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Guava-vegetable agroforestry system for sustainable production and system benefits following circular agriculture concept

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ABSTRACT

Sustainable agriculture through circular agroforestry in Bangladesh improves resilience by integrating diverse crops and trees, boosting productivity and soil health, and supporting rural livelihoods while reducing environmental impacts. This study assessed the performance of seasonal vegetables in guava-based agroforestry systems under various fertilizer management practices, focusing on productivity, economic returns, soil quality, and sustainability in Bangladesh. Conducted from July 2024 to June 2025 at Gazipur Agricultural University, the experiment employed a randomized complete block design with treatments comprising 100% vermicompost (VC), 100% inorganic fertilizer (IF), and a mixture of 50% VC and 50% IF, alongside control plots without fertilizer and trees. Results showed that okra and cauliflower grown in the agroforestry system with the 100% VC treatment had significantly higher growth and yield than other treatments and monoculture controls. Guava trees grown under agroforestry also demonstrated increased canopy volume, fruit yield, and other growth parameters, benefiting from inputs applied to understory crops. Soil analysis revealed notable increases in organic matter and total nitrogen in agroforestry plots, especially where vermicompost was used, improving soil fertility and sustainability. Economic analysis confirmed that the 100% VC + okra + guava treatment achieved the highest gross and net income, benefit-cost ratio (BCR) (3.15), and land equivalent ratio (LER) (2.33), demonstrating the system's superior profitability and land-use efficiency. Guava-based agroforestry combined with organic nutrient management can increase crop productivity, improve soil health, and provide economic benefits, promoting climate-resilient agriculture and food security in Bangladesh. This research advocates for agroforestry as a sustainable alternative to monoculture farming in challenging agronomic and environmental conditions.

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Introduction

Despite its geographic location in Bangladesh, the country is increasingly vulnerable to climate change-induced disasters and hazards due to the intensification of rainstorms from the north, melting Himalayan ice caps, and rising tides in the Bay of Bengal to the south (Rahman *et al.*, 2023; Das *et al.*, 2020). Bangladesh has a population of nearly 173.5 million (BBS, 2024), projected to reach 200 million by 2050 (UN, 2025). The sustainable livelihoods of these individuals are heavily dependent on agriculture, a sector that not only serves as the backbone of the economy but is also facing significant threats from climate change and human activities (Banerjee *et al.*, 2018; Rahman *et al.*, 2018). Rapid industrialization, unplanned urbanization, and an increase in settlements are collectively causing the loss of 69,000 hectares of agricultural land each year. If the current trend continues at its current rate, Bangladesh could be left with no cultivable land within the next 50 years (Das *et al.*, 2020; Muhsin *et al.*, 2018). In addition, 7.8 million ha of the 14.8 million ha of cultivable land have less than 1.5% soil organic matter (OM) (Hossain *et al.*, 2017), compared to the need for good agricultural land of 2% (Sultana *et al.*, 2015). Therefore, alternative, nutrient-sensitive, and climate-smart agricultural practices should be pursued to overcome the constraints in existing crop production.

