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Comparative analysis of good agronomic practices (GAP) and conventional methods in Sri Lankan vegetable farming

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Abstract
The agricultural sector in Sri Lanka faces persistent challenges in optimizing crop yields, reducing production costs, and enhancing farmers' incomes. This study evaluates the economic viability of Good Agronomic Practices (GAP) compared with conventional farming practices across four vegetable crops (tomato, pole bean, cabbage, and carrot) cultivated in two agroecologically distinct vegetable production areas: Balangoda and Boralanda. Using a participatory field trial design, we assessed crop yield, cultivation costs, and net income over two growing seasons. The results indicate that the GAP plots produced agronomic and economic improvements or no losses compared to conventional plots, though effects varied by crop and season. For cabbage, no significant differences were observed in season one; however, in season two, GAP recorded a 35% higher cultivation costs ($p < 0.001$), an 18% higher yield ($p < 0.05$), and a 31% increase in gross returns ($p < 0.05$), without significant improvements in net returns or benefit–cost ratio (BCR). For carrots, season one showed 10% lower cultivation costs ($p < 0.001$) and 33.9% higher yields ($p < 0.05$) under the GAP, although net returns were not significantly different. In season two, GAP achieved significantly higher net returns (an 83.2% increase; $p < 0.05$) and BCR (a 50.3% improvement; $p < 0.05$). For pole beans, season one recorded 20% lower cultivation costs ($p < 0.001$) and a 53.1% higher BCR ($p < 0.05$) under the GAP. In contrast, in season two, GAP production costs were 43% higher ($p < 0.001$) but achieved statistically non-significant increase in net returns and the BCR. Importantly, GAP consistently used fewer chemical inputs than the control, suggesting its potential for safer, more sustainable production. These findings highlight the importance of context-specific GAP packages to inform policy and guide farmers toward profitable, sustainable vegetable production.

Keywords Benefit–cost ratio, Income, Safe production, Sustainable cultivation, Farming

1 Introduction

The growing population and decreasing arable land from urbanization have pressured vegetable demand and supply in Sri Lanka. The country's average per capita consumption of fruits and vegetables (F&V) is 150 g/day, with vegetable consumption at 112 g/day, 50% below WHO recommendations [40]. With proper support, the country could double its vegetable production to meet demand and enhance food security while improving smallholder farmers' livelihoods [38].

Sri Lanka has 2.3 million ha of agricultural land, with 80% used for non-plantation crops including rice, maize, vegetables, fruits, and other field crops. The agricultural sector employs 25% of the labor force [9], with farming being the primary income for 70% of rural populations [7]. About 1.65 million smallholder farmers operate less than 2 hectares and contribute 80% of annual food production [51]. Vegetable farming is crucial for farmers' livelihoods in upcountry areas and significantly contributes to agricultural output. However, many farmers remain below the poverty line [13].

Sri Lanka's landscape supports diverse fruit and vegetable cultivation. Farmers in upcountry areas practice 3–4 crop cycles yearly without a fallow period [10]. Despite favorable conditions, challenges include low productivity, declining yields, and unsustainable practices. Production has decreased since 2019 [52] due to climate change, chemical input shortages, and increased costs [3]. The total annual production of main vegetables was over 0.77 million t [8].

Esham and Usami [11] noted that low productivity in vegetable cultivation in Sri Lanka stems from underuse of appropriate technologies. Major commercial vegetable-based cropping systems in Sri Lanka follow conventional production, which is less sustainable than traditional systems, despite yield and quality advantages [42, 46]. Conventional vegetable production systems are intensive and environmentally unsustainable due to their heavy reliance on chemical inputs and the overuse of natural resources, risking human and environmental health.

A key challenge in vegetable farming is farmers' non-adherence to standard recommendations for fertilizer and chemical application, including correct dosage, type and composition, timing, method, and frequency. Despite site-specific fertilizer recommendations, blanket application of N, P, and K combinations leads to under- or over-fertilization. Samarakody and Silva [37] found that soil supporting vegetable cultivation in Sri Lanka's upcountry was generally high in phosphorus. Acidic or alkaline soils reduce phosphate uptake, increase toxic ions, and hinder crop growth [4]. Applying fertilizers without understanding soil nutrient content and without bringing the soil pH to the ideal range (6.5–7) is inefficient and creates an unfavorable environment for plant growth.

Chemical fertilizer consumption in Sri Lanka has fluctuated but increased from 1972 to 2021 [28]. Studies show that synthetic fertilizers are used at higher dosages in upcountry vegetable farming systems [48, 50]. Fertilizer use under subsidy schemes in upcountry vegetable cropping has resulted in 100–425% of recommended levels [18]. Heavy application of chemical fertilizers can harm the ecosystem and lead to crop failure [25]. Plants utilize only up to 50% of applied nitrogen fertilizer, with the remainder volatilizing or entering water systems [12], cited in [20]. Integrated use of organic and chemical fertilizers increases nutrient use efficiencies more effectively in upcountry soils [49]. However, farmers apply less than 50% of the recommended organic manure.

Suboptimal management of fertilizers and amendments results in no significant productivity response to the added chemical fertilizers in upcountry vegetable cultivation [45].

The overuse and misuse of agrochemicals in vegetable cultivation have been reported in numerous studies [14, 16, 27, 30, 41, 47]. Mismanagement of agrochemicals challenges sustainable vegetable production. Incorrect agricultural practices cause point-source pesticide pollution in conventional farming. [53], cited in Kılıç et al. [20], found that less than 0.1% of pesticide reaches the target organism, while 99.9% threatens the ecosystem.

