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REVIEW ARTICLE

Synergizing crops and conservation: A comprehensive review of bio-intensive complementary cropping system

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Abstract

Cropping system represents a holistic approach to farming that emphasizes synergy among plant species, soil organisms and ecological processes. Exploring novel farming techniques has become essential in light of the growing environmental concerns and the increasing demands for sustainable agriculture. Bio-intensive complementary cropping offers promising strategy for a more sustainable and resilient future by integrating conservation agriculture practices. This approach diverges from traditional cropping systems by prioritizing productivity, resource optimization through complementary cropping, strategic resource management and ecological resilience. Key conservation methods include suitable crop intensification for optimum space use, irrigation strategies for minimizing water wastage, weed management for encouraging smothering effect and nutrient management that enhance the soil fertility by prioritizing organic inputs and local resource. By reducing pesticide use, enhancing biodiversity and lowering greenhouse gas emissions through reduced dependence on fossil fuel intensive inputs, bio-intensive systems contribute significantly to environmental sustainability. This review critically analyses soil health, crop productivity, emission profiles and economic outcomes, providing insights that advance scientific understanding and offer practical solutions for farmers. Ultimately, it highlights the potential of bio-intensive cropping systems to synergize crop production with conservation, paving the way for more sustainable agricultural practices.

Keywords: climate resilience; crop diversification; economic viability; food security; sustainable agriculture

Introduction

The world's population is facing a serious threat from climate change, which affects a wide range of natural systems including freshwater habitats, agriculture, coastal areas, vegetation, forests and snow cover. It also influences geological processes such as floods, desertification and landslides leading to long-term consequences for both human health and food security (1). Since agriculture, forestry and fisheries depend heavily on these natural resources, climate change is expected to have a significant negative impact on these sectors. According to FAO, this could lead to reduced production of fish, livestock, poultry, industrial crops, food, feed, fibre and energy, ultimately exacerbating food insecurity and malnutrition (2, 3). As global food demand increases, there is a growing need for innovative and sustainable agricultural practices. One such technique that is gaining popularity is the bio-intensive complementary cropping system, this combines components of biodiversity, effective resource utilization and ecological balance.

A bio-intensive farming system is a biologically intensive mixed farming system that depends on farmers active participation, crop rotations to optimize organic recycling, integrated plant nutrient management and integrated organic pest management using bio-pesticides and botanical pesticides, among other methods all aimed at maximizing food production while reducing environmental impact (4). Sustainable intensification through techniques like bio-intensive complementary cropping system (BICCS), allows farmers to produce more food than traditional systems, while also promoting soil health and minimizing environmental damage (5).

Integrating legumes, oilseeds, millets and vegetables into the cropping system is a prevalent approach nowadays to ensure food security and promote ecological sustainability (6). In the past, rural residents have typically consumed large amounts of rice and supplemented it with vegetables or pulses. In fact, pulses are a rich source of vegetable protein and green vegetables are a major source of vitamins and minerals (4). It was discovered that growers using bio-intensive farming systems consumed more seasonal vegetables on a daily basis than growers using conventional farming systems (7). Only 9 % of households consumed 210 g of vegetables/person/day in 2006; this number rose to 18 % in 2007 and then to 56 % in 2008 (8). By adopting bio-intensive systems, farmers can optimize limited resources, improving both food security and ecological sustainability (9).

Additionally, small and marginal farmers can use scarce land and water resources more sustainably with the help of BICCS (10). The use of BICCS, which involves crop intensification, diversification and land configurations to support two or more crops of synergistic nature simultaneously on the same piece of land, can help small holders enhance income generation. This kind of system not only provides natural control over weeds, pests and diseases but also presents opportunities to enhance the efficiency of water and nutrient use efficiency (11). With the application of bio-intensive agriculture techniques, it is feasible to produce a nutritionally complete vegetarian diet comprising cereals, pulses, oilseeds and vegetables for one person within a 4000 sq. ft. area while ensuring a modest income. Additionally, these practices generate sufficient biomass for composting, which helps to maintain fertile soil (6). The fundamental principles guiding the bio-intensive farming (BIF) system are illustrated in Fig. 1.

Effect of intercrop under BICCS

The concepts of crop intensification and diversity can aid in resource conservation and maintain current levels of yield (12). In both conventional and organic agriculture, intercropping greatly increases the crop resilience to stress and improves the grain quality. It also contributes to effective control of pests, diseases and weeds while increasing yield per unit area compared to sole cropping (4, 13). It is crucial to identify viable and ecologically sustainable BICCS by integrating cereals, vegetables, oilseeds and pulses. Incorporating more resilient cereals and pulse crops into the system to create bio-intensive complementary cropping systems that are more viable and environmentally sustainable is essential (14).