Circular agroforestry is not a new concept; pre-industrial societies widely practiced it. However, it has been sidelined by modern farming methods, which focus on large-scale, monoculture, and intensive practices that often prioritize profit over environmental protection (Wilson & Lovell, 2016). The business model of large-scale, specialized agricultural farms typically does not align with circular agriculture. Transitioning to circular agriculture requires greater emphasis on supporting smallholder farms through organic, mixed, and agroforestry practices. Circular agriculture, which promotes diverse production, is associated with better health and nutrition, in contrast to export-oriented monocrop systems that have often led to increased food insecurity (Helgason *et al.*, 2021). Additionally, circular agriculture is more labor-intensive than conventional farming, providing a strategy to boost rural economies. Adopting circular farming practices can significantly contribute to poverty reduction, food security, and the creation of new employment opportunities, especially for rural women. While conventional farming often requires substantial capital to purchase expensive seeds, fertilizers, and pesticides, circular agricultural practices can lower barriers for women to enter the sector by reducing input requirements (Bonilla-Cedrez *et al.*, 2023). The practice of planting trees alongside pastures or crops is known as agroforestry and is a crucial component of circular agriculture (Wilson & Lovell, 2016). Planting trees improves soil fertility by increasing organic matter from decaying plant material and helps restore biodiversity in agricultural areas. Agroforestry can also enhance circularity by reducing reliance on chemical fertilizers and pesticides (Fahad *et al.*, 2022). Among various agroforestry systems, fruit tree-based systems are considered particularly suitable for sustainability, overall production, and compatibility with crops (Montes *et al.*, 2019). However, farmers often face lower economic returns in the initial years until the fruit trees begin bearing fruit. There is significant potential to utilize this early period—about 5 to 6 years—by growing arable crops in between the trees (Kumar *et al.*, 2014). The positive effects of organic matter from forest trees on soil health and crop performance are well documented (Nair *et al*., 2022; Sanchez *et al.*, 1997). In these systems, trees and crops are grown together, competing for resources like light, water, and nutrients. Agroforestry can also reduce the need for plastic mulch by using leaves and other plant materials as organic cover. Importantly, fruit tree-based agroforestry offers opportunities to implement circular agriculture with lower ecological impacts.

Guava (*Psidium guajava* L.) is a popular tropical fruit enjoyed for its delicious taste in many tropical and subtropical regions. It is valued for its refreshing flavor and rich nutritional profile, which includes vitamins C, A, and B6, as well as minerals, fats, cholesterol, sodium, magnesium, potassium, carbohydrates, proteins, iron, and calcium (Joshi *et al.*, 2019; Uddin *et al.*, 2002). As a result, it is an ideal fruit for high yield, nutritional security, and economic growth (Omayio *et al.*, 2019).

In the national context, fruit tree-based agroforestry systems are crucial within circular agriculture practices and can play a significant role in addressing nutritional issues, while offering substantial economic and ecological benefits. With increasing demand for fruits and vegetables and decreasing agricultural land, boosting the production of these commodities in Bangladesh is crucial. During early establishment stages, guava orchards can be systematically intercropped with seasonal vegetables, providing year-round income and reducing the risk of crop failure. Moreover, the integration of suitable crops or vegetables with fruit trees, along with efforts to promote this system among the broader population, has rarely been evaluated or practiced. Therefore, this study aims to address these challenges (i) to evaluate the performance of seasonal vegetables in guava-based agroforestry systems compared to monoculture under different fertilizer management practices following the circular agriculture concept, (ii) to assess the benefits of guava-based agroforestry in terms of productivity, economic returns, and land use for system sustainability, and (iii) to determine the quality of soil in agroforestry and non-agroforestry systems under various management practices.

Materials and Methods

Study location and climatic conditions

The study was carried out at the research farm of the Department of Agroforestry and Environment at Gazipur Agricultural University, Bangladesh (24° 02′ 10.3′′ N;

90° 23′ 57.4′′ E) from July 2024 to June 2025 (Fig. 1). The minimum and maximum temperatures of the study area throughout the experimental periods ranged from 20.91 to 31.11 °C, with an average precipitation and relative humidity of 1096.67 mm and 74.27% during the growing season (Fig. 2). The weather data for the study period were collected from the Department of Agrometeorology, GAU. The physiographic unit of the soil of this land is silty clay loam in texture, representing the agro-ecological zone of Madhupur Tract (AEZ-28).

Experimental design and treatment composition

A 1-year-old well-established guava orchard was converted into an agroforestry system

