a significant opportunity for yield improvement, indicating that farmers' conventional practices had fallen considerably short of what could be achieved with the new technology (Singh *et al.*, 2019).

Table 7 : Effect of implementation of integrated crop management technology on yield and yield attributes in black pepper cultivation (n=10).

Parameter	Conventional			Demonstration			Statistical Outcome (α = 0.05)
	Mean	SD	Variance	Mean	SD	Variance	
Spike Length (cm)	12.10	1.35	1.82	15.15	1.63	2.66	Significant
Spike Weight (g)	8.16	1.49	2.22	10.56	1.82	3.32	Significant
Yield (kg/100 vines)	166.00	21.88	478.67	240.01	27.06	732.3	Significant

Table 8 : Economics of implementation of integrated crop management technology for black pepper cultivation (n=10).

Parameters	Conventional	Demonstration
Gross Cost (Rs. ha^{-1})	61650	66455
Gross Return (Rs. ha^{-1})	176390	228525
Net Return (Rs. ha^{-1})	114740	161890
B:C Ratio	2.92	3.54

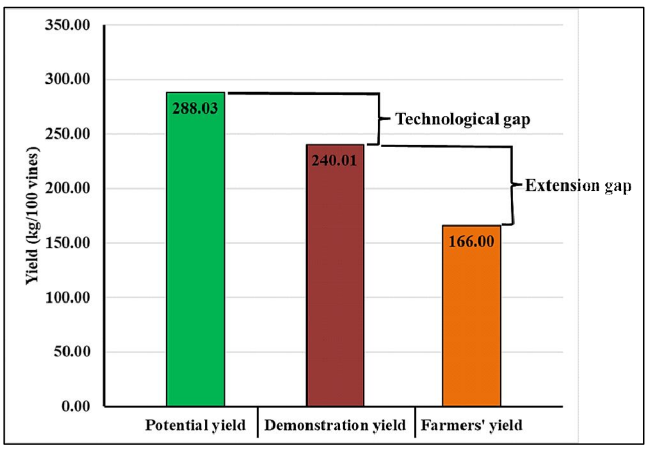

Fig. 1 : Yield gap analysis for black pepper in the study area.

This large gap suggested that a substantial increase in productivity and profitability was possible by encouraging farmers to adopt the new methods.

The technology gap of 51.53 kg/100 vines showed a notable difference between the demonstration plot's yield and the crop's maximum potential. This suggested that while the technology was effective, there was still some room for optimization and further improvement to reach the full genetic potential of the pepper variety. The technological index of 17.89% reinforced this, indicating that the demonstration technology was operating at approximately 82% of its potential efficiency.

Comparing the extension gap and the technology gap revealed a key takeaway: while there was some scope for improving the technology itself, the bigger challenge and opportunity lay in transferring the existing technology to farmers (Katare *et al.*, 2011). The extension gap was wider than the technology gap, which meant that closing the gap between farmers' practices and the demonstration plot's performance would have a greater immediate impact on overall productivity than further refining the technology (Parmar *et al.*, 2017). Therefore, a focused extension strategy involving training, field visits and farmer education was crucial to help them achieve yields closer to the demonstration plots and, in turn, significantly boost their income.

Conclusion

This study demonstrates that the integrated crop management technology significantly improves soil health and nutrient availability in black pepper cultivation compared to conventional practices which led to a 44.60 per cent increase yield compared to conventional farmer's practice. The technology resulted in favourable modifications to soil pH, electrical conductivity and nutrient dynamics, particularly enhancing the availability of critical micronutrients, while maintaining balanced macronutrient levels. The significant reduction in disease incidence and improvement in yield parameters, further validate the efficacy of this holistic approach. The findings highlight the importance of adopting integrated soil and crop management strategies that combine precision nutrient application, microbial inoculants and targeted amendments to optimize soil-plant interactions. By improving soil health and nutrient use efficiency, this technology not only boosts productivity but also promotes long-term sustainability in black pepper farming systems. In conclusion, while the technology has proven to be highly effective and productive, the primary challenge lies in bridging the gap between scientific knowledge and on-the-ground farming practices. A focused strategy on extension services, such as farmer training programs, field demonstrations and hands-on workshops, is necessary to help farmers close this extension gap and realize the full potential of the new technology.

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