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RESEARCH ARTICLE

Evaluating bio-intensive cropping systems for enhanced profitability and sustainability in garden land ecosystems

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Abstract

Mounting challenges such as excessive use of synthetic inputs, poor resource use efficiency and declining soil health undermine the sustainability of conventional agriculture. Bio-intensive complementary cropping, an ecologically sound approach offers a sustainable alternative by integrating synergetic crop species and their integration with appropriate nutrient management boost productivity and improves soil health. In this context, the present study was conducted in a split-plot design with four main plots and five subplots, replicated thrice to assess the performance of different bio-intensive complementary cropping. Results revealed that maize intercropped with cowpea and sunnhemp recorded the highest productivity with cotton equivalent yield of 2556 kg/ha. This system also showed greater competitiveness with a land equivalent ratio of 1.13, indicating a clear advantage over sole cropping. Among the nutrient management practices, application of 50 % recommended NPK through chemical fertilizers along with 50 % recommended N through vermicompost on N equivalent basis and 5 % fermented fish extract as foliar spray showed the most significant improvement with soil available nitrogen, phosphorous and potassium reaching 209.5, 14.7 and 622.3 kg/ha, respectively. The study concludes that bio-intensive system involving legumes, green manures integrated with organic amendments plays a significant role in enhancing agricultural sustainability. Among the tested combinations, maize intercropped with cowpea and sunnhemp supplemented with 50 % NPK through chemical fertilizers and 50 % N through vermicompost along with 5 % fermented fish extract foliar spray resulted in highest cotton equivalent and nutrient uptake. This integrated approach not only significantly increases the productivity of the system but also improved soil health by boosting nutrient availability and enhanced resource use efficiency.

Keywords: crop productivity; intercropping; nutrient management; soil fertility

Introduction

The global agricultural landscape is being challenged by the dual burden of ensuring food and nutritional security while also protecting environmental sustainability. Rapid population growth, decreasing natural resources, climate variability and soil degradation as a result of indiscriminate use of chemical inputs have put immense pressure on conventional farming systems. Conventional methods have often emphasized maximizing yields through input-intensive monocultures, yet such systems results in decreasing soil fertility and increasing pest and disease outbreaks (1). Therefore, the need for farming systems to evolve towards resilient, resource-efficient and ecologically sound system is becoming more evident under current agricultural challenges. One promising approach to achieving this transformation is the adoption of Bio-Intensive Complementary Cropping Systems (BICCS), which integrate ecological principles into crop production to promote biological interactions, enhance productivity and sustain soil health. Unlike traditional intercropping, which primarily aims at simple crop diversification, BICCS are designed to maximize the synergistic interaction between the crops. It promotes resource use efficiency, enhances biodiversity and maintains soil health by cultivating multiple, mutually supportive crops together. The crops are selected based on traits that allow them to support each other's growth through mechanisms such as spatial and temporal complementarity, nutrient sharing and microclimate moderation to promote the biological interactions and resource use efficiency.

Maize is an important cereal crop valued for its versatility as both a food and animal feed and widely cultivated for its adaptability and high yield potential. However, as a nutrient-intensive crop, the availability and management of soil nutrients has a significant impact on its productivity. In this context, leguminous crops have become crucial components of sustainable agriculture due to their ability to fix atmospheric nitrogen, thereby reducing the dependence on synthetic fertilizers (2). Intercropping maize with legumes such as cowpea creates a biologically complementary system that helps fulfill their nutrient demands. These systems not only enhance resource-use efficiency but also promote sustainable intensification by enhancing the yield and soil health. Cotton, characterized by its wide spacing, slow growth and extended cultivation period, offers considerable opportunities for intercropping with short-duration, fast-growing and non-competitive crops exhibiting distinct growth patterns. This combination optimizes resource utilization, as intercrops effectively utilize the available space and nutrients without interfering the cotton growth. Integrating vegetable crops like onion into the cotton-based system further amplifies these benefits by improving the productivity and land use efficiency. Additionally, it reduces risk by providing farmers with an alternative source of income when cotton yields are affected by environmental factors or market fluctuations (3).