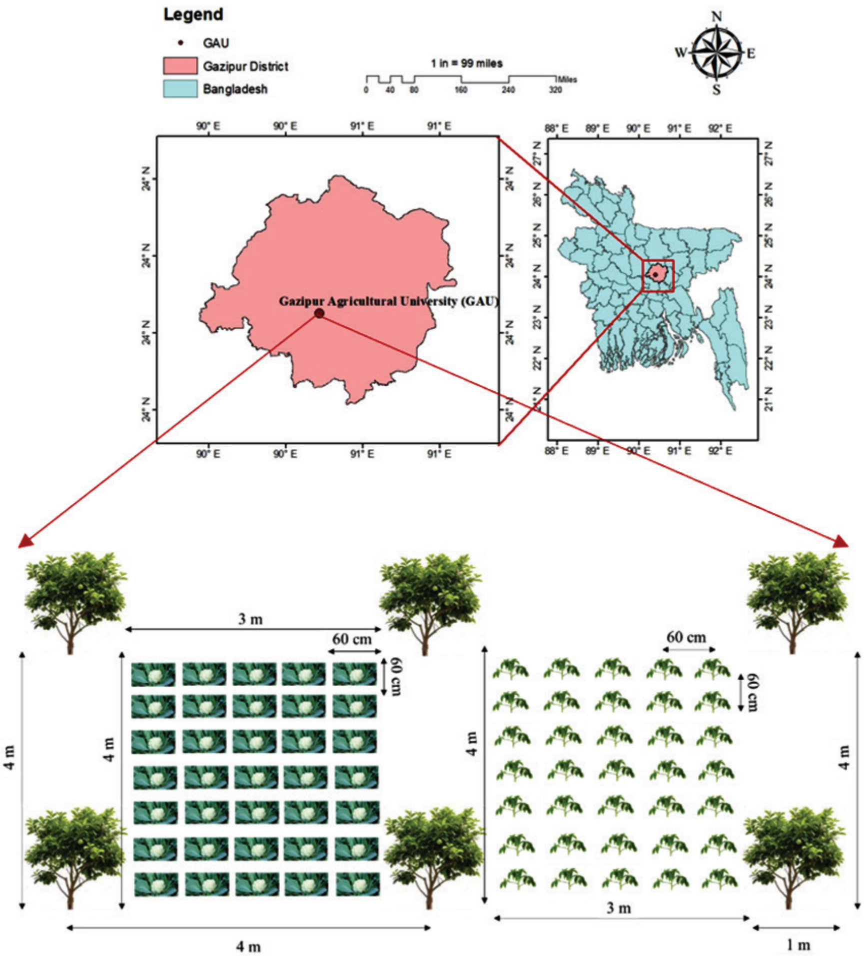

Fig. 1. Location and illustration of a single replication/block showing the planting design of trees, crops, and spices in a guava-based agroforestry system.

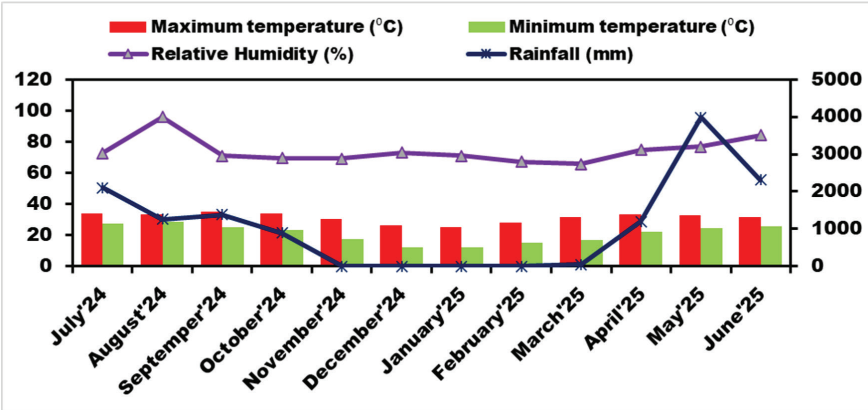

Fig. 2. Meteorological data during the experiment period from July 2024 to June 2025.

to grow various vegetables between the rows of guava trees. The row of a guava tree, consisting of 4 trees with three distinct blocks were considered as three replications; however, guava trees were planted following 4 m × 4 m spacing (Fig. 1). In addition, Robi season vegetable, like cauliflower (var. BU fulkopi-1) and Kharif season vegetable, like okra (BARI dherosh-2) seeds were sowing at a spacing of 60 cm × 60 cm.