The overuse of fertilizers and chemicals results in higher levels of pesticide residues and heavy metals in soil and vegetables. Premarathne et al. [31] reported elevated levels of Cd, Ni, Cu, Pb, and Zn in the topsoil of upcountry vegetable-growing areas, with Cd exceeding acceptable limits in some places. The heavy metal concentration is correlated with years of cultivation. Heavy fertilizer application in upcountry farming also pollutes groundwater [22, 37]. Analysis of cabbage, capsicum, and tomatoes showed pesticide residues exceeding EU maximum residue levels (MRLs) [23]. Farmers primarily get fertilizer and pesticide information from dealers focused on increasing sales, resulting in excessive chemical use.

While studies have focused on fertilizers [45] and integrated plant nutrient management [6] in Sri Lankan agricultural systems, research on holistic approaches to soil health and plant management for sustainable vegetable production is lacking. Integrated pest management (IPM) has not been widely adopted in vegetable production, and farmers' participatory trials have been recommended to promote IPM in Sri Lanka [16]. To address these challenges, implementing sustainable farming practices that reduce chemical inputs is crucial. Adopting technologies to enhance productivity, developing climate change mitigation strategies, and promoting efficient resource management are essential for improving crop yield while ensuring sustainability. This research addresses this knowledge gap by comparing the economic viability of Good Agronomic Practices (GAP) and farmers' conventional practices for vegetable crops. The study investigated the impacts of farmers' practices and GAP package on crop yield, costs, and income in two agricultural settings in Sri Lanka (Balangoda and Boralanda).

2 Materials and methods

2.1 The approach and study locations

Numerous studies have emphasized the significance of harnessing technological innovation to enhance resource utilization and boost productivity [29, 33]. Farmers often face poor yields and low incomes due to poor farm management and the non-adoption of cost-effective agricultural technologies [1, 34].

The CGIAR science program, Better Diets and Nutrition (BDN), is actively engaged in designing, testing, and promoting technologies to improve year-round access to safely produced vegetables through sustainable diversification and intensification. The BDN established two agroecologically distinct vegetable production hubs in the Boralanda Agrarian Service Division in the Welimada Divisional Secretariat (DS) division (non-seasonal continuous vegetable cultivation system in sloping lands of the up-country) and the Damahana Agrarian Service Division in Balangoda DS division (rice-based seasonal vegetable cultivation) for participatory technological development and the delivery of suitable technologies for safe and sustainable vegetable cultivation (Fig. 1). Rainfall is

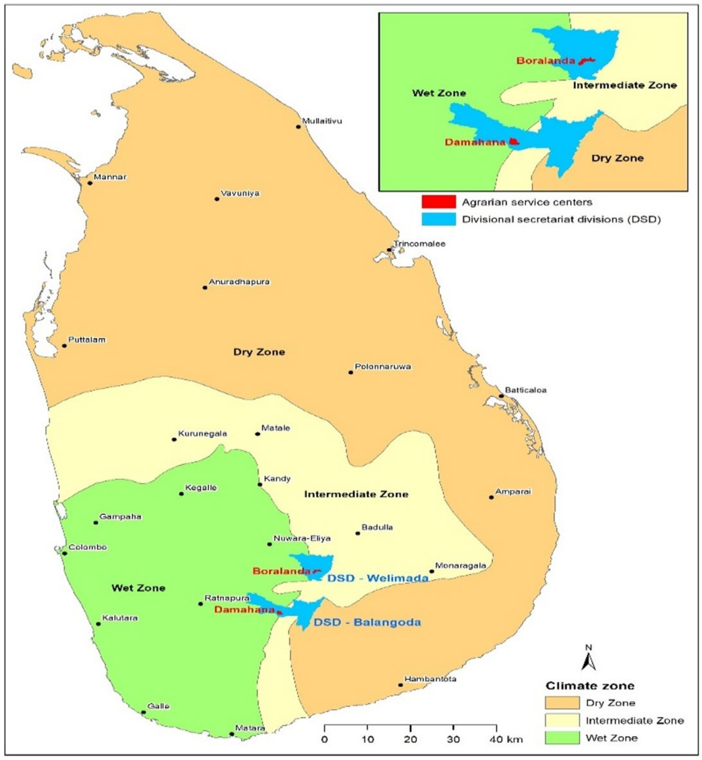

Fig. 1 Map of the study locations Source: Map prepared by Niranga Alahacoon (IWMI)

received through two distinct monsoons: the southwest monsoon during April to September (dry season) and the northeast monsoon during October to March (wet season). The average annual rainfall in the study areas ranges from 2000 to 2500 mm, with clear variations along the terrain.

Participatory trials were conducted in the dry seasons of 2023 and 2024 in Boralanda and Balangoda divisions, encompassing two rounds of comparative trials in farmers' fields with tomato (*Solanum lycopersicum*), carrots (*Daucus carota*), cabbage (*Brassica oleracea*), and pole beans (*Phaseolus vulgaris*).

2.2 Treatment details

Farmer participatory trials were conducted with two treatments: (1) a good agronomic practices package (GAP) and (2) conventional practices employed by farmers (control). In each trial, the farmers allocated 250 m^2 to GAP, and the remaining area was cultivated using conventional practices, measuring at least 250 m^2. The GAP was designed to increase input use efficiency and reduce their negative environmental impacts, including improving the efficiency of fertilizer and pesticide applications. The GAP framework is defined as a holistic, systems-based approach to crop production that synchronizes multiple management strategies to optimize yield, food safety, and sustainability. While individual components like Integrated Nutrient Management (INM) or Integrated Pest Management (IPM) focus on specific resource efficiencies, GAP integrates these into a synergistic lifecycle. The GAP comprises healthy seedling production, integrated soil health and nutrient management, and integrated plant health management. Table 1 provides a detailed description of both the GAP and the control. Control plots with conventional farming practices were established adjacent to the GAP plots. Due to the 2023

Table 1 Sample size—Trial and control fields included in analysis

Location	Year	Tomato		Pole bean		Carrot		Cabbage	
		GAP	Control	GAP	Control	GAP	Control	GAP	Control
Boralanda	2023	–	–	9	9	16	16	9	9
	2024	–	–	19	19	10	10	17	17
Balangoda	2023	4	4	–	–	–	–	–	–
	2024	13	13	15	15	–	–	–	–
Total		17	17	43	43	26	26	26	26