A non-conventional edible oilseed crop that significantly contributes to narrowing the gap between domestic oil demand and production is sunflower (4). With its short life cycle and deep roots, this high value crop offers a potential for integration in a variety of cropping systems. Through biological nitrogen fixation, intercropping with legumes such as green gram helps to enhance the soil nutrient status and reduces the need for synthetic fertilizers. Furthermore, it offers additional benefits such as controlling soil erosion, enhancing soil structure and increasing organic matter content which contribute to long-term soil health and sustainability (5). Chilli stands out as one of the most significant spice crop valued both in its green and dried forms. In India, farmers in many states widely cultivate it in mixed cropping system, but in some regions like Andhra Pradesh and Tamil Nadu it is grown as sole crop. The wider row spacing and the initially slow growth of chilli makes it suitable for intercropping them with short-duration vegetables like onion which enhances land-use efficiency, resource utilization and diverse farm income.

In bio-intensive systems, sustaining the productivity and soil health not only relies on selection of crops but it also depends on effective nutrient management practices (6). Applying organic amendments such as farmyard manure (FYM), vermicompost, poultry manure and neem cake supplies the essential micro and macronutrients which improves the soil structure, rejuvenate degraded soils and improves nutrient availability. Additionally, they promote soil organic matter and beneficial microbial populations, which in turn enhance nutrient cycling, soil fertility and disease suppression. Also, the incorporation of biologically active foliar inputs, in addition to soil applied manures, further complements nutrient management strategies in bio-intensive systems. A fermented organic input derived from fish waste helps improve nutrient uptake and promotes plant growth, especially in systems where crops are densely planted and have high nutrient requirements. The synergistic effect of combining organic manures with fish extract boosts nutrient availability, leading to improved crop performance and soil vitality. Furthermore, cultivating and incorporation of green manures within the crop rows offer significant agronomic and ecological benefits. Green manure such as sunnhemp, when incorporated into the soil at ideal stage, releases essential nutrients that improves the nutrient availability and soil fertility (7).

Previous studies on intercropping and integrated nutrient management have demonstrated improvements in crop yield, land-use efficiency and soil fertility. However, most of these investigations have focused either on simple cereal-legume systems or on individual nutrient management practices in isolation. There is limited evidence on how diverse bio-intensive complementary cropping systems, particularly those integrating cereals, legumes, vegetables and green manures perform when combined with integrated organic and inorganic nutrient sources along with foliar amendments. Keeping the above point in view the present study aims to evaluate the performance of different bio-intensive complementary cropping under varied nutrient management practices that enhances productivity, maintain soil health and promote long term sustainability for farmers. Unlike earlier studies, it emphasizes both productivity and soil nutrient dynamics, thereby providing a more holistic understanding of how crop diversification and integrated nutrient strategies can enhance agricultural sustainability.

Materials and Methods

Experimental site description

The experiment was conducted in the Eastern block of Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India during the *kharif* season of 2024. The research field is situated in the western agro-climatic zone of Tamil Nadu, at 11.01° N latitude and 76.93° E longitude with an altitude of 426.7 m above the mean sea level. The soil has a sandy loam texture with neutral pH of 7.10, electrical conductivity of 1.308 dS/m, organic carbon of 5.12 g/kg, available nitrogen of 218.4 kg/ha, available phosphorous of 16.1 kg/ha and available potassium of 658 kg/ha.