For evaluating crop performances by incorporating different dosages of vermicompost and NPK, the newly formed Guava-based agroforestry system, therefore, consisted of four treatments in which cauliflower or okra were planted in the rows of guava. Afterward, the crop performances under the agroforestry system were also compared with the performances of the corresponding crop grown in an open field (referred to as control). Under the agroforestry scheme, the guava tree was considered a common source of additional income. Given this, the growth and yield-related output of a guava tree under the agroforestry system was compared with that of a guava tree outside the system. The experiment was laid out in a randomized complete block design to minimize plot errors, as the soils were not homogeneous across the entire field. We, therefore, identified nine treatment compositions, as follows, in relation to the guava trees, considering the interaction between crops and spices.

- VC 100% + Okra/ Cauliflower + Guava
- IF 100% + Okra/ Cauliflower + Guava
- VC 50% + IF 50% + Okra/ Cauliflower + Guava
- Control (without tree and fertilizer for crops)
- Control (for guava)

Field preparation, fertilizer application, and intercultural operations

In each season, land preparation was done to obtain good tilth for planting crops. The physicochemical properties of the initial soil are presented in Table 1. Additionally, recommended doses of fertilizers (Table 2) were also applied. Full doses of vermicompost, TSP, and MoP were applied during final land preparation in general. However, half of the urea was applied as a basal dose during final land preparation, and the rest was added as two equal installments at the time before flowering and fruiting for okra and cauliflower. For intercultural operations, including irrigation, weeding, and the application of pesticides (specifically Dursban 20 EC at a rate of 2 mL L^{-1} of water), and for organic management, neem and mahogany extracts were used as viral vector controllers for the respective crops, as per the crop requirements. Importantly, in the agroforestry system, no supplemental management operations, such as irrigation and fertilization, were applied to guava trees other than pruning, whereas sole guava trees received all management operations, including irrigation on an as-needed basis and recommended fertilizer doses (Table 2) during the experimental period.

Growth and yield-contributing attributes of crops and trees

Growth and yield attributes of plants (okra and cauliflower) from each treatment were recorded following each harvest. All harvested data were then summed up to obtain the

Table 1. Physicochemical characteristics of experimental terrace soil surface layer (at a depth of 12 cm)

Textural soil	Soil temperature (°C)	Soil moisture (%)	Soil pH	Organic Matter (%)	Nitrogen (%)	Phosphorus (ppm)	Potassium (meq 100 g^{-1})
Silty clay loam	21.88	11.08	6.10	1.99	0.86	7.42	0.35

Parts per million (ppm); milliequivalent (meq).

Table 2. Applied dosages of fertilizer during the experimentation

Crop	Treatment	Vermicompost (t ha^{-1})	Urea (kg ha^{-1})	TSP (kg ha^{-1})	MoP (kg ha^{-1})
Cauliflower	VC 100%	5	0	0	0
	IF 100%	0	195	87	150
	VC 50% + IF 50%	2.5	98	44	75
	CK	0	0	0	0
Okra	VC 100%	5	0	0	0
	IF 100%	0	130	44	67
	VC 50% + IF 50%	2.5	65	22	34
	CK	0	0	0	0

TSP, triple super phosphate; MoP, muriate of potash; VC, vermicompost; IF, inorganic fertilizer; and CK, control.

final yield. Measurement of plant height and canopy volume was conducted to evaluate the growth performance of the guava tree using the equation proposed by Halder (2013). The number of fruits per plant and the individual fruit weight of guava were recorded at each harvesting time and subsequently averaged to obtain the yield per plant.

Assessment of soil properties, economic performances, and land use efficiency

Soil samples were assembled from both the fields of agroforestry and non-agroforestry (sole) before and after completion of the experimentations. The procedures of Jackson (1958) and Bremner (1965) were followed to estimate the contents of total nitrogen and organic matter, respectively. The economic and land-use benefits of guava-based agroforestry systems were evaluated by calculating the benefit-cost ratio (BCR) and land equivalent ratio (LER), following the equations reported by Miah *et al.* (2018).

Statistical analysis

All the data were analyzed by a one-way analysis of variance (ANOVA) using RStudio software. Different alphabetical letters represent significant differences among the treatments at $P < 0.05$, as determined by a Tukey's honestly significant difference (HSD) test. All the data presented in the figures and tables are means with standard errors (SEs) of three replications for each treatment.

