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Conventional to Agroecological Vegetable Production: Five-Year Evidence on Productivity, Profitability, Variability and Whitefly Management under Smallholder Conditions in Southwest Ethiopia

Obsuman D Muleta

obsuman.muleta@ju.edu.et

Jimma University

Chala G. Kuyu

Jimma University

Esayas Mendesil

Jimma University

Abebe Nigussie

Jimma University

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Abstract

Smallholder vegetable production in Ethiopia often relies on synthetic inputs, while multi-year on-farm evidence on agroecological alternatives remains scarce. We evaluated a five-year (2021–2025) transition from conventional management (2021) to an agroecological package (2022–2025) on a multi-plot vegetable farm at the Eladale research site of Jimma University, southwest Ethiopia. From 2022 onward, synthetic fertilizers and insecticides were replaced with animal manure and garlic maceration, alongside crop diversification, rotation, and marigold companion planting in pepper and tomato plots. All eight crops showed significantly higher annual revenue under agroecological management than at baseline, whereas mean harvest increased in 30 of 32 comparisons ($p < 0.0001$). All crops profit margins increased, by up to about 18.5 percentage points. Since implied unit prices rose approximately three to five fold, these economic gains are nominal and partly price-driven. Monte Carlo simulation (1,000 iterations per crop) indicated wider revenue variability for pepper, carrot and garlic, than for beetroot and onion. Carrot had the highest fertilizer-use productivity (14.2 kg/kg), whereas garlic and pepper had the highest prices (170 and 85 ETB/kg). A composite stress index for conventional management was highest for tomato (0.62 units/kg) and pepper (0.37) and lowest for carrot (0.16). Whitefly was recorded in pepper and tomato in 2021, in 2022 only in tomato, and not in 2023–2025. The findings suggest association, rather than causation, as the agroecological practices were applied jointly without replication or untreated controls. The agroecological transition appears productive and viable, with crop selection weigh returns, risk and input efficiency.

1. Introduction

Global food systems face a persistent tension between maximizing crop productivity and limiting the environmental and economic costs of synthetic inputs. Emerging evidence from nutrition-sensitive agroecological interventions in East Africa suggests that diversified, ecologically managed farms can reduce food insecurity and depressive symptoms among women (Santoso et al., 2021). Smallholder vegetable production in Ethiopia is under increasing pressure. Erratic rainfall, rising temperatures, recurrent droughts and floods, and land degradation are increasingly threatening productivity and rural livelihoods in Ethiopia (Gebrechorkos et al., 2019; World Bank, 2024; Abebe and Amare, 2025; Asmare et al., 2026; Bokke et al., 2026). Hence, addressing these multifaceted challenges requires comprehensive approaches that enhance agricultural productivity, strengthen agricultural resilience, improve livelihood opportunities, and promote sustainable development practices across the country (Neglo et al., 2021; United Nations, 2023).

Similar to any conventional agriculture that is based essentially on external inputs, such as inorganic fertilizers, pesticides, and herbicides (Seufert et al., 2012), conventional vegetable production are also typically relies on synthetic fertilizer and insecticide to secure yield. But, this dependence carries rising input costs, pesticide resistance risk, and environmental externalities, particularly for pest prone Solanaceous crops such as tomato and pepper. In Ethiopia, frequent excessive pesticide application has been documented among smallholder vegetable producers (Mengistie et al., 2017), and pesticide residues have been reported in tomato and onion samples (Loha et al., 2020).

Agroecology is the redesign of farming systems around ecological processes such as nutrient cycling, biological pest regulation, and functional biodiversity. In addition to increasing production and productivity, protecting ecosystems and strengthening capacities to adapt to climate change and extreme weather conditions, this goal also promotes the global adoption of resilient agricultural practices (United Nations, 2023). Agroecology integrates crop diversification, agroforestry, soil and water conservation, and reduced reliance on synthetic inputs to build climate-resilient and biodiversity-friendly farming systems. The agronomic and environmental benefits of agroecology, such as improved soil health, enhanced ecosystem services, and greater resilience to climate shocks, are already well documented in low-income, rainfed contexts (Mouratiadou et al., 2024). Transitions to agroecological farming may be triggered by the need to mitigate negative environmental impacts generated by intensive approaches or from the need to improve food security for smallholder farmers in developing countries (Mouratiadou et al., 2024). Since agroecology encompasses a range of principles that vary in both scale and timeframe, transitions to agroecology have been depicted as a series of levels, from adoption of farming practices and cropping systems to more complex and comprehensive food system redesign (Gliessman, 2014).

Agroecology is perceived as a prominent solution to increase the sustainability of agricultural and food systems (Wezel et al., 2020). It is a dynamic concept that has gained importance and recognition in recent years in scientific, agricultural, and political discourses. This is due to its varied potential benefits such as stabilization of yields and productivity, enhanced resource use efficiency, reduced greenhouse gas emissions, and culturally sensitive and socially just approaches (Pretty et al., 2006; D'Annolfo *et al*., 2021). A larger majority of studies (78%) found evidence with positive outcomes linked to the use of agroecological practices on food security and nutrition in of smallholders in low and middle income countries (Kerr et al., 2021). Agroecology has great importance in the African context because most agricultural production is in the hands of smallholder peasant farmers who often do not have enough money to invest in costly conventional agricultural inputs (Altieri, 2009). With agroecological farming, manure and compost can easily be obtained from household waste, while animal droppings and urine can be used as fertilizers and pesticides (Snapp et al., 2010)

This study addresses three key research gaps. First, much of the existing evidence from Ethiopia comes from short-term, single-crop trials of one input (Gererufael et al., 2020; Tamene and Alemu, 2026), whereas smallholders typically manage multiple crops and agroecological practices simultaneously across several seasons. Second, to our knowledge, few studies integrated yield, profitability, production risk, input-use productivity, and pest outcomes in a single multi-year farm record. Third, environmental burdens are seldom compared among crops within the same farm, although composite indices offer a potential approach for such comparisons (Sabiha et al., 2016). This study addresses these gaps using five years (2021–2025) of on-farm records from a multi-plot vegetable farm at the Eladale research site of Jimma University, southwest Ethiopia. The 2021 season was managed conventionally and served as the reference (baseline). From 2022 onward, synthetic fertilizer and insecticide were replaced by animal manure and garlic maceration, together with crop diversification, rotation, and marigold companion planting in the pepper and tomato plots. The overall objective of this study was to evaluate the

effectiveness of agroecological vegetable production relative to conventional production under actual smallholder conditions. Since the practices were introduced together and were not randomized, the results are interpreted as associations within a real-world transition rather than as causal effects.

2. Materials and Methods

2.1. Description of the study area

The study was conducted at Eladale research site of Jimma University College of Agriculture and Veterinary Medicine (JUCAVM), Jimma Zone, Oromia Regional state, Ethiopia, during the 2021–2025 cropping seasons. The research site is located at an altitude of approximately 1,722 m above sea level, at 7°33'00"N latitude and 36°57'00" E longitude). The site has mean maximum and minimum annual temperatures of 26.8°C and 11.4°C, respectively. The mean annual maximum and minimum relative humidity are 91.4% and 39.92%, respectively, while mean annual rainfall is approximately 951.5 mm. The soil is predominantly reddish-brown clay, with soil pH ranging from 5.07 to 6.0 (BPEDORS, 2000).

The Eladale research site has been used as an educational and research farm for evaluating alternative agricultural management practices. The present study used farm-level production records collected over five consecutive cropping seasons to compare crop productivity, economic performance, inputs use, and selected environmental indicators under conventional and agroecological farming system.

2.2. Study Design and Farm Management

The study followed a longitudinal farm-based comparative design covering five consecutive cropping seasons (2021–2025). The 2021 cropping season represented the conventional management baseline, whereas the 2022–2025 cropping seasons represented the agroecological management period.

According to the farm's conventional production practices, crops were managed using synthetic fertilizer and synthetic insecticide during the 2021 conventional season. Beginning in 2022, the farm adopted an agroecological management package based on botanical pest management, organic nutrient management, crop diversification and rotation, and companion planting with marigold. The Field was organized into four major plots with different crop group: (1) root vegetables (beetroot, carrot, garlic, and onion); (2) leafy vegetables (cabbage and lettuce); (3) pepper; and (4) tomato. Each crop was cultivated on standardized beds of approximately 30 m².