Cereal-legume intercropping systems were superior to mono cropping and moreover intercropping of millets with pulses, such as finger millet with pigeon pea produced more yield compared to sole cropping (15, 16). The components of the intercrops use water and nutrients in complementary ways so that intercropping finger millet with pulses decreased the need for external inputs which resulted in high yield. Therefore the system not only helps to address the production issue, but it also helps farmers to generate more income while incurring less expenses for cultivation. Moreover it facilitates the efficient use of time for agricultural activities such as field preparation, sowing and harvesting as well as efficient use of resources for growth, allowing for a numerical increase in the amount of land used for cultivation (17). Contrastingly a low yield of pigeon pea was reported when intercropped with cowpea, green gram and soybean but the pigeon pea equivalent yield (PEY) was higher under pigeon pea + green gram (18). Similarly, castor yield was reduced under 1:3 ratio system while, castor + foxtail millet and castor + proso millet in 2:4 ratio recorded the maximum castor equivalent yield (19). In light of this, monoculture is advantageous in systems that prioritize mechanization and uniformity, while intercropping is better suited for diverse, resource-conserving systems that require resilience and productivity (10).

Sole pigeon pea recorded higher yield but it was on par with pigeon pea + green gram (2:1) intercropping (18). While comparing the performance of different intercrops in terms of maize equivalent yield (MEY) *Bt* cotton + soybean (1:3) recorded higher MEY which was *on par* with *Bt* cotton +

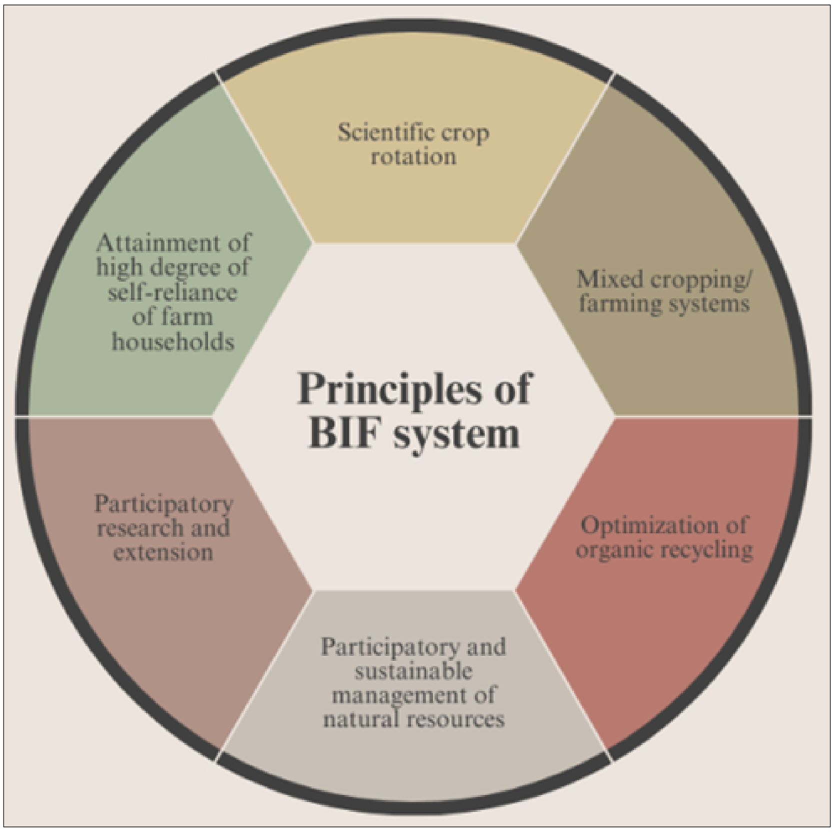

Fig. 1. Principles of bio-intensive farming (BIF) system.

green gram (1:2 and 1:3) (20). Growing of maize with soybean (1:1, 1:2 and 2:2) is a suitable option to increase the productivity of the system (21). However, maize + soybean (1:2) and maize + groundnut (2:4) recorded equivalent grain yield while compared to sole maize (22).