Experimental design

The field experiment was conducted in a split-plot design with three replications. The main plot factor was bio-intensive complementary cropping and the subplot factor was integrated nutrient management practices. In each replication, the main plots were first randomized and then the sub-plots were randomized within each main plot. The main plot consists of M_1 - maize + cowpea + sunnhemp, M_2 - cotton + onion + sunnhemp, M_3 - sunflower + green gram + sunnhemp and M_4 - chillies + onion + sunnhemp. The subplot consists of S_1 - 100 % recommended NPK through chemical fertilizers, S_2 - 50 % recommended NPK through chemical fertilizers + 50 % recommended NPK through FYM on N equivalent basis + 5 % fermented fish extract (FFE) as foliar spray, S_3 - 50 % recommended NPK through chemical fertilizers + 50 % recommended NPK through vermicompost on N equivalent basis + 5 % FFE as foliar spray, S_4 - 50 % recommended NPK through chemical fertilizers + 50 % recommended NPK through poultry manure on N equivalent basis + 5 % FFE as foliar spray and S_5 - 50 % recommended NPK through chemical fertilizers + 50 % recommended NPK through neem cake on N equivalent basis + 5 % FFE as foliar spray. The crop combinations were chosen based on the ecological complementarity and farmers preference. The main crop represents predominant commercial crops of the region and the intercrops were selected for their short duration, ability to utilize understorey niches and economic value.

The variation in growth cycles and nutrient requirements, enable them to efficiently share resources such as water, nutrient, sunlight and space. All the crops were raised in furrow irrigated raised beds of 90 cm width, 400 cm length and 20 cm height to accommodate two rows of main crop in the bed and in-between spaces were utilized for growing intercrops. Sunnhemp were raised in the furrows and incorporated *in-situ* at 20 DAS as green manure to enhance the soil organic matter. As per treatment specification, organic manures were applied on N equivalent basis. FFE were prepared following the standard procedure and applied as foliar spray on 20 and 40 DAS. Irrigation, weeding, pest and disease management were carried out as per standard package of practices.

Assessment of competition indices

To assess the performance of different intercropping systems, various competitive indices like crop equivalent yield (CEY), Land equivalent ratio (LER), Aggressivity (A), Competition ratio (CR) and Area time equivalent ratio (ATER) were calculated using standard formulas.

CEY

The yield of each crops were converted into cotton yield based on market price using a standard formula and expressed in CEY.

$$\text{CEY} = \text{Yield of cotton} + \frac{\text{Intercrop yield (kg/ha)} \times \text{Price of intercrop (Rs./kg)}}{\text{Price of cotton (Rs./kg)}}$$

(Eqn. 1)

LER

LER refers to the proportion of land area needed for a pure stand of a crop species to produce an equal yield as attained from intercropping, with similar management practices (8). It is used to assess the overall efficiency of the intercropping system and calculated using the following formula:

$$\text{LER} = \frac{Y_{mi}}{Y_m} + \frac{Y_{ii}}{Y_i} = \text{LER}_{main} + \text{LER}_{intercrop}$$

(Eqn. 2)

Where Y_m and Y_i are the sole crop yield of the component species m and i respectively; Y_{mi} and Y_{ii} represent the yield of component species in intercrop situations.

Aggressivity (A)

Aggressivity is used to assess the competitive relationship between two crops and indicates the dominance of one crop over the other crop used in intercropping (9). It was calculated using the following formula:

$$A_{main} = \frac{Y_{mi}}{Y_m \times P_{mi}} - \frac{Y_{ii}}{Y_i \times P_{ii}} \quad \text{(Eqn. 3)}$$

$$A_{intercrop} = \frac{Y_{ii}}{Y_i \times P_{ii}} - \frac{Y_{mi}}{Y_m \times P_{mi}} \quad \text{(Eqn. 4)}$$

Where P_{mi} and P_{ii} are the planting proportions of main and intercrop in the mixture, respectively.

If either A_{main} or $A_{intercrop}$ is equal to zero, it indicates that both species are equally competitive. A positive A_{main} value signifies that main crop is the dominant species, while a negative value suggests that the intercrop is more dominant than the main crop.

CR

CR was used to assess competition between different crops and it indicates the relative competitive ability of component crops (10). The CR was computed by following the formula:

$$\text{CR}_{main} = \frac{\text{LER}_{main}}{\text{LER}_{intercrop}} \times \frac{P_{ii}}{P_{mi}} \; ; \; \text{CR}_{intercrop} = \frac{\text{LER}_{intercrop}}{\text{LER}_{main}} \times \frac{P_{mi}}{P_{ii}}$$

(Eqn. 5)

Where P_{mi} and P_{ii} is the proportion of main and intercrop in the association respectively.