Results and Discussion

Performance of crops

Between the guava trees, okra, and cauliflower grown were fertilized with different rates of organic manure to promote growth. The plant height, number of fruits per plant, fruit length, fruit width, single fruit weight, yield per plant, and yield per plot of okra were varied significantly due to the application of different organic and inorganic fertilization treatments compared to the non-fertilized plot (Fig. 3). The maximum growth and yield attributes of okra were recorded in vermicompost treated plot in guava-based agroforestry system with an increase of plant height (by 32.87, 26.02, and 44.35%), number of fruits per plant (by 63.18, 28.93, and 46.80%), fruit length (by 39.38, 11.87, and 31.74%), fruit width (by 42.06, 4.67, and 24.30%), individual fruit weight (by 34.17, 16.76, and 23.78%), yield per plant (by 54.61, 19.08, and 36.84%), and yield per plot (by 83.03, 48.23, and 72.58%) in VC 100%, IF 100%, and VC 50% + IF 50% plots, respectively compared to CK (control) plant (Fig. 3).

However, in the case of cauliflower was also tested, which revealed significant variations among the treatments in all observed parameters, including curd length, curd width, curd weight, and yield per plot (Fig. 4). As compared to the control (CK) plot, curd length, curd width, curd weight, and yield per plot of cauliflower increased by 30.83, 10.98,

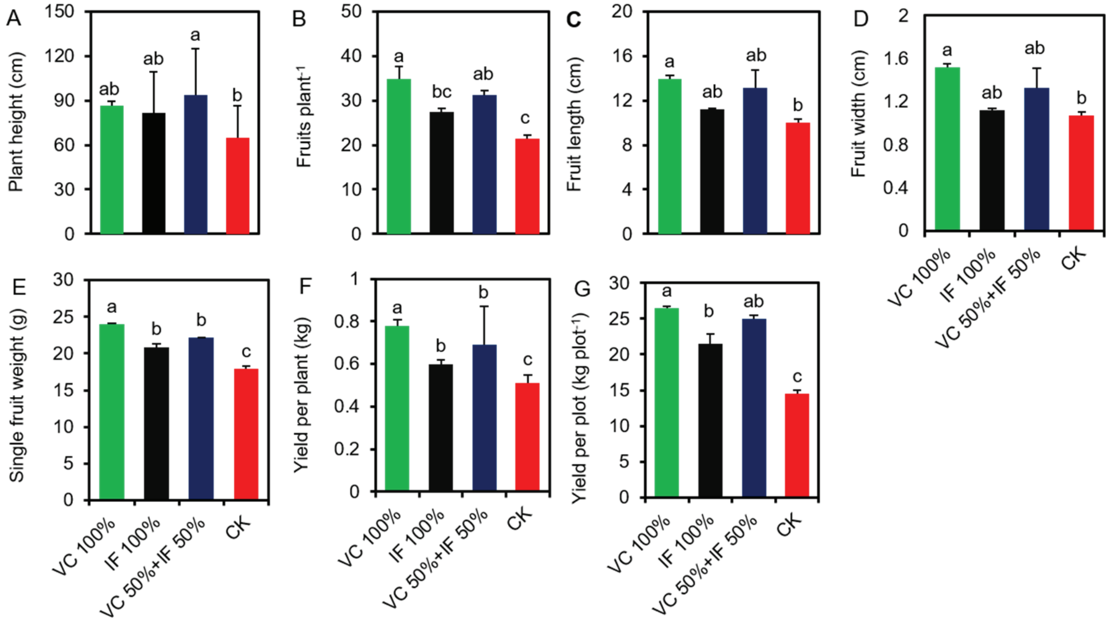

Fig. 3. Okra performance in guava-based agroforestry system, including open conditions. [Values are means ± standard errors of three replication plots. Bar graphs under a parameter having the different alphabetical or same letter(s) above different bars do not differ significantly for HSD ($p<0.05$); VC, vermicompost; IF, inorganic fertilizer; CK, control; cm, centimeter; g, gram; kg, kilogram; and tha^{-1}- tons per hectare].

and 19.58%; 21.47, 10.25, and 19.17%; 44.25, 13.37, and 38.04%; 68.03, 27.50, and 44.02% in the VC 100%, IF 100, and VC 50% + IF 50% plots, respectively (Fig. 4).