Table 2 Variety, spacing, and number of plants in GAP and control

	GAP			Control		
Crop	Variety	Spacing (cm)	No. of plants/ hole	Variety	Spacing (cm)	No. of plants/ hole
Pole bean	Kekulu (Department of Agriculture-Sri Lanka)	30×40	2	Black Cora (Hayleys), Kabri (locally self-pollinated)	30×30	3–4
Carrot	Hercules (Sakata Seed Corporation)/ Magma (Agro-Culture Trends Pvt. Ltd.)	5×15	1	Hercules (Sakata Seed Corporation), Rupika (Multigrow Pvt. Ltd.)	5×15	1
Cabbage	Sishiro (Takii Seed)	30×45	1	YR, AS39 (Onesh Seed), Sishiro(Takii Seed)	25×30	1
Tomato	Platinum (East–West Seed)	80×50	1	Padma (East–West Seed), Platinum (East–West Seed)	80×40	1

drought in Boralanda, the produce was not harvested from 11 pole bean farms out of 20 pole bean farms, 11 cabbage farms out of 20 cabbage farms, and 4 carrot farms from 20 carrot farms. Many farmers removed damaged crops from the farms before data could be collected; hence, these farms were excluded from the analyses.

The trials employed protocols designed to implement good agronomic practices (GAP treatment), aiming at efficient resource use and safe production. The main features of these GAP protocols are outlined below:

1. Variety selection and seed treatment: The tested varieties were chosen based on their yield performance and suitability for cultivation in specific agroclimatic zones. Consumer preferences and market demand were also considered when selecting varieties. The varieties used for the GAP treatment were Platinum (tomato), Black Cora (pole bean in Balangoda), Kekulu (pole bean in Boralanda), Sishiro (cabbage), and Hercules and Magma (carrot). However, farmers used different varieties in conventional cultivation in addition to the above varieties (Table 2) which represent a study limitation. Ideally, the varieties should have been exactly the same for both the GAP and control fields. However, it was challenging to control as farmers were reluctant to adopt unfamiliar varieties for their entire cultivation. If the purchased seeds were not pretreated to disinfect them from seed-borne or soil-borne pathogenic organisms, seed treatment was performed by applying the recommended chemicals.
2. Nursery preparation and transplanting: Cabbage and tomato seedlings were cultivated in seedling trays. Nursery soil medium was prepared by mixing topsoil, sand, and compost in a 3:1:1 ratio. The nursery provided regular irrigation without overwatering. A Trichoderma solution, serving as a biopesticide, was applied. Farmers were encouraged to use an insect-proof net with a 40-mesh size to protect the nursery from pests. The seedlings underwent a hardening process one to two days before transplantation into field conditions. Three-week-old seedlings were transplanted

into the fields of selected farmers at two hub locations, with the recommended time for transplantation being the evening. Nursery trays and biopesticides were not used in the control fields. Pole beans and carrot seeds were sown directly in the fields, with two seeds planted per hole and subsequently thinned to one. However, in conventional fields, farmers planted 3–4 seeds per hole. The study provided recommendations on crop spacing guidelines.

3. Soil and land preparation and soil nutrient management: Soil samples were collected from the GAP fields to test pH, EC, and soil nutrients (N, P, K). Given the slightly acidic nature of the soil in these areas, farmers were supplied with the recommended quantity of lime to adjust the soil pH to a range of 6.5–7. Poultry manure was applied at a rate of 5 t/ha. Integrated crop-specific nutrient management was implemented based on the test results and crop nutrient requirements. Synthetic fertilizers were administered as straight fertilizers for basal and top dressings [urea, triple superphosphate (TSP), and muriate of potash (MoP)]. This fertilization approach aligns with the 4R Nutrient Stewardship framework, which emphasizes the right source, right rate, right time, and right place. The basal dressing was split into two doses: the initial dose was applied at planting to meet the recommended TSP and MoP rates, while the second dose, containing the recommended urea amount, was used 7–10 days after planting. Sadhukhan et al. [36] also reported that precision nutrient management positively influences productivity and nutrient use efficiency. In contrast to conventional fields, farmers typically do not practice soil testing or adjust the soil pH. Instead of applying the recommended fertilizer doses to meet plant nutrient requirements, farmers used various fertilizer mixtures and different growth regulators, as advised by chemical traders. The use of mulch with rice straw or other locally available crop residues has been encouraged in GAP treatments to conserve soil and moisture, prevent nutrient leaching, and control weed growth. Farmers seldom use mulching in conventional cultivation, keeping the soil open.
4. Irrigation: Regular irrigation was performed to avoid underwatering or overwatering. Farmers were advised to irrigate in the morning rather than in the evening. Irrigation for control fields was conducted at the farmers' convenience, regardless of whether it was restricted to morning hours.
5. Special management: Tomato and pole bean plants were staked to enhance their health and increase yield potential. For beans, the staking process commenced two weeks after germination. For carrots, thinning and earthing up were conducted on the 30th day. These practices were common in both the GAP and control fields.
6. Pest and disease management: The GAP was regularly scouted for early detection and management of pests and diseases. A blue net, 1 m high, was installed in the GAP plots to mitigate damage from wild animal pests. To prevent the spread of pests and diseases, good plant hygiene practices were implemented, including the removal of diseased plants and surrounding weeds. Trichoderma solution was sprayed fortnightly as a method of biological control. It has been found that the application of Trichoderma solution can partially replace synthetic pesticides and insecticides [26, 39, 44]. After transplantation, yellow sticky traps were placed on wooden poles at the canopy level. When using pesticides, the appropriate pesticide and dosage were administered to address the specific pest or disease identified. Chemical pesticides

were used as a last resort, following the extension staff's recommendation. Conversely, the control farmers did not adhere to the recommended hygienic practices, such as regular field scouting and weed management, nor did they implement seed treatment or use biopesticides. Additionally, blue nets were not used to safeguard crops from wild animal pests. Instead, chemical pesticides were applied at regular intervals based on the farmers' previous experiences and advice primarily obtained from chemical traders.