If the CR value of main crop exceeds 1, it is more competitive than intercrop. Conversely, a value less than 1 indicates that the intercrop is more competitive.

Assessment of soil available NPK

Post-harvest soil samples were collected randomly from each treatment plot; shade dried and ground using a wooden pestle, passed through a 2mm sieve and these samples used for chemical analysis. The available nitrogen was determined using alkaline $KMnO_4$ method, available phosphorous by Olsen's method and available potassium by neutral normal ammonium acetate method.

Statistical analysis

Data were recorded for analysing cropping system indices (cotton equivalent yield, land equivalent ratio, aggressivity and competition ratio) and soil characteristics (available nitrogen, phosphorous and potassium). The collected data were subjected to analysis of variance (ANOVA) appropriate to the standard procedure for split plot design. Treatment means were compared using the least significant difference at 5 % level of significance to determine the best treatment. Based on the statistical significance of the results, conclusions were made.

Results

Effect on cotton equivalent yield (CEY)

The different bio-intensive complementary cropping and nutrient management strategies had significantly influenced CEY (Fig. 1). Among the systems, maize + cowpea + sunnhemp cropping recorded higher CEY (2556 kg/ha), which was followed by cotton + onion + sunnhemp (2230 kg/ha). However, the lowest CEY was observed in sunflower + green gram + sunnhemp (1463 kg/ha). With respect to nutrient management, the application of 50 % NPK through inorganic + 50 % N through vermicompost + 5 % FFE spray recorded the highest CEY (2236 kg/ha). In contrast, the lowest CEY was observed with the application of 100 % recommended NPK through fertilizers alone, suggesting that integrated nutrient management approaches combining organic and inorganic sources are more efficient in enhancing productivity. The interaction between the main and sub-factor was found to be significant. The highest CEY was recorded by maize + cowpea + sunnhemp with 50 % NPK through inorganic + 50 % N through vermicompost + 5 % FFE spray (2850 kg/ha), which was followed by maize + cowpea + sunnhemp (2706 kg/ha) with 50 % NPK through inorganic + 50 % N through poultry manure + 5 % FFE spray (kg/ha). These significant interactions highlight the relevance of nutrient management strategies to specific system for optimizing productivity.

Effect on competitive indices

Various BICCS influenced competitive indices such as LER, RCC, A and CR (Table 1). In LER, maize + cowpea + sunnhemp achieved a LER of 1.13, indicating a 13 % yield advantage compared to sole

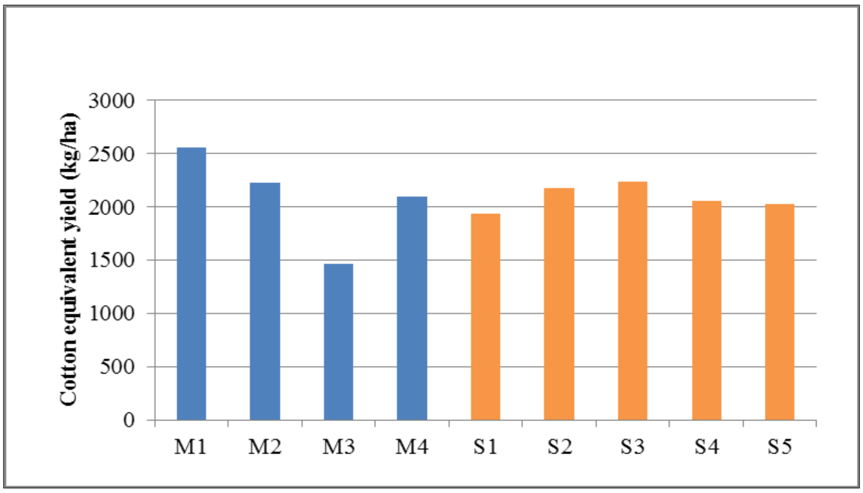

Fig. 1. Effect of BICCS and nutrient management on CEY.