Concurrently, the results of the experiment revealed that, for all crops except okra plant height, the highest data were observed when the plot was treated with VC at 100%. The integration of vermicompost in crop growth and yield within an agroforestry system was more influenced compared to the control due to reduced competition between the understory (crop) and upper-story (guava tree) components for resources such as sunlight, water, and nutrients during the initial stage of the guava orchard. Additionally, vermicompost contains significant amounts of nutrients, beneficial microbial populations, and biologically active metabolites—particularly gibberellins, cytokinin, auxins, and group B vitamins (Kumar *et al*., 2017)—all of which positively affect photosynthesis and translocation, leading to higher yield factors. This study supports the findings of Dulal *et al*. (2021), Kar *et al*. (2019), and Kumar *et al*. (2016).

Performance of guava

Guava plants grown under the agroforestry system benefited from the inputs used for crops cultivated in sequential seasons

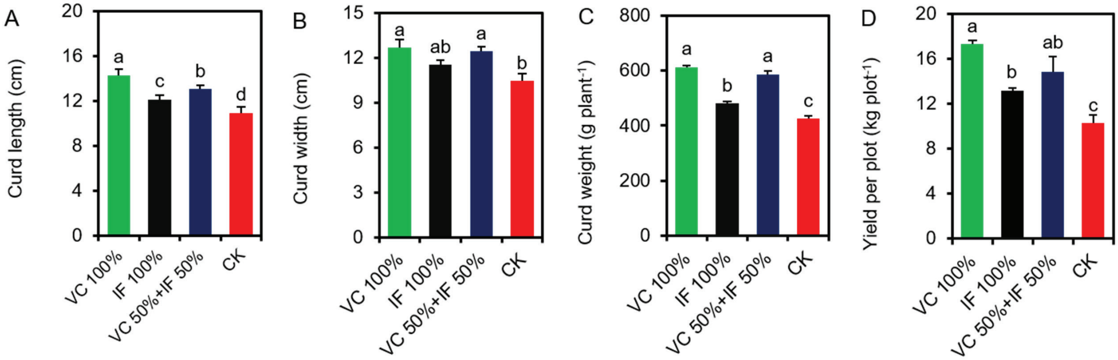

Fig. 4. Yield and yield contributing characteristics of cauliflower grown in guava-based agroforestry system, and open field (non-agroforestry). [Values are means ± standard errors of three replication plots. Bar graphs under a parameter having the different alphabetical or same latter(s) above different bars do not differ significantly for HSD ($p<0.05$); VC, vermicompost, IF, inorganic fertilizer, CK, control; cm, centimeter, g, gram; kg, kilogram, and tha^{-1}- tons per hectare].

throughout the year. These plants showed improvements such as a 10.80% increase in canopy volume, a 34.62% rise in fruits per plant, a 1.02% increase in fruit length, a 0.82% increase in fruit diameter, a 6.52% boost in individual fruit weight, and a 17.67% higher yield per plant compared to control plants. However, a 7.40% reduction was observed in plant height (Table 3). The enhancement in the yield attributes of guava trees under the agroforestry system can be attributed to the fact that they utilized a significant amount of production inputs, especially irrigation water and fertilizers applied to the understory crops. Consistent with the past findings, Das *et al*. (2020) also reported that the yields of malta trees significantly improved in a malta-vegetables-based agroforestry system compared to a monoculture malta orchard. This study supports the findings of Das *et al*. (2022) on jajube, Al Riyadh *et al*. (2019) on jackfruit, and Miah *et al*. (2018) on jackfruit.