In 2022, all crops were cultivated on the same plots used during the 2021 conventional baseline. From following seasons, crops were rotated among different plots as part of the farm's agroecological management practices. Therefore, the study was not a permanent fixed-plot experiment. The 2021 conventional was used as the reference condition for comparison with the subsequent agroecological farming practices (2022–2025), and the analysis was intended to characterize practical differences in farm performance between management periods rather than to estimate a randomized treatment effect.

From 2022 onward, three basic farming management changes were applied in combination as indicated in the following sub-sections.

2.2.1. Organic fertilizer management

During the 2021 conventional season, synthetic fertilizer was used at a mean application rate of approximately 2.05 kg/bed. Beginning in 2022, synthetic fertilizer was replaced by animal manure as the principal nutrient input, with a mean application rate of approximately 8.38kg/bed during 2022–2025. The quantity and type of fertilizer applied to each bed were recorded and used in subsequent analysis of inputs use and farm economic performance. Because synthetic fertilizer and animal manure differ in nutrient concentration, comparisons of material quantities were interpreted separately from nutrient based efficiency measure.

2.2.2. Botanical pest management

Synthetic insecticide used during the conventional baseline cropping season was replaced with garlic-based botanical preparation during the agroecological management period. Garlic maceration was used a biopesticide for management of whitefly infestation. The garlic based preparation was applied at approximately 1 L of spray solution per 10 m² of cropped area over two application rounds. Field observations of insect infestation and qualitative efficacy of the treatment were recorded during the cropping season. The application of garlic-based botanical preparations for insect management is consistent with previously reported field applications of garlic-derived botanicals against (Sumaili et al., 2021).

2.2.3. Marigold companion planting

Marigold was introduced as a companion plant in pepper and tomato production beginning in agroecological farming in 2022. Marigold was established within the pepper and tomato beds, with eight beds allocated to the companion planting arrangement in each relevant sub-plot.

Marigold was not harvested or marketed as production crop and therefore was not assigned yield or revenue values in the production dataset. Its function was to serve as a companion plant within the agroecological pest management system. The use of marigold as a companion plant for management of insect pests including whitefly, has previously documented (Conboy et al., 2019). Since the study did not include a separate randomized treatment isolating the effect of marigold, its contribution was assessed as a component of overall agroecological management package rather than as an independently randomized treatment.

2.3. Data Collection

Production and management data were collected for each crop, bed, and cropping season during 2021–2025. Recorded variables included labor requirements, input use, production costs, fertilizer or manure type and quantity, insect infestation, pest management treatment, qualitative treatment efficacy, harvested quantity, and sales revenue.

Labor was recorded in terms of the number of persons involved and the number of working days required per bed. Input costs were recorded in Ethiopian birr (ETB) per bed. Fertilizer and manure quantities were recorded in kilograms (kg) per bed. Crop harvest was recorded as harvested weight in kilograms, while revenue was recorded as the corresponding sales value in ETB.

Observations related to insect infestation and the field performance of the garlic-based botanical treatment was also recorded for the agroecological management period. Information on marigold use in pepper and tomato production was documented as part of the farm management records. The collected data were used to describe sequential trends in crop harvest, revenue, production costs inputs use, nutrient use efficiency, market value, and selected environmental indicators under conventional and agroecological farm management.

2.4. Data Analysis

2.4.1. Crop productivity and revenue

Crop productivity was expressed as harvested weight per bed (kg/bed), while economic output was expressed as revenue per bed (ETB/bed). For each crop and cropping season, descriptive statistics, including mean and standard deviation were calculated. The 2021 conventional season was used as the reference year, and the performance of the same crops during the agroecological management period (2022–2025) was compared with it.

Annual changes in harvest and revenue were expressed as absolute differences and percentage changes comparative to the 2021 baseline. Comparisons were interpreted at the crop and management period level rather than as direct repeated measurements of permanently plots as of that crop locations were rotated after 2022.

2.4.2. Economic Analysis

Production profitability was assessed using revenue and documented production costs. Gross profit was calculated as:

Profit margin was expresses as:

$$Gross\ Profit = Revenue - Production\ cost$$

$$Profit\ margin\ (\%) = [(\ Revenue - Production\ cost)/Revenue] \times\ 100$$

Production cost included the recorded costs of applicable farm inputs and labor. Where an input was produced on-farm and did not have a direct purchase price, its cost was treated according to the cost-recording procedure used by the farm. The economic performance was compared between crops and across the conventional baseline and agroecological farm management periods.

2.4.3. Nutrient-use efficiency

Nutrient-use efficiency (NUE) was calculated as harvested yield relative to the recorded fertilizer input, consistent with the definition used in the manuscript:

$$NUE = Total\ harvest\ \ (kg)\ /Total\ fertilizer\ applied$$

Since the available farm records articulate fertilizer input as martial quantity rather than nutrient-equivalent quantity, the resulting measure represents yield per unit of fertilizer material applied rather than nutrient specific recovery efficiency. This difference was considered when interpreting the NUE results.

2.4.4. Monte Carlo simulation

A Stochastic Monte Carlo simulation was used to characterize variability in crop yield, revenue, and fertilizer use. For each crop, 1,000 simulation iterations were performed using the available farm records as the empirical basis for the simulation. The simulation generated distribution of possible yield, revenue, and fertilizer use outcomes rather than depending solely on observed mean values. The resulting distributions were summarized using the mean and standard deviation and were used to describe relative variability among the evaluated crops. Since the current farm records do not document a separate probability distribution fitting procedure, the simulation results were interpreted as stochastic representations of variability in the observed data rather than as probabilistic forecasts of future production.

2.4.5. Environmental stress index

A composite environmental stress index was used to facilitate relative comparison of environmental burden among the eight vegetable crops under conventional farm management. The index followed the general concept of composite environmental impact indices used in agricultural sustainability assessment (Sabiha et al., 2016).

The environmental stress values were generated through Monte Carlo simulation and integrated uncertainty across multiple environmental impact factors. Stress intensity was expressed per kilogram of harvested crop by dividing the composite environmental stress units by average harvested quantity. The resulting values were intended for relative comparison among crops and did not represent direct physical units such as kg CO^2- equivalent or m^3 of water.

The available manuscript records do not provide sufficient methodological detail to reconstruct the individual environmental impact components, probably distributions, or weighting procedure used to generate the composite stress score. Therefore, the index is interpreted as a relative, modeled indicator of environmental stress rather than an absolute environmental footprint.

2.4.6. Insect incidence and management observations

Pest management observations were summarized descriptively for the pepper and tomato production plots. The presence or absence of recorded whitefly infestation, management treatment applied,

application rate, and qualitative treatment efficacy were compared between the conventional baseline and agroecological farm management period.

Since marigold, garlic maceration, crop rotation, and other agroecological practices were implemented as a combined management package and no untreated control was maintained, changes in pest incidence were interpreted as associations with the overall management transition rather than as evidence of an independent casual effect of marigold or garlic maceration.

2.4.7. Statistical comparison

Descriptive comparisons were first performed to c

haracterize differences in crop harvest, revenue, input use, and profitability between the conventional baseline of 2021 and the agroecological management period of 2022–2025.

Given that the conventional and agroecological management periods were not established as randomized experimental treatments and that the crop plots were rotated after 2022, statistical comparisons were interpreted as comparisons of observed farm performance between management periods rather than estimates of a randomized treatment effect. Where inferential statistical tests were retained in the analysis, their results were reported together with the descriptive differences and interpreted in the context of the observational, longitudinal farm design. Statistical significance was evaluated at $\alpha = 0.05$.

3. Results

3.1. Harvest and Revenue Trends

Across the five-year observation period, mean harvest and revenue generally increased following the transition from conventional farm management in 2021 to the agroecological farm management implemented from 2022–2025 (Table 1; Figs. 1 and 2). All observed vegetable crops showed higher mean harvest and revenue in 2025 than in the 2021 conventional reference year. Since the study used a longitudinal, farm-based comparative design rather than a randomized fixed-plot experiment, the findings represent observed changes between management periods and should not be interpreted as isolated causal effects on individual agroecological practices.