Table 1. Effect of BICCS and nutrient management on competition indices

Treatment	LER	Aggressivity	Competition ratio
Bio-intensive complementary cropping system			
M_1	1.13	0.10	1.28
M_2	0.79	0.28	6.10
M_3	0.94	0.32	4.18
M_4	0.46	0.08	2.16
Nutrient management practices			
S_1	0.77	0.18	3.40
S_2	0.87	0.20	3.48
S_3	0.89	0.21	3.53
S_4	0.81	0.19	3.32
S_5	0.80	0.19	3.42

cropping and highlighting their superior efficiency in land use. Conversely, chillies + onion + sunnhemp registered the lowest LER of 0.46, indicating suboptimal land use efficiency compared to other BICCS. Regarding the nutrient management, highest LER of 1.25 was recorded by maize + cowpea + sunnhemp with the application of 50 % NPK through inorganic + 50 % N through vermicompost + 5 % FFE spray. However, chillies + onion + sunnhemp with 100 % NPK through fertilizers alone recorded the lowest LER of 0.44 due to lack of organic inputs and inefficient land use.

All the main crops registered a positive aggressivity value indicating their dominance over the intercrops. Among the treatments, sunflower + green gram + sunnhemp recorded the highest aggressivity value 0.32 indicating a strong competitive advantage over the green gram. In contrast, maize + cowpea + sunnhemp recorded a positive and balanced aggressivity value of 0.1, suggesting a more complementary interaction between the component crops. Under nutrient management, the aggressivity value remains higher (0.21) in sunflower + green gram + sunnhemp with the application of 50 % NPK through inorganic + 50 % N through vermicompost + 5 % FFE spray. However, maize + cowpea + sunnhemp with the application of 50 % NPK through inorganic + 50 % N through vermicompost recorded the lowest aggressivity value (0.18) reflecting a more balanced and complementary interaction.

The CR value was greater than one in all the systems, indicating the competitive dominance of main crops. The cotton + onion + sunnhemp exhibited a highest CR value of 6.10, implies the strong dominance and competitive potential of cotton under intercropped condition. In contrast, maize + cowpea + sunnhemp recorded the lowest CR value of 1.28 indicating a more equitable resource sharing and complementary interaction between the component crops. Regarding nutrient management, the higher CR value of 3.53 was observed in sunflower + green gram + sunnhemp with the application of 50 % NPK through inorganic + 50 % N through vermicompost + 5 % FFE spray.

Effect on soil nutrient status

The post-harvest soil analysis revealed that the available NPK levels were significantly influenced by BICCS and nutrient management practices (Table 2). The highest available N (209.3 kg/ha), P (14.9 kg/ha) and K (620.4 kg/ha) in the soil was recorded under maize + cowpea + sunnhemp. In contrast, the lowest N (168.5 kg/ha), P (12.2 kg/ha) and K (586.9 kg/ha) content was observed in cotton + onion + sunnhemp. With respect to nutrient management, highest N (209.5 kg/ha), P (14.7 kg/ha) and K (622.3 kg/ha) content was recorded with the application of 50 % RDF through inorganic + 50 % N through vermicompost + 5 % FFE sprays. Meanwhile, the lowest N (174.2 kg/ha), P (12.6 kg/ha) and K (575.3 kg/ha) was recorded with the application of 100 % RDF through chemical fertilizers alone. The interaction effect showed that maize + cowpea + sunnhemp with 50 % RDF through inorganic + 50 % N through vermicompost + 5 % FFE resulted in the highest soil available N (227.3 kg/ha), P (15.9 kg/ha) and K (646.2 kg/ha). However, the lowest available N (150.5 kg/ha), P (11.1 kg/ha) and K (560.3 kg/ha) was recorded in cotton + onion + sunnhemp (kg/ha) with the application of 100 % RDF through inorganic fertilizers alone.