2.3 Data collection

This study collected data from both GAP and control plots managed by farmers during the dry seasons of 2023 and 2024, focusing on the production costs of all the inputs. These inputs included the monetary value of seeds, organic fertilizers, inorganic fertilizers, synthetic pesticides, and expenses associated with organic/bio pest control. Additionally, yield data were collected.

2.4 Economics

2.4.1 Cost of cultivation

The cost of cultivation refers to the total purchased input expenses incurred to cultivate one hectare of a crop. The limitation is that labor costs were not considered, as tracking time and manpower for different treatments was challenging for participating farmers.

2.4.2 Gross returns

The monetary returns obtained from marketable produce were computed by multiplying the output quantity by its unit price received by the farmers at the time of sale:

2.4.3 Net returns

This was calculated by subtracting the total cultivation cost from the respective gross return.

This value provides the actual profit obtained by the farmer as follows:

Net Return (LKR/ha) = Gross Return (LKR/ha) – Cost of cultivation (LKR /ha).

2.4.4 Benefit–cost ratio

The benefit–cost ratio (BCR) in terms of net return per rupee investment was calculated using the following formula:

$$\text{B:C} = \frac{\text{Gross return (LKR/ha)}}{\text{Cost of cultivation (LKR/ha)}}$$

2.4.5 Statistical analysis

Treatment effects on response variables were analyzed using a generalized linear model (GLM) with a gamma distribution and log-link function, appropriate for continuous, positive data with heteroscedastic variance. Model diagnostics confirmed good fit, with no systematic residual patterns and no evidence of overdispersion. Coefficients estimated on the log scale were back-transformed to the original scale for interpretation. All statistical analyses were performed in R software (version 4.5.1) using the glm function with the family set to Gamma (link = 'log').

3 Results

3.1 Tomato (Balangoda)

In season one (n = 4), the GAP yielded a non-significant increase of 5.04 t/ha (± 7.09, $p = 0.5037$), with 27.5 t/ha in GAP and 22.46 t/ha in control. Production cost was higher in GAP (LKR 0.96 million/ha) than control (LKR 0.77 million/ha). Gross income increased by LKR 0.428 million (± 653,000, $p = 0.5370$) in GAP (LKR 2.45 million/ha) compared to the control (LKR 2.05 million/ha). Net income rose by LKR 0.245 million (± 598,000, $p = 0.6967$) in GAP (LKR 1.523 million/ha) compared to the control (LKR 1.28 million/ha), though increases were not significant. The BCR showed a non-significant change of -0.0569 (± 0.628, $p = 0.9308$).

In season two (n = 13), the GAP treatment yielded a non-significant gain (± 2.83, $p = 0.6939$), with yields of 18.02 t/ha versus 16.89 t/ha in the control. Production cost was significantly higher in GAP (LKR 1 million/ha) than control (LKR 0.71 million/ha). Income increased in GAP (LKR 3.30 million/ha) compared to the control (LKR 3.07 million/ha), but the difference was not statistically significant. Net income decreased in GAP (LKR 2.3 million/ha) versus control (LKR 2.36 million/ha), but the difference was not statistically significant. The BCR showed a non-significant decrease of -1.02 (± 0.648, $p = 0.1295$).

3.2 Pole bean (Boralanda)

In season one (n = 9), GAP treatment resulted in a non-significant increase in yield of 7.3 t/ha versus 6.1 t/ha in the control. However, the GAP led to a statistically significant reduction in total cost by LKR 0.262 million (± 47,500, $p < 0.0001$), with costs of LKR 1.04 million/ha versus LKR 1.30 million/ha in control. Gross income increased by LKR 0.54 million (± 601,000, $p = 0.3789$) in GAP (LKR 3.15 million/ha) versus control (LKR 2.61 million/ha), and net income rose by LKR 0.81 million (± 654,000, $p = 0.2358$) in GAP (LKR 2.11 million/ha) versus control (LKR 1.31 million/ha), these differences were not statistically significant. The BCR increased significantly by 1.04 (± 0.421 ($p = 0.0253$).

In season two (n = 19), GAP treatment resulted in a non-significant yield increase, with a total yield of 19.14 t/ha versus 18.31 t/ha in control. Total costs were similar: LKR 1.26 million/ha (GAP) versus 1.27 million/ha (control). Gross income (LKR 5.44 million/ha in GAP, 5.17 million/ha in control), net income (LKR 4.18 million/ha in GAP, 3.89 million/ha in control), and BCR (change of 0.261 ± 0.459, $p = 0.5734$) showed no significant differences.

3.3 Pole bean (Balangoda)

In season two (n = 15) at Balangoda, the GAP treatment resulted in a non-significant yield increase of 0.67 t/ha (± 1.71, $p = 0.6972$) compared to the control. The cost difference between GAP and control was significant, with an increase of 0.315 million (± 1.71, $p = 0.6972$). In contrast, costs significantly rose under GAP, with a rise of LKR 3.15 million ± 20,600 ($p < 0.0001$). Gross income showed a non-significant increase of LKR 0.1 million ± 472,000 ($p = 0.8309$), and the profit margin declined non-significantly by LKR 0.213 million ± 477,000 ($p = 0.6585$). The BCR showed a marginal, but statistically non-significant reduction of 1.16 ± 0.57, nearing significance ($p = 0.0523$).