The magnitude and sequential pattern of change varied among crops. By 2025, carrot had increased in mean harvest from 30.88 kg/bed in 2021 to 48.00kg/bed, while mean revenue increased from 926.25 to 4,320.00 ETB/bed. Pepper showed a similar increase in revenue, from 496.76 ETB/bed in 2021 to 4,239.71 ETB/bed in 2025. These correspond to approximately 367% and 753% increase in revenue respectively, relative to the 2021 reference year. Garlic showed the largest proportional increase in mean harvest, rising from 6.00kg/bed in 2021 to 14.88 kg/bed in 2025, equivalent to an increase of approximately 148%.

For the majority crop-year comparisons, the original statistical analysis indicated statistically significant differences from the 2021 reference values ($p < 0.0001$). However, lettuce showed a different pattern. Its mean harvest increased from 23.28 kg/bed in 2021 to 32.56 kg/bed in 2022 and 33.00 kg/bed in 2025. The differences in lettuce harvest were statistically significant in 2022 ($p < 0.0001$) and 2025 ($p = 0.0003$), but not in 2023 ($p = 0.0597$) or 2024 ($p = 0.0924$). In contrast, lettuce revenue was higher than the 2021 reference in each post-baseline year, with < 0.0001for all four comparisons.

Generally, the results indicate that the agroecological management period was escorted by increases in both physical output and farm-gate revenue for most crops, although the magnitude and consisencey of change differed among crops and years. The continuing increase in revenue was generally larger than the corresponding increase in harvested quantity for several crops, indicating differences in crop specific market values and annual selling prices.

Table 1
Mean harvest and revenue of eight vegetable crops under conventional (2021) and agroecological management (2022–2025)

Crop	Year	Mean Harvest (Kg)	Mean Revenue (ETB)	Harvest t-value	Harvest p-value	Revenue t-value	Revenue p-value
Beetroot	2021	14.22	213.33	-	-	-	-
	2022	22.67	566.67	-12.10	< 0.0001	-26.21	< 0.0001
	2023	24.44	855.56	-16.31	< 0.0001	-48.58	< 0.0001
	2024	24.50	980.00	-17.25	< 0.0001	-63.30	< 0.0001
	2025	25.13	1,256.25	-18.01	< 0.0001	-70.38	< 0.0001
Cabbage	2021	30.56	458.44	-	-	-	-
	2022	40.81	1,020.31	-14.99	< 0.0001	-42.74	< 0.0001
	2023	39.06	1,367.19	-12.61	< 0.0001	-56.59	< 0.0001
	2024	39.00	1,560.00	-9.55	< 0.0001	-38.04	< 0.0001
	2025	40.88	2,248.12	-10.12	< 0.0001	-37.30	< 0.0001
Carrot	2021	30.88	926.25	-	-	-	-
	2022	46.88	1,875.00	-24.07	< 0.0001	-39.92	< 0.0001
	2023	46.81	2,574.69	-24.42	< 0.0001	-56.33	< 0.0001
	2024	46.75	3,038.75	-21.21	< 0.0001	-51.36	< 0.0001
	2025	48.00	4,320.00	-21.10	< 0.0001	-54.55	< 0.0001
Garlic	2021	6.00	450.00	-	-	-	-
	2022	11.19	1,118.75	-11.22	< 0.0001	-15.18	< 0.0001
	2023	13.31	1,996.88	-21.52	< 0.0001	-36.01	< 0.0001
	2024	14.19	2,837.50	-23.21	< 0.0001	-40.69	< 0.0001
	2025	14.88	3,718.75	-25.33	< 0.0001	-45.62	< 0.0001
Lettuce	2021	23.28	698.33	-	-	-	-
	2022	32.56	1,302.22	-5.29	< 0.0001	-11.14	< 0.0001
	2023	27.22	1,497.22	-2.08	0.0597	-11.41	< 0.0001
	2024	26.56	1,991.67	-1.88	0.0924	-20.95	< 0.0001
	2025	33.00	2,640.00	-5.55	0.0003	-30.32	< 0.0001

Crop	Year	Mean Harvest (Kg)	Mean Revenue (ETB)	Harvest t-value	Harvest p-value	Revenue t-value	Revenue p-value
Onion	2021	12.81	358.75	-	-	-	-
	2022	19.44	738.63	-14.82	< 0.0001	-25.72	< 0.0001
	2023	20.63	1,134.38	-15.44	< 0.0001	-33.50	< 0.0001
	2024	20.56	1,439.38	-14.41	< 0.0001	-34.56	< 0.0001
	2025	22.44	1,907.19	-19.83	< 0.0001	-48.60	< 0.0001
Pepper	2021	16.56	496.76	-	-	-	-
	2022	26.74	1,069.41	-19.85	< 0.0001	-30.17	< 0.0001
	2023	26.15	1,830.29	-20.36	< 0.0001	-48.96	< 0.0001
	2024	25.68	2,567.65	-18.31	< 0.0001	-50.31	< 0.0001
	2025	28.26	4,239.71	-25.80	< 0.0001	-71.11	< 0.0001
Tomato	2021	12.03	360.88	-	-	-	-
	2022	17.62	704.71	-16.42	< 0.0001	-27.96	< 0.0001
	2023	19.65	982.35	-19.02	< 0.0001	-34.58	< 0.0001
	2024	21.06	1,263.53	-27.34	< 0.0001	-55.83	< 0.0001
	2025	22.65	2,038.24	-26.36	< 0.0001	-54.04	< 0.0001

3.2. Profit Margins

Profit margins increased over the study period for all eight vegetable crops when the 2021 conventional reference year was compared with the subsequent agroecological management years (Fig. 3). However, the magnitude of improvement varied among crops. Carrot had the highest profit margin throughout the study period, increasing from 93.41% in 2021 to 97.10% in 2025. Beetroot and cabbage showed the largest absolute increases in profit margin between 2021 and 2025, with improvements of approximately 18.5 and 15.5 percentage points, respectively. The remaining crops also showed higher profit margins during the agroecologcal management period than in the 2021 baseline year.

The observed improvement in profit margins corresponded with the transition from synthetic fertilizer and insecticide inputs to animal manure and botanical pest management, together with crop diversification, rotation, and companion planting. Nevertheless, because these practices were introduced as a combined management package and were not independently randomized, the observed improvement in profitability cannot be attributed to any single practice. Rather, the results depicted the economic performance of the farm under the management system implemented during 2022–2025.

The profitability pattern observed in this farm-based assessment is broadly consistent with evidence from larger comparative studies. Sánchez et al. (2022), in a global meta-analysis of diversified farming systems, reported that diversified systems generally achieved higher gross income and profits than simplified systems, although costs and labor requirements also varied among systems. More recent evidence from a 2026 meta-analysis of agroecological transitions in the Global South likewise reported positive average changes in crop yield, gross income and production costs, while emphasizing that outcomes vary with management and local biophysical conditions.

3.3. Monte Carlo Simulation of Yield, Revenue, and Fertilizer Use

The Monte Carlo simulation (1,000 iterations per crop) was used to summarize variation in yield, revenue, and fertilizer input; crop-level means and standard deviations are presented in Fig. 4. The simulated revenue distributions were comparatively more variable for garlic, pepper, and carrot, whereas beetroot and onion showed narrower distributions.

The simulation indicates that yield magnitude and revenue potential were not distributed in the same order across crops. Carrot had the highest simulated mean yield (approximately 44 kg), followed by cabbage (about 38 kg), whereas garlic had the lowest mean yield (about 12 kg). However, the revenue simulation placed carrot, pepper, and garlic among the higher-return crops. This divergence is important because it shows that physical productivity alone does not determine the economic value of a crop. In the present dataset, the relatively high selling prices of garlic and pepper partly compensate for their lower simulated yield, whereas carrot combines high yield with a more moderate unit price. The relatively wide revenue distributions for garlic, pepper, and carrot also indicate greater exposure to variation in the economic outcome, even though their mean revenues were comparatively high. This interpretation is consistent with empirical risk analyses showing that yield, input response, and financial returns can vary substantially across crops and production environments, and that production risk should therefore be evaluated jointly with expected returns rather than from mean yield alone (Rötter et al., 1997). More recent evidence from smallholder systems in sub-Saharan Africa likewise shows that incorporating uncertainty into fertilizer and profitability decisions can change the economically preferred input strategy, particularly for risk-averse farmers (Asamoah *et al*., 2026).