Table 2. Effect of BICCS and nutrient management on soil available NPK

Treatment	N (kg/ha)	P (kg/ha)	K (kg/ha)
Bio-intensive complementary cropping system			
M_1	209.3 a	14.9 a	620.4 a
M_2	168.5 c	12.5 b	586.9 c
M_3	186.5 b	12.2 b	604.5 b
M_4	206.4 a	14.7 a	595.7 bc
SEd	**4.3**	**0.3**	**5.9**
CD (P=0.05)	**10.5**	**0.7**	**14.4**
Nutrient management practices			
S_1	174.2 d	12.6 c	575.3 d
S_2	197.5 b	13.8 b	610.8 b
S_3	209.5 a	14.7 a	622.3 a
S_4	197.9 b	13.9 b	607.8 b
S_5	184.2 c	13.1 c	593.1 c
SEd	**4.3**	**0.3**	**7.0**
CD (P=0.05)	**8.7**	**0.6**	**14.3**

Discussion

Cotton equivalent yield

The variation in CEY across the treatments can be attributed to the differences in nutrient requirements and nutrient utilization under varied conditions. The maize + cowpea + sunnhemp recorded the higher CEY (2000 kg/ha) highlighting the potential of intercropping in improving the productivity through efficient resource utilization. Cowpea being a short duration crop, contributed significant in reducing the competition and played a pivotal role in biological nitrogen fixation which enriched the soil to increase productivity (11). Furthermore, raised beds facilitate better root development and nutrient uptake where sunnhemp contributes organic matter and nutrient enrichment. Regarding the nutrient management, the application of 50 % NPK through inorganic + 50 % N through vermicompost + 5 % FFE spray resulted in the maximum CEY across all systems. Application of vermicompost, favours slow and continuous release of essential nutrients which improved the soil microbial activity. Moreover, the growth promoting activity of fish extract further augmented nutrient availability and uptake, contributing to improved crop performance (12).

The interaction effect showed that maize + cowpea + sunnhemp with 50 % NPK through inorganic + 50 % N through vermicompost + 5 % FFE spray recorded the highest CEY underscoring the synergistic potential of legume based intercropping and integrated nutrient management. In contrast, the lower CEY was observed in sunflower + green gram + sunnhemp due to the tall and broad-leaves of sunflower caused the shading effect which suppresses the growth and productivity of greengram. The reduction in photosynthetically active radiation reaching the green gram canopy would have adversely affected the biomass and yield contribution to the system. Additionally, sunflower develops a deep and extensive root system that competes strongly for water and nutrients across soil layers, further limiting the growth of associated crops. These morphological and physiological traits collectively explain the high aggressivity of sunflower based systems. Moreover, the absence of organic amendments in the treatment limited the nutrient availability and microbial activity in the soil, further constraining productivity (13).

Land equivalent ratio

Assessing the competitive indices is essential for identifying the most advantageous system in intercropping. The higher LER in maize + cowpea + sunnhemp is attributed to effective utilization of inter-row space and maximum light use efficiency by cowpea. Moreover, inclusion of cowpea, a legume, contributes significantly to nitrogen enrichment in the soil supporting the nutrient demand of maize and reduced the competition. These complementary natures of the component crops allowed for more efficient use of available resources resulted in high LER compared to other system (14). In contrast the lower LER in chillies + onion + sunnhemp is attributed to reduced yield of both chilli and onion.

Competition ratio

CR provides a more accurate measure of the competition abilities between the main and intercrop. The highest CR value is observed in sunflower + green gram + sunnhemp indicating the competitive and dominant resource utilization over green gram. Sunflower with their tall stature and broad leaves exhibits superior light capture giving a competitive advantage. Despite the atmospheric nitrogen fixation and the taproot of green gram that access moisture and nutrients, its shorter stature making it vulnerable to shading which limits the photosynthesis and productivity. As a result, the performance of green gram is highly suppressed when intercropping with sunflower (15). In contrast, maize + cowpea + sunnhemp exhibited a competition ratio value of 1.2 indicates a balanced level of dominance over cowpea. Maize with their upright canopy and rapid vertical growth effectively captures sunlight whereas cowpea occupies the lower canopy and effectively utilizes the diffused light. In addition to this, variation in crop duration and rooting pattern enables them to coexist without significant competition and promotes complementary resource utilization (16).