Effect of sequential cropping system under BICCS

The increasing demand for food grain production is driving the need for crop intensification and diversification, which are crucial for enhancing productivity, profitability and sustainability in the long run (14, 23). The development of integration of resource use efficiency fosters maximum input usage efficiency, which can be achieved by identifying the suitable crops for the system (24). Factors such as yield potential, previous crop type and residual effects of fertilizers must be considered for sustained cropping (25). For instance, in the irrigated ecosystem of Uttar Pradesh, diverse system demonstrated increased profitability and production (26). One significant advantage of including leguminous crops in cropping system is their ability to improve soil fertility by fixing nitrogen through symbiotic relationship with rhizobium in the soil (16). As a result, cropping systems that incorporate legumes or fodder legumes as intercrops or preceding crops not only improve soil health but also contributes to long-term sustainability and productivity (10).

Leguminous crops in an intensive cropping system increase productivity and land use efficiency (27). Pulse-based cropping systems are among the most ecologically sound cropping systems since they need less irrigation, fertilizer and pesticides because of their mutualistic relationship, which improves the yield of succeeding crops and increases total productivity (28). Small farmers in the semi-arid tropics found annual grain and legume based cropping systems useful since they were 32 - 49 % more profitable than continuous sole maize cropping (29). Furthermore, compared to monocropping of cotton (14.12 q/ha), a yield gain of 11 % was observed in the cotton - legume - maize rotation (30).

Vegetable crops are also a good option for small-scale farming because of their high vitamins and minerals; their incorporation into conventional cropping systems may enhance the system's nutritional value (31). Higher yield was observed with rice based crop sequences that comprises vegetable crops (32). In the rice - wheat system, productivity was enhanced by substituting vegetable crops like potatoes and radish for wheat (33). The higher cotton equivalent yield (CEY) in the onion - cotton - maize system was driven by the high yield and higher market price of onion, maize and cotton (34). Potatoes, in particular, present farmers with a significant potential to increase their income, as they can yield five to ten times more than cereals, pulses or oilseeds. In comparison to rice - wheat system, maize based systems in the Trans-gangetic plains, such as maize - wheat - green gram, maize - potato - green gram and maize - potato - onion have substantially higher system productivity (35). Moreover, as a profitable cash crop, potatoes boosted the income of small and marginal farmers, thereby improving farmer equity. Additionally pigeon pea + baby corn - finger millet resulted in a PEY increase of 123 % while the pigeon pea + baby corn - vegetable field bean showed a PEY increase of 135 % (36).

Effect of land configuration under BICCS

Using several land configurations and seeding techniques, a two-year study was conducted to increase yield and establish a viable bio-intensive complementary cropping system based on chickpea. Among these, in both years of the chickpea treatments, one row planted on ridges produced a noticeably higher no. of pods/ plant, pod weight/plant, seed weight/ plant and 1000 seed weight (37). Moreover the cultivation of maize + vegetable cowpea in 1:1 ratio on broad beds (BB), along with sesbania in furrows during kharif, three rows of lentil on broad beds and mustard in furrows during rabi and three rows of green gram on beds during summer recorded the maximum yield (38). A benefit of the broad bed and furrow (BBF) system was that it allowed for *insitu* green manuring, with 35 t/ha of green foliage added after 35 days of sowing. Timely sowing of mustard in these furrows allowed for the harvest of an additional yield of lentil intercropped with mustard (39).

Effect of irrigation under BICCS

Since over exploitation has lowered the groundwater table below the threshold level of 10 m, water is the most important input and many places need to adopt water-saving crops (40). Better use of all resources, including nutrients, light and moisture, is ascribed to higher yield in terms of total biomass and grain production per unit area in a given season with minimum inputs under intensive system (41). Sustainability and conservation play a major role in irrigation design in bio-intensive farming. By directing irrigation water through furrows, the BBF system reduces the surface run-off and enhances water infiltration near the root zone, resulting in 40 % savings in irrigation water (39).

A condition of poor WUE occurs when there is high water demand and low productivity (34). Apparent causes of low water use efficiency include overuse of water and improper implementation of agricultural system (12). Adopting a suitable cropping strategy and using water efficiently are key to attaining high water usage efficiency. The water productivity of the maize - sunflower system was 21.46 kg/ha/mm, while the cotton + green gram (1:2) - maize system utilized the same amount of water (14).

However, investigations on net water savings, maize - potato - onion system and the maize (furrow) + turmeric (bed) - wheat (bed) + linseed (furrow) cropping system required 82 cm (32.09 %) and 165 cm (64.7 %) less irrigation water respectively, compared to the conventional rice-wheat system (12). Also, summer groundnut - potato - bajra (fodder) system resulted in a net savings of 109 cm (42.6 %) irrigation water. Additionally, maize - potato - spring maize and maize-potato-summer green gram system conserved 116 cm (45.54 %) and 120 cm (46.9 %) respectively. Another efficient system, maize (furrow) + radish (bed) - wheat (bed) + linseed (furrow) - summer green gram led to water savings of 139 cm (54.4 %). The maize (furrow) + turmeric (bed) - barley (bed) + linseed (furrow) system emerged as the best option, saving 172 cm (67.3 %) of irrigation water while maintaining high performance (Fig. 2).