The revenue-risk pattern also has implications for the crop diversification strategy used in this study. A farm that combines crops with different yield and revenue distributions can reduce dependence on the performance of any single crop and thereby spread production and market risk. This is supported by empirical modelling from diversified farming systems, where combinations of enterprises with imperfectly correlated returns reduced downside risk and improved the risk-return trade-off (Bell et al., 2021). Similarly, a global meta-analysis of 119 peer-reviewed studies found that diversified farming systems were at least as profitable as simplified systems, with higher gross income generally compensating for higher labour or management costs (Sánchez et al., 2022). More recent evidence synthesizing 184 meta-analyses and 17,989 original studies further indicates that the financial benefits

of agricultural diversification can increase over time, even when yield effects are not consistently positive (Raveloaritiana and Wanger, 2026). Thus, the relatively different revenue distributions observed among the eight crops should not be interpreted simply as evidence that high-variance crops are undesirable. Rather, the results suggest that high-return crops such as garlic and pepper may be valuable components of a diversified farm portfolio when their greater revenue variability is balanced by more stable crops such as beetroot and onion.

The fertilizer-demand simulation provides an additional dimension to this risk-return assessment. Cabbage and tomato showed comparatively high simulated fertilizer requirements, whereas carrot and garlic required less fertilizer in the simulated distributions. Importantly, higher fertilizer demand did not translate directly into higher simulated revenue or nutrient-use efficiency. This distinction agrees with field evidence from vegetable systems in sub-Saharan Africa showing that organic amendments can increase vegetable yield and nitrogen-use efficiency, but that responses depend on crop and fertilizer source (Anyega et al., 2021). Evidence from Ethiopia is particularly relevant: Mengistu et al. (2017) found that integrating vermicompost with mineral fertilizer increased tomato yield and produced the highest economic benefit among the tested nutrient combinations, while Gererufael et al. (2020) reported significant yield responses of onion to both farmyard manure and nitrogen, with economically attractive combinations of the two nutrient sources. These studies support the interpretation that locally available organic inputs can contribute to productive nutrient management, but they also show that the agronomic and economic response depends on the crop, nutrient rate, and source. Therefore, the higher simulated fertilizer demand for cabbage and tomato in the present study should not be interpreted as evidence of excessive fertilizer use by itself; it indicates greater input requirements relative to the other crops and should be evaluated together with yield, revenue, and NUE.

Taken together, the Monte Carlo results strengthen the economic interpretation of the five-year transition by showing that agroecological performance should be assessed not only by changes in mean yield and revenue but also by the dispersion of possible outcomes and the associated input requirements. The results suggest a useful portfolio trade-off: carrot combines high simulated yield with high nutrient-use efficiency, garlic combines relatively low yield with high market value and relatively wide revenue variability, while beetroot and onion show comparatively narrower revenue distributions. Such differences can guide crop allocation and risk-spreading decisions under smallholder conditions. Nevertheless, the simulation should be interpreted as an uncertainty analysis rather than a direct estimate of future probabilities. This is particularly important for fertilizer decisions because recent evidence shows that site-level variability and farmer risk preferences can materially alter economically optimal nutrient rates (Asamoah *et al*., 2026).

3.4. Nutrient Use Efficiency and Market Value

Table 2 compares the fertilizer use productivity index and average selling price for the eight crops. Carrot had the highest index (14.2 kg/kg), followed by lettuce (8.0 kg/kg), whereas tomato had the lowest value (2.2 kg/kg). These differences indicate variation among crops in harvested yield relative to the total mass of fertilizer applied under the study conditions. Carrot and tomato had the same reported average

selling price (60 ETB/kg), showing that unit price alone does not explain their contrasting fertilizer-use productivity. Carrot's relatively high index also coincided with lower modeled environmental-stress intensity under conventional management.

Market value did not follow the same ranking as fertilizer-use productivity. Garlic had the highest average selling price (170 ETB/kg) despite a relatively low index (2.8 kg/ kg), while pepper had a selling price of 85 ETB/kg and an index of 3.4 kg/kg. These results illustrate that crops can differ in their relative appeal depending on whether the criterion is harvested output per unit of fertilizer or the price received per kilogram. However, a high unit price does not by itself demonstrate high profitability: production costs, labour, yield, post-harvest losses, market access, and price variability also determine the financial return. The results indicate that fertilizer-use productivity and market value capture different aspects of crop performance. Carrot and lettuce had the highest values for the study's fertilizer-use productivity index, whereas garlic and pepper had the highest average selling prices. These contrasts suggest that crop planning should consider multiple objectives, including yield, fertilizer requirements, expected revenue, production costs, labour, market access, and price risk. Diversification may help balance these objectives. For the present farm, carrot appears comparatively strong in harvested output per unit of fertilizer applied, while garlic and pepper command higher prices per kilogram. These are preliminary indicators rather than profitability rankings; a defensible crop recommendation would require crop-specific net returns and consideration of production and market constraints.

Evidence from Ethiopian vegetable producers similarly identifies output prices and market bargaining, alongside production costs, as important influences on profitability (Aliyi et al., 2021). Nationally representative evidence also links farm size, output value, and profit outcomes, with input use and production technology contributing to observed differences (Ameye *et al*., 2025). Market value should therefore be considered alongside, rather than as a substitute for, fertilizer-use productivity and cost-based economic indicators.

Field studies in Ethiopia likewise show that crop response and economic return depend on nutrient source, application rate, and crop-specific requirements. In northwestern Ethiopia, Gererufael et al. (2020) reported that farmyard manure and mineral nitrogen affected onion growth and yield; importantly, the treatment with the highest yield was not necessarily the economically preferred option. In western Ethiopia, Bebayehu et al. (2023) found that combining NPSB fertilizer with vermicompost increased tomato yield and produced the highest net benefit among the tested treatments. These studies reinforce that increasing nutrient inputs does not necessarily produce a proportional increase in economic return: outcomes depend on crop response and the costs and benefits of the input combination. In the present dataset, tomato had the lowest fertilizer-use productivity index, although its average selling price (60 ETB/kg) was similar to that of several other crops.

Table 2
Nutrient use efficiency (NUE) and average selling price across the eight evaluated crops.

Crop	Nutrient use efficiency (kg kg^{-1})	Average selling price (ETB kg^{-1})
Beetroot	6.0	34.9
Cabbage	5.0	35.0
Carrot	14.2	60
Garlic	2.8	170
Lettuce	8.0	60
Onion	4.7	60
Pepper	3.4	85
Tomato	2.2	60

Note: Nutrient use efficiency (NUE) represents the harvested yield produced per unit of nutrient input (kg/ kg). Average selling prices are expressed in Ethiopian Birr (ETB/kg).

3.5. Environmental Stress Intensity under Conventional Farming

Under conventional management, tomato had the highest modeled environmental stress intensity (0.62 index units/kg harvested), followed by pepper (0.37 units/kg). Garlic and onion each recorded 0.29 unit/kg, while beetroot, cabbage, and lettuce ranged from 0.21 to 0.22 units/kg. Carrot had the lowest value (0.16 units/kg). These results identify tomato and pepper as the crop zones with the highest modeled stress per unit of harvested product in the baseline system. Because the values are derived from a composite index, they indicate relative differences within this study rather than measured quantities of a specific environmental impact.

Table 3
Environmental stress analysis under conventional farming: average harvest, composite stress units, and stress intensity per kilogram harvested.