Aggressivity

Aggressivity is a key index to understand the competitive relationship between the component crops in the intercropping system. All the main crops showed a positive aggressivity value indicating their dominant performance under intercropped condition. The sunflower + green gram + sunnhemp recorded the highest aggressivity value, indicating the strong dominance and competitive pressure over the intercrop. The reduced access to light by their tall robust stature and maximum absorption of water and nutrients by their taproots causes dominance over green gram (17). On contrary, maize + cowpea + sunnhemp, maize recorded a positive and moderate aggressivity value, indicating the balanced dominance over cowpea. The moderate growth habit of maize and complementary effect of legume crop, cowpea and green manure, sunnhemp contributed to increased nutrient availability and reduced interspecific competition results in balanced dominance (18).

Soil nutrient status

The highest soil available NPK was recorded under maize + cowpea + sunnhemp (kg/ha) by the inclusion of legume, which adds organic matter upon decomposition and enriched the soil nutrient status resulted in enhanced soil fertility. Legumes like cowpea fix atmospheric nitrogen through symbiotic relationships with rhizobia, thereby enriching the soil available N (19). Moreover, legume based intercropping systems improve the soil available phosphorus and potassium, enhancing the overall soil fertility and crop productivity (20). Regarding nutrient management, higher levels of post-harvest soil available NPK (200 kg/ha) was observed with the application of 50 % NPK through chemical fertilizer + 50 % N through vermicompost + 5 % FFE. Addition of vermicompost stimulates microbial population which caused the slow and continuous breakdown of nitrogenous compounds, made a steady N supply throughout the crop period results in increased soil available N (21, 22). Higher soil available P might be due to reduced phosphate fixation through chelation of Ca^{2+} and Mg^{2+} and protective cover on sesquioxides when applied along with inorganic fertilizer (23). Additionally organic acids released during decomposition of organic manures enhance native phosphorous availability. Also the available K in soil increased due to the release of aliphatic and aromatic hydroxy acids, humates and lignins during decomposition, which helps in nutrient mineralization and release (24). Furthermore, organic sources promote the solubilisation of mineral bound K and native K thereby enhancing its availability in the soil (25).

Conclusion

This study highlights the potential impact of bio-intensive complementary cropping combined with integrated nutrient management on enhancing crop productivity and soil fertility. The results indicate that maize intercropped with cowpea and sunnhemp consistently outperformed others in terms of equivalent yield, land equivalent ratio, aggressivity and competition ratio, indicating their superior compatibility and efficient resource utilization. Inclusion of cowpea in the system contributed to biological nitrogen fixation and addition of organic matter by sunnhemp reduced the competition for nutrients which improved the overall productivity of the system. Supplying the essential nutrients through a combined application of chemical fertilizers along with organic inputs like vermicompost enhanced the nutrient release pattern, microbial activity and soil properties. Additionally, foliar application of fermented fish extract acted as a bio-stimulant improved the nutrient uptake and crop vigor. This synergy between fast releasing chemical nutrients and slow releasing organic amendments ensured a more sustainable nutrient supply throughout the growth period boosted the overall system productivity. From a practical perspective, maize intercropped with cowpea and sunnhemp with integrated nutrient management involving vermicompost and fermented fish extract can be recommended for farmers in garden land ecosystems to maximize yield and sustain soil health. At the policy level, support for bio-intensive cropping practices through incentives for organic amendments, training programs on on-farm input preparation and demonstration of integrated systems can accelerate their adoption. Moreover, future research should focus on long-term monitoring of soil biological properties, region-specific system adaptations and economic feasibility to build a stronger scientific and practical basis for scaling up bio-intensive complementary cropping systems.

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Authors' contributions

GS prepared the manuscript. SPM, SSP, SK, SA and SBK reviewed and suggested improvements in the manuscript and guided in writing the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Grammarly tool to improve language and readability, with caution. After using the tool, SPM, SSP and GS reviewed and edited the content as needed and take full responsibility for the content of the publication.

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