3.4 Cabbage (Boralanda)

In season one (n = 9), the GAP treatment resulted a non-significant yield increase, with yields of 22.68 t/ha versus 18.01 t/ha in the control. Total cultivation cost was higher in GAP (LKR 1.26 million/ha) than control (LKR 1.14 million/ha), though the difference was not statistically significant. No significant differences were found in gross income (LKR 4.78 million/ha in GAP, LKR 3.34 million/ha in control), net income (increase of LKR 0.82 million ± 1.94 million, $p = 0.6789$) with LKR 3.52 million/ha in GAP and LKR 2.7 million/ha in the control, or BCR with a non-significant change of 0.79 ± 1.51, $p = 0.6080$).

In season two (n = 17), the GAP treatment significantly increased yield by 3.22 t/ha (± 1.43, $p = 0.0316$), with total yields of 20.61 t/ha in GAP and 17.40 t/ha in control. Cultivation costs were higher in GAP (LKR 1.32 million/ha) than control. Gross income rose by LKR 0.64 million (± 0.31 million, $p = 0.0458$) in GAP (LKR 2.74 million/ha) compared to control (LKR 2.09 million/ha). Net income increased in GAP (LKR 1.41 million/ha) over control (LKR 1.12 million/ha) but was not statistically significant. The BCR change was also not statistically significant (–0.0787 ± 0.259, $p = 0.7636$).

3.5 Carrot (Boralanda)

In season one (n = 16), GAP treatment yielded 13.55 t/ha compared to 10.11 t/ha in the control, a statistically significant increase. Total cultivation cost reduced significantly by LKR 0.11 million (± 0.26 million, $p = 0.0002$) in the GAP (LKR 1.03 million/ha) versus control (LKR 1.15 million/ha). While GAP showed higher gross income (LKR 4.13 million/ha vs 3.13 million/ha) and increased net income (LKR 3.09 million/ha vs 1.98 million/ha), these differences were not statistically significant. The BCR change was also not statistically significant (1.19 ± 0.894, $p = 0.1921$).

In season two (n = 10), the trial results were mixed. While yield increase in GAP (28.96 t/ha) versus control (25.80 t/ha) was not statistically significant, cultivation costs decreased significantly by LKR 148,380 (± 34,800, $p = 0.0005$) in GAP (LKR 0.97 million/ha) compared to the control (LKR 1.12 million/ha). Gross income increased in GAP (LKR 2.98 million/ha) versus control (LKR 2.31 million/ha), though not statistically significant. However, net income showed a statistically significant increase of LKR 0.82 million (± 0.39 million, $p = 0.0509$) in GAP (LKR 2.01 million/ha) compared to the control (LKR 1.19 million/ha). The BCR improved significantly by 1.0 (± 0.361, $p = 0.0126$).

3.6 Interaction effects of treatments and seasons on yield and economic benefits

Cabbage yield increased during season two, whereas carrots had a higher yield in season one. Tomato yield was greater in season one but declined in season two. Overall, seasonality negatively affected tomato and cabbage yields, whereas the carrot yield remained relatively stable (Annex Table 4).

The total cost of cultivation in season one was lower in GAP treatments compared to the control by 0.23. Cabbage, carrot, and tomatoes showed cost reductions of 0.14, 0.13, and 0.52 in GAP compared to the control. Season two slightly reduced the total cost, however, GAP with cabbage and tomato increased costs, while the combination of GAP, carrot, and season two further lowered costs by 0.39 (Annex Table 4). Gross income was positive for all crops under GAP packages. Season two increased overall gross revenue for crops in the GAP by 0.48, but reduced income for cabbage and carrots

(Annex Table 4). Net income from cabbage was unaffected by season, while carrots and tomatoes showed higher income in season one (Annex Table 4). The BCR of crops in GAP increased in season two by 0.74, though interactions with season two reduced BCR for cabbage by 1.13 and carrot by 1.03 (Annex Table 4).

4 Discussion

The results show that GAP treatments have provided higher yields or no statistically significant difference in yield and profitability compared to conventional practices, indicating that, generally, farmers are not at a disadvantage by adopting GAP. The adoption of the GAP package was economically most risky for tomatoes, where it resulted in reduced BCR, though the difference was not statistically significant. Results specific to each crop exhibited heterogeneity and were frequently contingent upon season and location. Seasonal and geographical differences are common factors affecting the productivity and profitability of vegetable production [35].

In the case of tomatoes in Balangoda, GAP had varying effects on yield, production cost, gross income, net income, and BCR across the two seasons (Annex Table 3). Yield increases were not statistically significant in either season. However, production costs were notably higher under GAP in both seasons, attributed to increased inputs, leading to a non-significant decline in net income during the second season amidst lower prices, marginal yield gains, market fluctuations, and seasonal variations. This indicates a potential financial risk associated with adopting the selected GAP package for tomato. Practices that are more affordable and better enhance tomato productivity should be identified in the future.

For pole beans, the effects of GAP varied: in Boralanda during the first season, total costs decreased significantly, and the BCR increased substantially, whereas the second season showed no significant differences. In Balangoda during the second season, GAP significantly increased total costs, with a non-significant decline in net income, highlighting the sensitivity to cost management and market conditions (Annex Table 3). The higher costs of GAP in season two in Balangoda compared to Boralanda are likely due to higher incidence of pests and diseases resulting in higher pests and disease management costs. Despite the increased production costs in season two, BCR increased under GAP in both locations.

In the case of cabbage cultivation in Boralanda, the first season showed non-significant increases across indicators, while the second season demonstrated statistically significant gains in yield and gross income despite higher costs; net income and BCR values increased, but not significantly. Although net income increased in season two, the difference was not statistically significant (Annex Table 3). The second season of cabbage showed that practices that significantly increase yield and gross profits can offset the higher costs associated with new practices.

Carrots in Boralanda exhibited the most consistent economic potential: the first season combined a significant yield increase with reduced costs (with non-significant income gains), and the second season achieved significant cost reductions and a statistically significant increase in net income, thereby improving the BCR (Annex Table 3). Overall, carrot was found to be the most economically responsive crop to the GAP package. The study underscores the necessity to investigate the drivers of seasonal variability to optimize the benefits of GAP.