Crop	Avg. Harvest (kg)	Environmental Stress Units	Stress Intensity (Units/kg)
Beetroot	22.09	4.85	0.22
Cabbage	38.03	8.53	0.22
Carrot	43.74	7.12	0.16
Garlic	11.82	3.42	0.29
Lettuce	28.67	5.92	0.21
Onion	19.24	5.63	0.29
Pepper	24.66	9.24	0.37
Tomato	18.76	11.72	0.62

Note: These environmental stress values are composite index scores generated through a Monte Carlo simulation (1,000 iterations) that integrates uncertainty across multiple environmental impact factors. The values are intended for relative comparison of environmental stress among crop types under conventional farming and do not represent direct physical units such as kg CO_2-equivalent or m^3 of water.

The environmental stress intensity index complements the yield, revenue, and fertilizer-use productivity results by showing that crop performance differs across economic and environmental dimensions. The high baseline scores for tomato and pepper are relevant to the study's subsequent shift from synthetic inputs toward an agroecological management package that included manure, crop diversification and rotation, marigold companion planting, and garlic-based biopesticide. Evidence from Ethiopian smallholder vegetable systems indicates that agroecological integrated pest management can reduce insecticide use: Williamson et al. (2025) reported an average 73% reduction in insecticide-application frequency among trained farmers, alongside reduced use of highly hazardous pesticides and no adverse effects on yield or profit. This external evidence supports the plausibility of reducing pesticide-related pressure through integrated management, but it does not demonstrate that any single intervention caused the scores observed in the present study.

The relatively low stress intensity for carrot (0.16 index units/kg) coincided with its comparatively high fertilizer-use productivity in Section 3.4. One possible explanation is that a larger harvested quantity reduces an impact score expressed per kilogram of product; however, the present composite index does not allow this relationship to be isolated or interpreted causally. More broadly, environmental impacts per unit of output depend on both input use and production level. In a life-cycle study of cherry tomato, Guo et al. (2021) reported that reducing fertilizer and pesticide inputs lowered several modeled impacts while maintaining yield and increasing net profit. This finding illustrates the potential for improved input

management to reduce environmental pressure without necessarily reducing production, although the specific effects depend on the production system and assessment boundary.

Evidence from Ethiopia also establishes the relevance of pesticide management to environmental and food-safety concerns in vegetable production. Mengistie et al. (2017) documented frequent and, in some cases, excessive pesticide applications among smallholder vegetable producers in the Central Rift Valley, including repeated insecticide and fungicide use in tomato production. Loha et al. (2020) reported pesticide residues in Ethiopian tomato and onion samples and elevated pesticide concentrations in surface waters associated with agricultural areas. Uncertainty is also important when considering composite environmental indicators. In a farmer-level life-cycle assessment of Colombian greenhouse tomato production, Bojacá et al. (2014) identified fertilization and pest management as important sources of uncertainty and found that fertilization contributed substantially to acidification and eutrophication potentials. The study also reported positively skewed impact distributions, indicating that a subset of farms with higher input use could account for disproportionately high impacts.

3.6. Whitefly Management under Agroecological Practices

Marigold was companion-planted in the pepper and tomato zones in every year of trial, excluding the 2021 conventional baseline, regardless of plot's physical field position under the rotation scheme (Table 1). The insect infestation record for these two zones showed a clear decline in recorded insect pest incidence across the transition (Table 4).

At the 2021 conventional baseline management, whitefly infestation was recorded in all monitored beds of both the pepper zone (treated with synthetic insecticide at 0.15 kg/bed, rated moderately effective) and the tomato zone (treated with synthetic insecticide at 0.25 kg/bed, rated effective). In 2022, the first year of agroecological management, whitefly infestation was recorded only in the tomato zone and was treated with a garlic maceration biopesticide spray, rated effective; consistent with documented field efficacy of garlic based botanicals against whitefly on tomato (Sumaili et al., 2021). No infestation was recorded in the pepper zone that year, and from 2023 through 2025 no insect infestation events were recorded in either plot.

Table 4
Recorded whitefly incidence, management practices, and treatment efficacy in pepper and tomato plots, 2021–2025.

Year	Management	Crop types	Pest Observed	Treatment	Efficacy
2021	Conventional (baseline)	Pepper	Whitefly	Synthetic insecticide (0.15 kg/bed)	Moderately effective
		Tomato	Whitefly	Synthetic insecticide (0.25 kg/bed)	Effective
2022	Agroecological	Tomato	Whitefly	Garlic maceration spray (1 L/10 m2, 2 rounds)	Effective
		Pepper	None recorded	-	-
2023–2025	Agroecological	All crops	None recorded	-	-

Over the same period, mean harvest and revenue of both crops increased (Table 1): pepper harvest rose from 16.56 to 28.26 kg/bed and revenue from 496.76 to 4,239.71 ETB/bed, and tomato harvest rose from 12.03 to 22.65 kg/bed and revenue from 360.88 to 2,038.24 ETB/bed (2021–2025). The reduction in recorded whitefly thus coincided with higher productivity rather than a loss of it, although the data do not show whether lower infestation contributed to the higher harvests.

4. Discussion

4.1. Harvest and Revenue Trends

The five-year farm-based assessment showed a general increase in vegetable harvest and revenue during the period in which the farm transitioned from conventional to agroecological management. This is consistent with broader evidence from the Global South. A 2026 geospatially augmented meta-analysis of more than 350 primary studies by the European Commission's Joint Research Center found that farms applying about six agroecological practices, compared with simpler systems using about two, had on average 14.3% higher crop yields, 44.5% higher gross income and 36.5% lower production costs (De Marinis et al., 2026). The same report noted that yield responses were moderated by pedoclimatic factors, whereas economic benefits were more consistent across scales and irrigation regimes. That proposes income gains depend more on management choices and input substitution than on biophysical restrictions. This may assist clarify why revenue at Eladale Agroecological farm increased more strongly and consistently than harvest.

The result also fits the wider evidence on diversification. A second order meta-analysis of 5,160 original studies found that diversification enhanced biodiversity, pest control, nutrient cycling, soil fertility and water regulation without compromising crop yields (Tamburini et al., 2020). It was reported that multi-

cropping and crop rotation reduced the organic to conventional yield gap to about 9% and 8%, respectively, when applied in organic systems (Ponisio et al., 2015). Rotation and crop diversification were both part of the Eladale farm package, so this offers a plausible, though untested, explanation for the observed performance.

Evidence from smallholder systems in sub-Saharan Africa points the same way. Schader et al. (2021) monitored 1,645 farms in Ghana and Kenya for 24 months. They found that yields and gross margins under organic management were mostly similar to conventional levels in four of five case studies, while pooled farm-level gross margins were 144% higher on organically managed farms. They also reported that adoption of organic principles was heterogeneous and often passive, and that limited capacity, inputs and market access remained key constraints. This supports the view that outcomes depend on how actively and consistently practices are implemented.

Ethiopian crop level studies are also consistent with the manure-based nutrient management at Eladale farm. In northern Ethiopia, in a trial in Tehuledere, vermicompost gave a marketable carrot yield of 41.7 t/ ha, comparable to 42.5 t/ ha under NPSB inorganic fertilizer (Hailu et al., 2024). In western Ethiopia, it was found that combining 10 t/ ha cattle manure with 100 kg/ ha NPSB gave the highest carrot yield (39.5 t/ha) and reduced root defects, disease and insect damage (Tamene and Alemu, 2026). That treatment included mineral fertilizer, so it is integrated rather than purely organic management. Even so, it shows that manure can raise carrot productivity in Ethiopian highland soils, and that moderate rates can outperform higher input levels.

Pest-management components may also have contributed to the observed improvements in crop performance and productivity. Marigold is widely described as a companion crop that traps pests such as fruit borers, whiteflies and nematodes and keeps populations below threshold levels, which can raise marketable yield in vegetables (Parihar et al., 2025). Evidence on yield benefits is less consistent. A meta-analysis of mixed cropping (Kuyah et al., 2022) found that companion plants strongly reduced weeds but this did not translate into higher crop yield, and non-legume companions tended to reduce yield. Botanical insecticides can also be effective in managing insect pests, particularly when they are prepared and applied appropriately. They can provide a relatively affordable and environmentally friendly alternative to synthetic pesticides. In a Ghanaian trial, aqueous neem seed extract gave the lowest *diamondback moth* and *webworm* populations, the highest marketable cabbage yield and the best cost benefit ratio, outperforming two synthetic insecticides (Fening et al., 2020). The same authors concerned that cost benefit ratios depended entirely on commodity prices during the study period, which is directly relevant to your revenue results.