Vermicompost-induced modification of soil nutrient dynamics

There was an increase in total nitrogen (N) and organic matter (OM) in the initial soils obtained from the guava-based agroforestry system compared to those of the initial soils from the open field (Fig. 5). The amount of total OM was found to be increased in Robi season (19.18, 7.69 and 17.03%) and in Kharif season (30.51, 18.08, and 19.30%) in VC 100%, IF 100%, and 50% VC + 50% IF treatment respectively, when compared to the NAF's (CK) (Fig. 5). Likewise, in comparison with soils of the non-agroforestry system (CK), total N was found to be increased in Robi and kharif season (13.58, 20.99 and 18.52%), and (28.57, 38.96 and 32.47%) in VC 100%, IF 100%, and 50% VC + 50% IF treatment respectively. Nevertheless, a decrease in

Table 3. Growth and yield attributes of guava as influenced by different levels of vermicompost and NPK in guava-based agroforestry system and control

Treatment	Plant height (cm)	Canopy volume (m^3)	Number of fruits plant^{-1}	Fruit length (cm)	Fruit diameter (cm)	Individual fruit weight (g)	Yield plant^{-1} (kg)
AF's	2.61±0.16a	22.67±2.73a	23.33±2.03a	5.95±0.29a	6.13±0.07a	110.13±2.13a	2.73±0.28a
NAF's	2.43±0.07a	20.46±0.78b	17.33±1.45b	5.89±0.11a	6.08±0.24a	103.38±3.66b	2.32±0.12b

AF's, Agroforestry system; NAF's, non-agroforestry system

total N (5.81 and 4.94%) and OM (3.70 and 2.75%) was also observed in open field soils after field experimentation, corresponding to that of the initial soils of the open field in Robi and kharif seasons, respectively (Fig. 5). The increase in OM across all treatments, where chemical fertilizers were replaced with vermicompost, was found to be higher in the VC 100% treatment compared to the other treatments. This increase is attributed to a higher microbial population, improved decomposition of vermicompost, and its ability to reduce phosphorus fixation in the soil, which in turn enhances organic matter content (Al-Maamori *et al*., 2023). On the other hand, VC contains a high level of organic matter and is the main source of nitrogen in soil (Mupambwa and Mnkeni, 2018). When organic fertilizers are added to soil to replenish the organic matter, nitrogen is one of the nutrients most commonly provided to the soil (Bellitürk, 2018; Celik *et al*., 2017).

Economic and land use performance of the guava-based agroforestry system

Initially, VC 100%+ okra + guava exhibited the highest production cost per hectare of land (505598 Tk), while the minimum cost of production (268663 Tk) was recorded in sole guava (Table 4). However, the VC 100% + okra + guava-based agroforestry system exhibited the highest gross income (BDT 568,750) and net income (BDT 63,152), followed by the sole treatment and other treatments incorporated into agroforestry systems. In contrast, the lowest values of these respective parameters were recorded in the sole guava (Table 4). However, the highest BCRs of 3.15 and 3.14 were observed in okra and cauliflower guava-based agroforestry systems, respectively, when the plots were treated with 100% VC followed by other incorporating treatments. It is worth noting that the overall lowest BCR was obtained from the sole okra (1.10), owing to the high cost involved in establishing a guava orchard (Table 4). Among the different crop-associated agroforestry systems, VC 100% + okra + guava had the highest LER (2.33), followed by the other treatments. In comparison, the lowest LER (2.03) was reported in an IF 100% + cauliflower + guava-based agroforestry system treatment (Table 4). The study found that incorporating