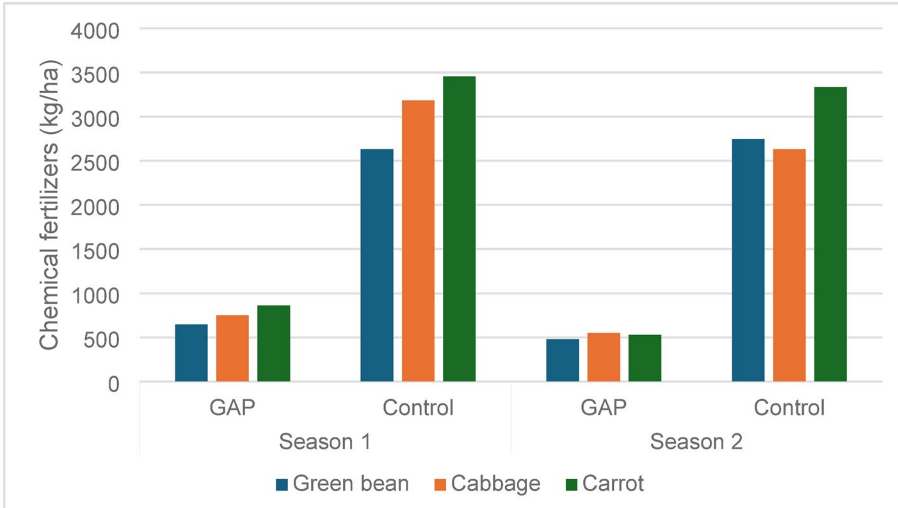

Fig. 2 Quantity of inorganic fertilizers used in the Boralanda production hub

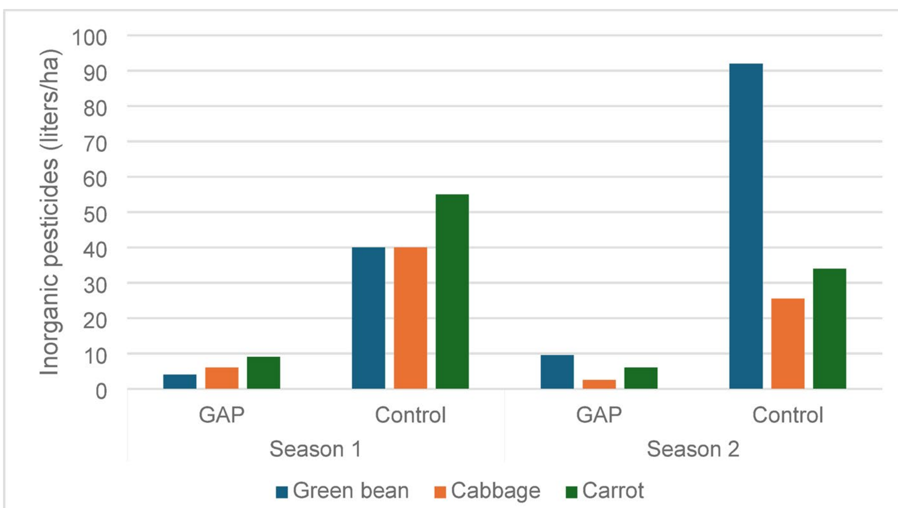

Fig. 3 Quantity of inorganic pesticides used in the Boralanda production hub

Farmers used GAP-based fertilizers and pesticides at the correct times and in appropriate quantities. Consequently, the application of these inputs within GAP is generally lower than in conventional practices, reflecting a more efficient and safer approach to crop production without adverse effects on yield (Figs. 2 and 3). This significant reduction in chemical inputs not only demonstrates GAP's potential to minimize environmental risks but also underscores its role in enhancing the overall sustainability of agricultural systems, which needs to be validated through further in-depth studies. Consistent with these findings, numerous prior studies [2, 20, 43] have documented similar reductions in fertilizer and agrochemical use, which have contributed to increased net income for farmers and improved the quality of produce among those adopting GAP [2, 20, 43]. This further corroborates the efficacy of these practices in fostering environmentally sustainable and productive farming.

The present study attributes the excessive use of agrochemicals in conventional agricultural systems to farmers' reliance on input dealers as primary sources of information, which incentivizes over-application. This was also the case in many other countries in the region, such as Nepal [19].

Economically, the reduction in costs, coupled with stable or improved yields, has enhanced returns, with the highest return on investment observed for carrots and pole beans. This aligns with the findings of Josie et al. [17] that GAP practices effectively enhance yield and income, while reducing production costs without significant yield loss. In instances where costs increased, such as cabbage and tomato, this may reflect short-term adjustment effects that could reverse over longer periods, necessitating larger samples and extended observation [24]. The prices of vegetables also fluctuate with the seasons, requiring a dynamic, longer-term analysis of costs and benefits. This study thus underscores the need to investigate the effects of seasonal variability on the economics of GAP in vegetable production.

Although the standard GAP packages adopted in many places show declining yields and income ([15, 20]), the package of good agronomic practices introduced in Sri Lanka has improved production efficiency and is likely to have contributed to food safety while reducing the risks of chemical contamination for farmers and consumers. This highlights the potential of the introduced package of practices to enhance production efficiency, improve food safety, and meet stringent global food safety standards while reducing risks to farmers and consumers, as highlighted in Purnama et al. [32] and Kharel et al. [19], based on the results obtained from the GAP intervention. Many studies indicate the importance of building awareness among farmers through training and in-field guidance [5, 13, 18]. GAP was promoted in Thailand's fruit and vegetable cultivation to ensure food safety, environmental conservation, sustainable cultivation, and competitiveness in international trade [21]. As awareness of food safety and environmental concerns increases, there may be opportunities to develop premium markets for GAP-certified produce, potentially leading to higher profits for farmers adopting these practices.