The variation observed among crops is expected, as different vegetable crops have distinct growth characteristics, nutrient requirements, maturity periods, yield potentials, and responses to environmental and management conditions. The relatively large increase in garlic harvest should be read against its low 2021 base. The faster revenue growth for carrot and pepper likely reflects price and quantity sold as well

as harvest. The study design cannot attribute gains to any single practice, and the results describe performance during a real-world transition, not a causal effect of agroecology.

4.2. Profit Margins

Profit margins rose for all eight crops, with carrot highest throughout (93.41% in 2021 to 97.10% in 2025), and beetroot and cabbage showing the largest gains in percentage points. Global syntheses support the general finding that diversified systems can be financially competitive. Sánchez et al. (2022) analysed 3,192 effect sizes from 119 articles and found that diversified systems had higher total costs, gross income and profits than simplified systems, with an equivalent benefit-cost ratio. For the 43 studies reporting labour, labour costs increased, but so did gross income, leaving profits equivalent. This matches the pattern of higher returns alongside possibly higher labour demand at Eladale farm.

For organic systems particularly, Crowder and Reganold (2015) analysed 55 crops on five continents. They found that without price premiums organic systems had lower benefit/cost ratios and net present values, but with actual premiums they were 22–35% more profitable. They also found that total costs did not differ significantly while labour costs were 7–13% higher. Pricing and market position matter as much as agronomy The Eladale farm margins therefore need to be interpreted in light of the prices received.

The JRC meta-analysis, by contrast, reports lower production costs under agroecological practices, which it links to input substitution (De Marinis et al., 2026). The Eladale shift from synthetic fertilizer and insecticide to manure and botanicals fits that mechanism, although preparation, transport and application of organic materials add labour. Tamene and Alemu (2026) reported that, in Ethiopian carrot trial, the application of manure and fertilizer raised production costs; however, the yield gains led to higher net benefits, with moderate input levels giving better economic returns than the highest application rates. Related Ethiopian work on wheat (Ng'ang'a *et al*., 2025) evaluated the profitability and risk of agroecological practices among smallholders and reported clear economic benefits. That study examined certified seed, optimal inorganic fertiliser rates and drainage, so it supports the general case for agroecological practices rather than the specific Eladale agrecological farm package.

Crop specific differences, such as the larger gains for beetroot and cabbage, likely reflect variation in yield response, price, input needs and labour. This provides practical evidence that a smallholder-oriented agroecological transition can be economically compatible with vegetable production under the conditions observed at the study site. The conclusions remain limited by the single conventional reference year, the lack of replication, and the integrated package design. Replicated plots, multiple farms, longer cost records and explicit accounting for labour and organic-input opportunity costs are needed before generalizing or attributing causality. Further research using replicated plots, multiple conventional and agroecological farms, longer-term cost records and explicit accounting of labour and organic-input opportunity costs would be required to determine the generalizability and causal magnitude of these economic differences.

4.3. Monte Carlo simulation of Yield, Revenue, and Fertilizer Use

The Monte Carlo analysis adds a useful uncertainty dimension to the mean yield and revenue comparisons. In the simulated distributions, carrot had the highest mean yield, followed by cabbage, while garlic had the lowest. However, revenue rankings differed from yield rankings where carrot, pepper, and garlic were among the higher-return crops, reflecting differences in selling price as well as harvested quantity. This shows why crop selection based only on physical output can overlook the economic contribution of high-value crops. This is consistent with risk-analysis approaches that evaluate expected returns together with variability, rather than treating average yield or revenue as sufficient indicators of performance (Rötter et al., 1997).

The fertilizer-demand distributions also differed by crop. Cabbage and tomato showed comparatively high simulated fertilizer requirements, whereas carrot and garlic were lower. Higher fertilizer demand did not automatically correspond to higher revenue or a higher fertilizer-use productivity index. This is agronomically plausible because crop nutrient demand, harvested biomass, and economic return vary by species and management. Research on vegetable nutrient management emphasizes that fertilizer source, rate, placement, and timing should be matched to crop demand, and that poor synchronization can reduce fertilizer recovery and increase residual nutrient losses (Jalpa and Mylavarapu, 2024).

4.4. Nutrient Use Efficiency and Market Value

The study's fertilizer-use productivity index varied substantially among crops. Carrot had the highest value, followed by lettuce, whereas tomato had the lowest value (2.2 kg/kg). This means that, under the recorded conditions, carrot produced more harvested mass per unit mass of fertilizer applied than the other crops, while tomato produced less (Jalpa and Mylavarapu, 2024). However, the index uses the mass of fertilizer applied, rather than the quantity of plant-available nutrients or nutrients recovered in the crop; fertilizer products and manure can differ markedly in nutrient concentration and availability. More direct assessment would require including crop nutrient uptake, soil nutrient changes, or a defined agronomic or recovery-efficiency calculation

The market-value ranking differed from the fertilizer-use productivity ranking. Garlic had the highest average selling price (170 ETB/kg) despite its relatively low index (2.8 kg/kg), while pepper sold for 85 ETB/kg with an index of 3.4 kg/kg. Carrot combined the highest index with a price of 60 ETB/kg, equal to the reported price for tomato, whose index was much lower. These contrasts show that physical output per unit of fertilizer and price per kilogram represent different dimensions of crop performance. A high selling price does not necessarily mean the highest net return, because profitability also depends on total yield, labor, other inputs, post-harvest losses, market access, and price variability. Crop planning should therefore consider gross revenue and production costs together with input productivity and risk. The global meta-analysis by Sánchez et al. (2022) similarly found that diversified farming systems can be financially competitive, although outcomes depend on the specific system and its management.

For the present farm, carrot and lettuce appear comparatively favorable in terms of harvested output per unit of fertilizer mass, whereas garlic and pepper offer higher unit prices. These are complementary signals rather than a single overall ranking. They should not be used to recommend replacing one crop with another without crop-specific net-return data and a clearer nutrient-based efficiency measure. In particular, the low tomato index warrants investigation of manure nutrient content, application rate, timing, and crop nutrient uptake before concluding that tomato nutrient management was inefficient. Manure mass and synthetic fertilizer mass are not directly equivalent measures of nutrient supply.

4.5. Environmental Stress Intensity under Conventional Farming

The composite environmental stress index identified tomato as the crop with the highest modeled stress intensity under the 2021 conventional baseline (0.62 index units/kg harvested), followed by pepper (0.37). Garlic and onion each recorded 0.29 unit's/kg; beetroot, cabbage, and lettuce ranged from 0.21 to 0.22, and carrot had the lowest value (0.16). Tomato also had the highest total composite stress score (11.72 units), while carrot combined a relatively high average harvest (43.74 kg) with a lower total score (7.12 units). These values indicate that the baseline system's modeled environmental burden per kilogram differed by crop, with tomato and pepper standing out for further assessment. The intensity measure is useful for comparing crops relative to harvested output. The index values are composite scores, not direct measurements of greenhouse-gas emissions, water use, pesticide residues, or nutrient losses. These composite indicators can summarize multiple dimensions of environmental pressure (Sabiha et al., 2016). The current values support a relative comparison within this dataset. The high baseline intensity for tomato and pepper is consistent with treating these plots as priorities for closer scrutiny of input management, particularly because the study recorded whitefly in both zones during the conventional year. The subsequent agroecological package coincided with higher harvests and revenues and a decline in recorded whitefly incidence. Manure substitution, marigold companion planting, garlic-based biopesticide, crop diversification, rotation, and year-to-year conditions changed together. The relatively low carrot intensity may partly reflect the larger harvested quantity over which its composite score is expressed. Similarly Life-cycle and environmental assessment studies of horticultural production show that fertilizer and pest-management practices can contribute to several environmental impact categories (Sabiha et al., 2016).