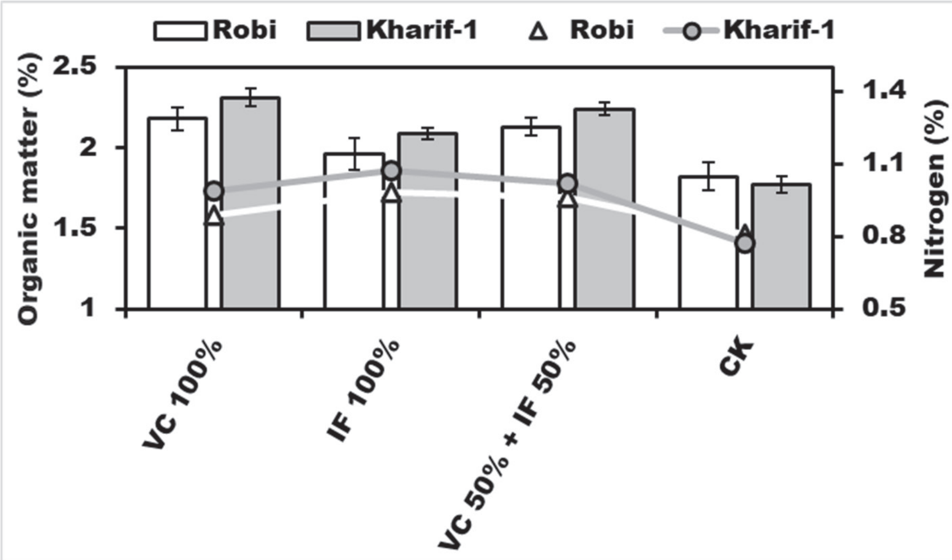

Fig. 5. Status of total nitrogen and soil organic matter of guava-based agroforestry systems and monocropping, in both robi and kharif seasons. [Values are means ± standard errors of three replicated plots. VC, vermicompost; IF, inorganic fertilizer; and CK, control].

Table 4. Economic and land use performance as influenced by different levels of vermicompost and NPK in guava-based agroforestry systems and monocultures

Crop	Agroforestry system	Yield in AF's and NAF's (t/ha)	Total cost (TK ha^{-1})	Gross income (TK ha^{-1})	Net return (TK ha^{-1})	BCR	LER
Okra + Guava	VC 100%	16.25	505598	568750	63152	3.15	2.33
	IF 100%	12.50	457827	437500	-20327	2.99	2.06
	VC 50% + IF 50%	14.37	481712	503125	21413	3.07	2.19
Cauliflower + Guava	VC 100%	12.77	460085	510834	50749	3.14	2.26
	IF 100%	10.02	412753	400833	-11920	3.00	2.03
	VC 50% + IF 50%	11.79	436419	471667	35248	3.11	2.17
Sole okra		14.16	447098	495845	48747	1.10	-
Sole cauliflower		11.80	401585	472223	70638	1.18	-
Sole guava		5.80	268663	464000	195337	1.73	-

VC, vermicompost; IF, inorganic fertilizer; CK-control; tha^{-1}, tons per hectare; AF's, Agroforestry system; NAF's, non-agroforestry system; BCR, benefit-cost ratio; and LER, land equivalent ratio.

vermicompost into the agroforestry system resulted in the highest BCR and LER. This study corroborated the findings of Kumar *et al*. (2017) and Kar *et al.* (2019). The result also showed that the BCR of agroforestry systems remained higher than that of sole crops, as did gross and net income (Table 4). The findings were supported by those of Rahman *et al*. (2018), who reported the highest BCR in the jackfruit-eggplant-based agroforestry system. More importantly, the study revealed a high LER value in the agroforestry system, indicating that more land would be required to achieve comparable production from the sole cultivation of similar components (Table 4). The elevated LER in agroforestry systems was also reported by Miah *et al*. (2018) in a jackfruit papaya-eggplant-based agroforestry system, and Yang *et al*. (2016) in a jujube-wheat-based agroforestry system.

Conclusions

Guava-based agroforestry systems that incorporate seasonal vegetables, such as okra and cauliflower, along with vermicompost and inorganic fertilizers, have shown significant improvements in crop growth, yield, and soil quality compared to monoculture systems. The use of 100% vermicompost consistently enhanced the growth and yield of both vegetable crops and guava. This improvement is attributed to the rich nutritional composition of vermicompost and its positive microbial activity. These agroforestry systems not only increased soil organic matter and total nitrogen levels but also promoted soil fertility and sustainability. They exhibited higher benefit-cost ratios and land-use efficiency, particularly when vermicompost was applied. As a result, these systems generated superior gross and net returns compared to sole cropping. These findings highlight the potential of guava-based agroforestry systems that follow the principles of circular agriculture to enhance production, economic sustainability, and soil health. This approach provides an environmentally responsible framework for climate-sensitive agricultural improvement in Bangladesh.

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Conflict of Interest

The authors declare that they have no competing interests.

Author Contributions

Planning, designing, and conceptualization were made by M.A.R.; and S. R.S. Data collection was done by A.K.A.; N.N.; B.T.K., and A.Y. Data curation, analysis, preparation of Figures, discussion, and explanation were made by A.K.A. Manuscript preparation and editing were made by M.A.R.; S.R.S.; and A.K.A.

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