4.1 Study limitations

The main limitation of this study is the small sample size in the participatory trials for certain crops, particularly in the first season, due to drought-related plot losses. Another limitation is that farmers introduced various crop varieties in addition to the selected varieties in the conventional plots, which may have influenced the results to some degree. For future studies, it is recommended to combine participatory trials with controlled on-station trials. The study also has limitations due to its short-term focus, which does not capture the long-term effects of GAP implementation. The sample size and geographic scope may limit the generalizability of the findings. Market fluctuations and external economic factors can significantly influence profitability but were not fully considered. Additionally, differences in farmer engagement and training can affect the effectiveness of GAP practices, potentially skewing results. Finally, limited crop variety and the potential impact of environmental factors on productivity may warrant further investigation.

5 Conclusions

Vegetable farming in Sri Lanka's upcountry regions generates income and supports livelihoods. The area's climate and soil conditions are well-suited for cultivating vegetables for both domestic consumption and export. This sector contributes to agricultural diversification, value addition, and reduced market risks. It also contributes to the country's agricultural output and economy but faces various challenges. The implementation of Good Agronomic Practices (GAP) has demonstrated a potential to optimize resource use efficiency, enhance crop productivity, and mitigate the intensive agrochemical application across selected vegetable crops in two vegetable production hubs in Sri Lanka. GAP package was the most successful on carrot where it consistently increased net profits and BCR due to reduced production costs and increased yields. As GAP packages sometimes increase production costs (particularly for tomato and cabbage), future efforts should identify more cost-effective alternative practices. While the current study provides robust preliminary evidence, the scope was constrained by the sample size of the participatory trials and variation among farmers. Despite this limitation, the findings from two seasons underscore the viability of GAP in fostering sustainable horticultural systems. Optimizing and scaling these interventions requires stakeholders to recognize the potential of GAP for substantial reductions in agrochemical use and enhanced ecosystem services. Consequently, it is recommended that National Agriculture Research and Extension Systems (NARES) pilot the GAP approaches across broader agro-ecological zones in Sri Lanka. Expanding the participatory framework to include a larger cohort of farmers will be essential to validate outcomes and provide the empirical basis required for large-scale promotion. Furthermore, the widespread adoption of GAP is contingent upon a high degree of multi-sectoral coordination between state agencies, research institutions, and agrarian organizations. Such efforts must be underpinned by comprehensive capacity-building initiatives, including the establishment of demonstration plots, farmers' field days, and systematic knowledge-transfer programs. Ultimately, sustained collaboration among government bodies, the private sector, and farming communities is imperative to institutionalize these strategies and facilitate a transformative shift toward sustainable agricultural intensification. Financial incentives, supportive policies, access to GAP inputs, and assistance systems influence farmers' adoption of sustainable approaches. Considering technical and socioeconomic factors in agricultural development may foster a more resilient and environmentally conscious vegetable sector in Sri Lanka.

Annexure

(See Tables 3 and 4).

Table 3 Estimates of treatment effects and statistical significance of economic and yield performance of good agricultural practices (GAP) vs. farmers' practices (Control) across two seasons

Parameter	**Season one (n = 4) estimate (GAP-control)**	**t-value**	***p* value**	**Season two (n = 13) estimate (GAP-control)**	**t-value**	***p* value**
Tomato (Balangoda)						
Yield (t/ha)	5.04 ± 7.09 (ns)	0.711	0.5037	1.13 ± 2.83 (ns)	0.398	0.6939
Production cost (LKR)	182,893 ± 74,400 (*)	2.458	0.0493	287,302 ± 30,700 (***)	9.359	< 0.0001
Income (LKR)	427,600 ± 653,000 (ns)	0.655	0.5370	226,954 ± 515,000 (ns)	0.441	0.6631
Net income (LKR)	244,707 ± 598,000 (ns)	0.409	0.6967	− 60,348 ± 511,000 (ns)	− 0.118	0.9070
BCR	− 0.0569 ± 0.628 (ns)	− 0.091	0.9308	− 1.02 ± 0.648 (ns)	− 1.570	0.1295

Parameter	**Season one (Boralanda) (n = 9) estimate (GAP-control)**	**t-value**	***p* value**	**Season two (n = 15) (Balangoda) estimate (GAP-control)**	***p* value**	**Season two (n = 19) (Boralanda) estimate (GAP-control)**	**t-value**	***p* value**
Pole bean (Boralanda—Season one; Balangoda &Boralanda—Season two)								
Yield (t/ha)	1.16 ± 1.69 (ns)	0.686	0.5023	0.672 ± 1.71 (ns)	0.6972	0.834 ± 2.23 (ns)	0.374	0.7104
Production cost (LKR)	− 261,604 ± 47,500 (***)	− 5.504	< 0.0001	315,037 ± 20,600 (***)	< 0.0001	− 10,306 ± 26,600 (ns)	− 0.388	0.7003
Income (LKR)	544,253 ± 601,000 (ns)	0.905	0.3789	101,707 ± 472,000 (ns)	0.8309	271,705 ± 573,000 (ns)	0.474	0.6385
Net income (LKR)	805,858 ± 654,000 (ns)	1.232	0.2358	− 213,331 ± 477,000 (ns)	0.6585	282,012 ± 577,000 (ns)	0.489	0.6279
BCR	1.04 ± 0.421 (*)	2.467	0.0253	− 1.16 ± 0.573 (ns, $p = 0.052$)	0.0523	0.261 ± 0.459 (ns)	0.568	0.5734