4.6. Whitefly Management under Agroecological Practices

Whitefly was recorded in both pepper and tomato under conventional management, in tomato only in 2022, and in neither crop from 2023–2025, alongside increases in harvest and revenue (Table 4; Section 3.6). This model is consistent with a protective effect of the agroecological package but does not reveal one. French marigold has been shown to slow whitefly population growth on greenhouse tomatoes through airborne limonene, although it does not eliminate the pest (Conboy et al., 2019). It has also been reported as a trap or companion crop for managing whiteflies, fruit borers, and nematodes in solanaceous vegetables (Parihar et al., 2025). Garlic extracts, used together with a parasitoid, formed part of a whitefly control programme that improved tomato yield (Sumaili et al., 2021). The reason of

push-pull integrated pest management is that repellent and attractant plants shift pest populations while natural regulation builds up (Cook et al., 2007).

The 2022 record suggests that the garlic maceration spray, rather than marigold alone, controlled the residual infestation in the first agroecological year, and the later absence of whitefly may reflect the cumulative effect of marigold, rotation and the removal of synthetic insecticide. The data cannot separate these contributions, because the practices were applied jointly and no untreated or marigold-free comparison beds were reserved. Therefore, the concurrent increases in pepper and tomato harvests cannot be attributed to marigold, as meta-analysis evidence suggests that companion planting does not necessarily improve crop yields (Kuyah et al., 2022). The findings suggest that reduced recorded whitefly incidence coincided with maintained or improved productivity under the combined agroecological management package. These findings should be interpreted cautiously because pest observations were qualitative rather than quantitative, and weather and plot rotation varied across years. A replicated comparison of marigold and marigold-free beds under identical management, using quantitative pest counts, is needed to isolate marigold's contribution to pest suppression.

5. Conclusions and Recommendations

Over transition time from conventional to agroecological farming system (2022–2025), this multi plot smallholder vegetable system showed significant increases in harvest and revenue across eight crops. The profit margin was approximately improved by 4 to 18 percentage points following the transition from conventional to agroecological management. The marked decline in recorded whitefly incidence in the pepper and tomato plots was concurrent with the continuous presence of a marigold push-pull and the replacement of synthetic pesticide with a garlic-based biopesticide. These results align with prior evidence on marigold based whitefly suppression and diversified farming profitability, and support agroecological transition.

The agroecological practices including intercropping with marigold, crop association and rotation, biopesticide and natural composting was a practical pathway to improved yield, profitability, and pest management in smallholder vegetable systems. As the practices were implemented together without replication or untreated controls, the findings signify associations rather than causation. The agroecological package was associated with improved productivity and profitability at the study site, but the contribution of individual practices remains unclear. The package of manure use, crop rotation, diversification, marigold companion planting and garlic maceration can be promoted for farmers and extension services. Crop portfolios could combine higher return but more variable crops (garlic, pepper, carrot) with more stable ones (onion, beetroot) and manure rates for cabbage and tomato should be optimized. Market information and linkages should complement technical support, as the profitability of agrecological vegetable productions depends heavily on prevailing market prices.

From policy perspective, incorporating training in botanical pesticide preparation and manure management, and the inclusion of vegetable production systems in the National Agroecology Strategy

could support the wider adoption of these practices. A controlled, replicated trial comparing marigold and marigold-free beds, with quantitative pest counts, is needed to assess marigold's contribution to pest suppression.Future studies should use multi-farm trials with conventional controls; inflation adjusted full-cost analysis, nutrient-based efficiency measures, soil indicators, and environmental-stress assessments under both management systems. Finally, the Monte Carlo simulation and environmental-stress index require transparent reporting of input variables, probability distributions, and calculation formulas to guarantee reproducibility and avoid interpreting the results as absolute environmental measures.

Declarations

Author Contribution

O.D. led the study, coordinated the research activities, and developed the original manuscript draft. C.G. conducted the data analysis and contributed to manuscript development. E.M. and A.N. critically revised the manuscript and provided constructive input. Finally, All authors reviewed and approved the final manuscript.

Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Figures

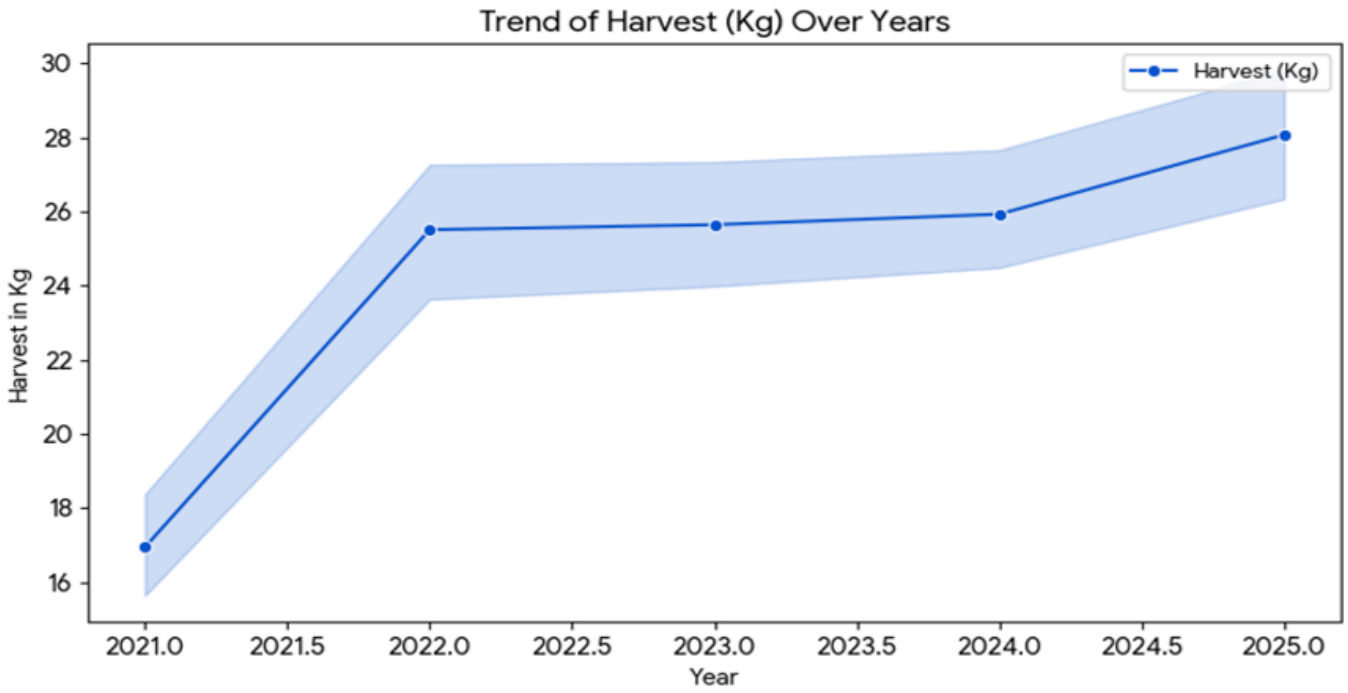


Figure 1

Sequential trend in mean harvest (kg/bed) of the eight monitored vegetable crops during the conventional baseline year (2021) and agroecological management period (2022-2025).

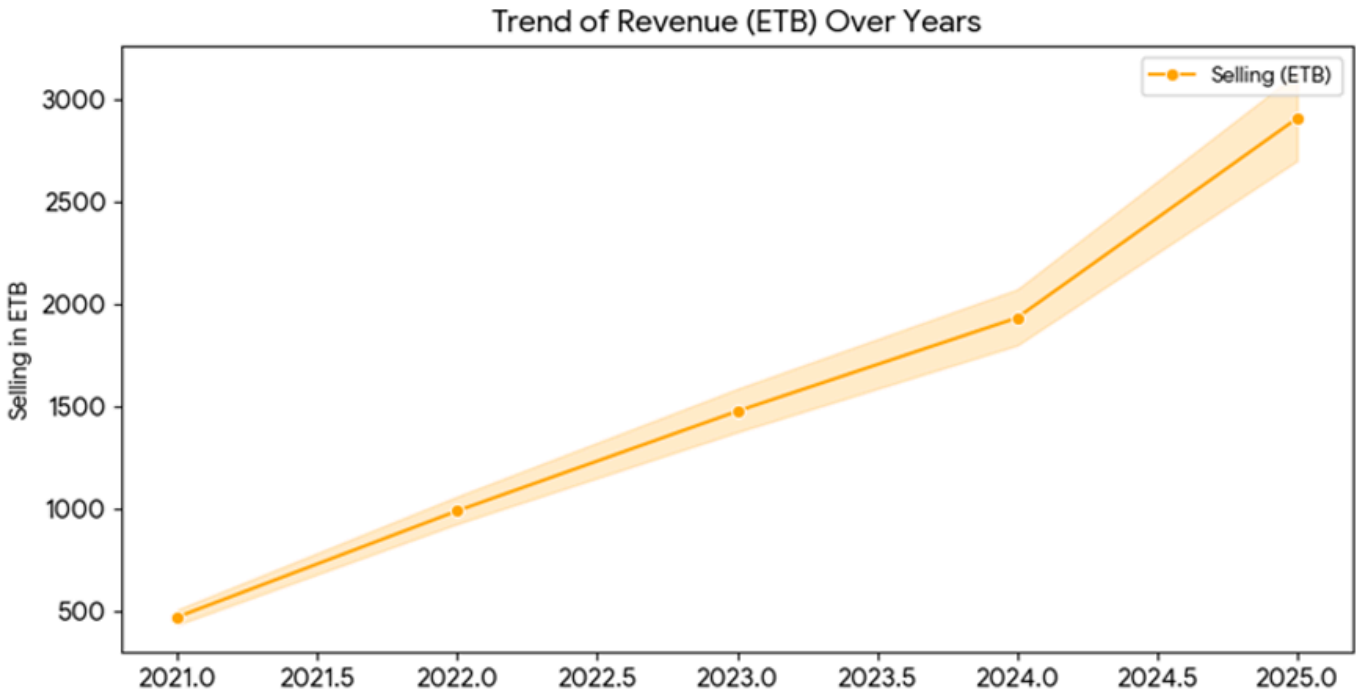


Figure 2

Sequential trend in mean revenue (ETB/bed) of the eight monitored vegetable crops during the conventional baseline year (2021) and agroecological management period (2022-2025).

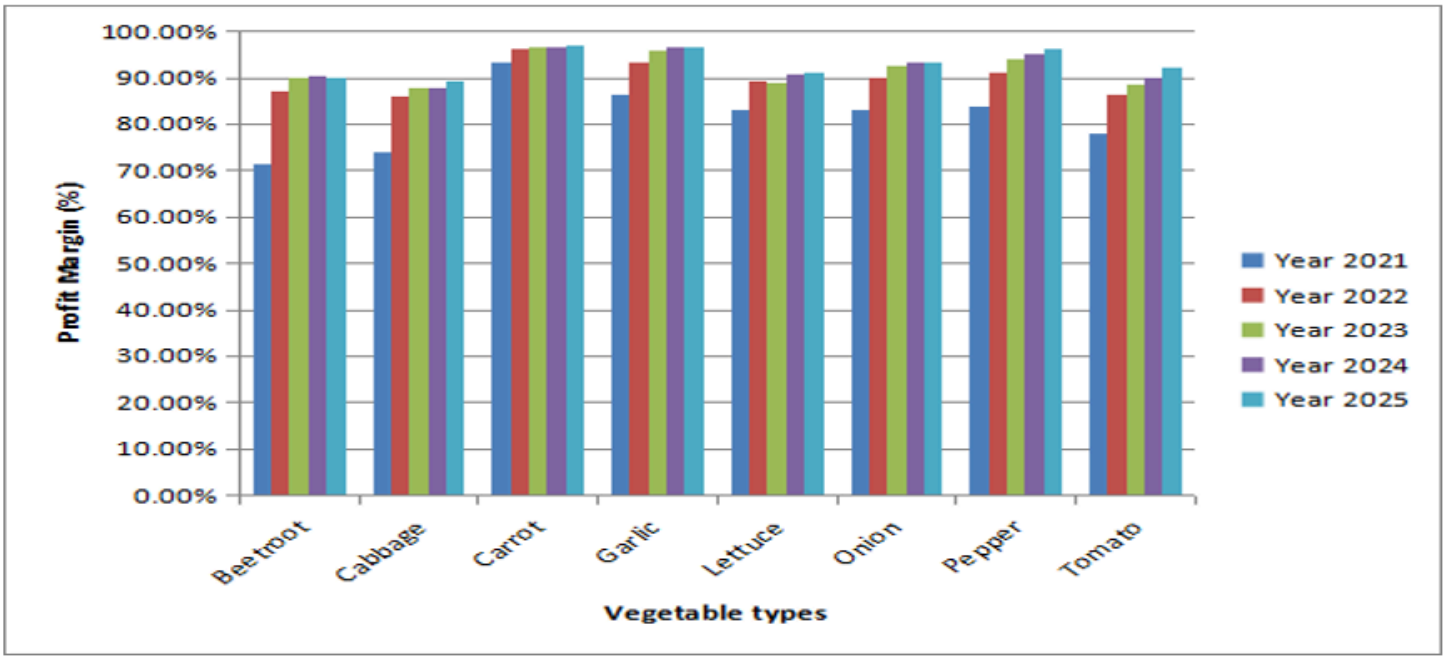


Figure 3

Profit margin (%) of the eight monitored vegetable crops during the conventional baseline year (2021) and agroecological management period (2022–2025).

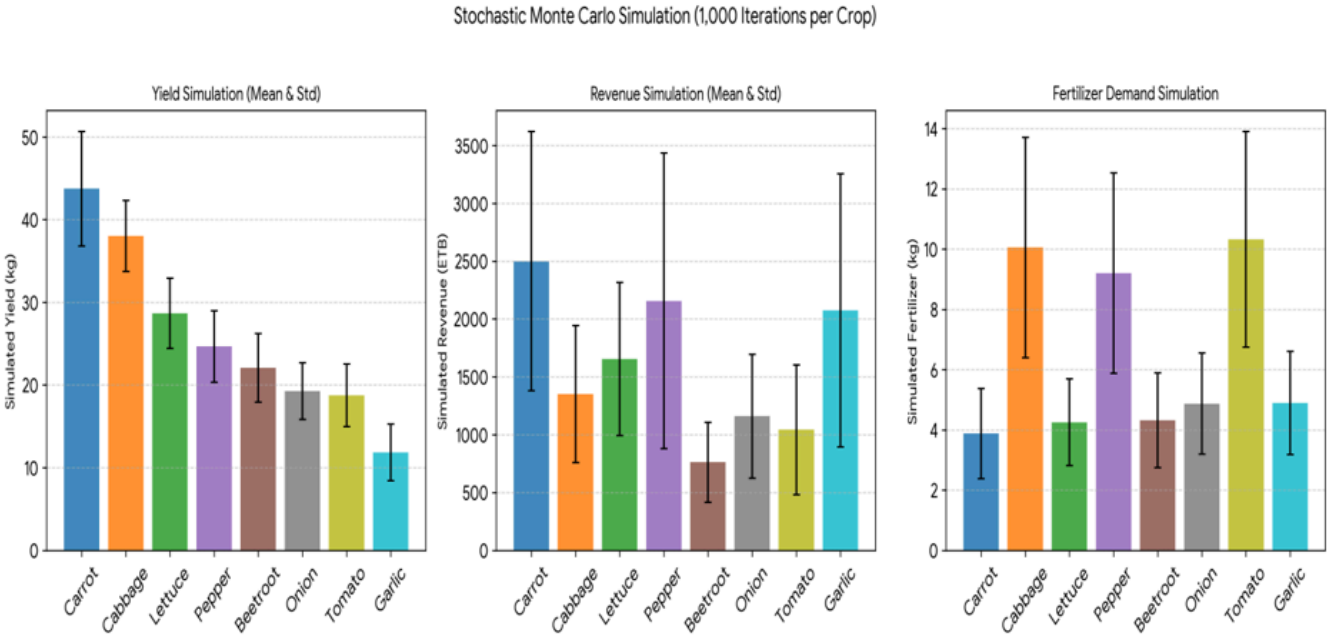


Figure 4

Stochastic Monte Carlo simulation (1,000 iterations per crop) of yield, revenue, and fertilizer demand, showing mean and standard deviation by crop.