Parameter	**Season one (n = 9) estimate (GAP-control)**	**t-value**	***p* value**	**Season two (n = 17) estimate (GAP-control)**	**t-value**	***p* value**
Cabbage (Boralanda)						
Yield (t/ha)	4.67 ± 8.09 (ns)	0.578	0.5716	3.22 ± 1.43 (*)	2.248	0.0316
Production cost (LKR)	123,233 ± 100,000 (ns)	1.227	0.2376	343,406 ± 23,600 (***)	14.556	< 0.0001
Income (LKR)	941,733 ± 1,940,000 (ns)	0.485	0.6343	640,518 ± 308,000 (*)	2.078	0.0458
net income (lkr)	818,500 ± 1,940,000 (ns)	0.422	0.6789	297,112 ± 305,000 (ns)	0.975	0.3369
BCR	0.79 ± 1.51 (ns)	0.523	0.6080	− 0.0787 ± 0.259 (ns)	− 0.303	0.7636

Parameter	**Season one (n = 16) estimate (GAP-control)**	**t-value**	***p* value**	**Season two (n = 10) estimate (GAP-control)**	**t-value**	***p* value**
Carrot (Boralanda)						
Yield (t/ha)	3.44 ± 1.42 (*)	2.416	0.0220	3.16 ± 3.2 (ns)	0.255	0.8011
Production cost (LKR)	− 114,503 ± 26,700 (***)	− 4.294	0.0002	− 148,380 ± 34,800 (***)	− 4.620	0.0002
Income (LKR)	999,425 ± 942,000 (ns)	1.060	0.2974	675,180 ± 355,000 (ns)	1.149	0.2642

Table 3 (continued)

Parameter	Season one (n = 16) estimate (GAP-control)	t-value	*p* value	Season two (n = 10) estimate (GAP-control)	t-value	*p* value
net income (lkr)	1,113,928 ± 1,000,000 (ns)	1.110	0.2759	823,560 ± 394,000 (*)	1.523	0.1434
BCR	1.19 ± 0.894 (ns)	1.335	0.1921	1 ± 0.361 (**)	2.029	0.0560

GAP, good agricultural practices; FP, farmers' practices (control).

The number of farmers is denoted by 'n'.

Significance levels are indicated by asterisks, where * denotes $p < 0.05$, ** denotes $p < 0.01$, and *** denotes $p < 0.001$, while 'ns' indicates non-significance.

Table 4 Interactions between the treatments and seasons on crop parameters variables

Term	Estimate	Std. Error	t-value	*p* value
Yield				
(Intercept)	1.820	0.141	12.950	< 2e – 16 ***
Crop cabbage	1.071	0.199	5.388	1.88e – 07 ***
Crop carrot	0.494	0.176	2.812	0.00539 **
Crop tomato	1.291	0.253	5.097	7.61e – 07 ***
Season S2	1.043	0.158	6.601	3.19e – 10 ***
Crop cabbage: season S2	– 1.078	0.235	– 4.590	7.57e – 06 ***
Crop tomato: season S2	– 1.328	0.288	– 4.607	7.02e – 06 ***
Total cost of cultivation				
(Intercept)	14.08030	0.04636	303.707	< 2e – 16 ***
Group GAP	– 0.23070	0.06133	– 3.762	0.000218 ***
Crop cabbage	– 0.13712	0.06557	– 2.091	0.037683 *
Crop carrot	– 0.12728	0.05795	– 2.196	0.029150 *
Crop tomato	– 0.52210	0.08358	– 6.247	2.24e – 09 ***
Season S2	– 0.22952	0.05214	– 4.402	1.70e – 05 ***
Group GAP: crop cabbage	0.33929	0.08857	3.831	0.000168 ***
Group GAP: crop tomato	0.44304	0.11590	3.822	0.000173 ***
Group GAP: season S2	0.35169	0.07000	5.024	1.07e – 06 ***
Crop GAP: season S2	0.20273	0.07656	2.648	0.008706 **
Group GAP: Crop Carrot: season S2	– 0.39049	0.10543	– 3.704	0.271
Gross income				
(Intercept)	14.77447	0.17816	82.929	< 2e – 16***
Season S2	0.47794	0.20035	2.385	0.01793*
Crop cabbage: season S2	– 1.08146	0.29780	– 3.631	0.00035***
Crop carrot: season S2	– 0.78280	0.29421	– 2.661	0.00839**
Net income				
(Intercept)	14.082354	0.263631	53.417	< 2e – 16***
Season S2	0.887439	0.296477	2.993	0.00309**
Crop cabbage: season S2	– 1.768320	0.440675	– 4.013	8.31e – 05***
Crop carrot: season S2	– 1.397628	0.435366	– 3.210	0.00153**
BCR				
(Intercept)	0.66967	0.17005	3.938	0.000111***
Crop cabbage	0.48461	0.24048	2.015	0.045142*
Season S2	0.73897	0.19123	3.864	0.000148***
Crop cabbage: season S2	– 1.12907	0.28424	– 3.972	9.74e – 05***
Crop carrot: season S2	– 1.02997	0.28082	– 3.668	0.000309***

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Author contributions
Mohamed Aheeyar (MA), Lokeshwar Kesamreddy (LK), Lukas Pawera (LP) and Ramasamy Srinivasan co-prepared the manuscript. MA conducted an additional literature review, revised the draft, and prepared data collection tools. MA and Duleesha Nisansala (DN) carried out primary data collection. LK, Stephen Othim (SO), and LP conducted data analysis and interpretation. KMS Kodikara assisted in conducting field research and implementing GAP. Mohsin Hafeez contributed to manuscript preparation and the internal review of the paper.

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Data availability
Data will be made available from the corresponding authors upon a reasonable request.

Declarations

Ethics approval and consent to participate

This study was approved by the IWMI's Institutional Review Board (IRB), with exempt certificate number 2023_43. IWMI's IRB approved the protocol used, aligned with Section 45 CFR 46.101(b) of the US Federal Policy for the Protection of Human Subjects, Exempt Category (2)(ii) Educational tests, surveys, interviews, or observation, and Exempt Category (4) Secondary data research. All procedures were performed in accordance with the ethical standards of the IWMI research ethics committee. All participants were informed about the purpose of this study and provided their informed consent before participating.

Consent for publication

Not applicable.

Competing interests

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