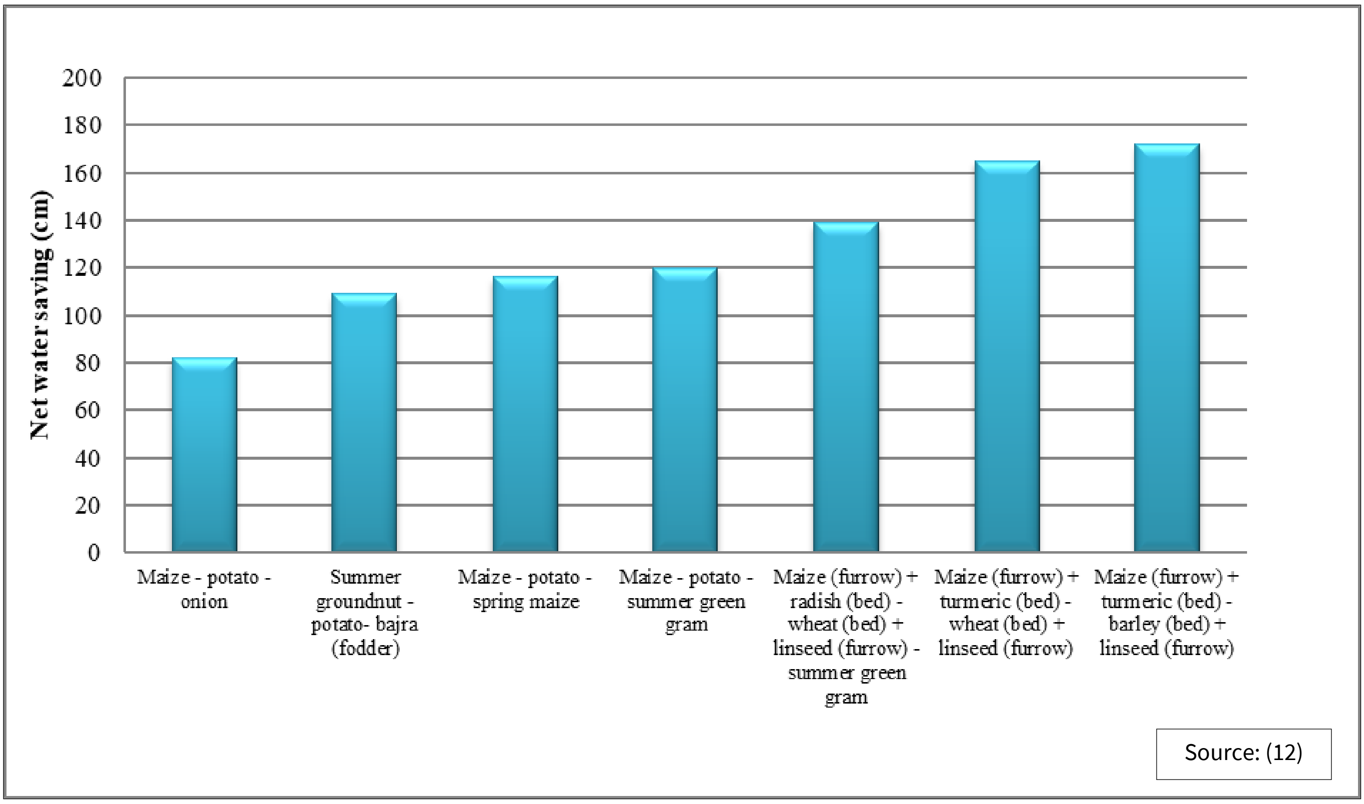

Fig. 2. Net water saving (cm) of different BICCS compared to rice - wheat system.

Effect of nutrient management under BICCS

In most conditions, grain yield was increased when adequate nutrition was provided to the crop through both organic and inorganic sources (42). Integrating inorganic and organic nutrient management strategies crop production can be sustained by improving the availability of major and minor nutrients in the soil that would enhance the efficiency of chemical fertilizers (43). The quality of the substrate such as crop residues, cattle dung and urine, as well as the methods used for collection and handling, affect the chemical and nutritional makeup of manures (10). A substantially higher yield of chillies was obtained through 100 % N as Enriched FYM + bio-compost + neem cake + intercrop (onion) (44).

Green manure is essential for increasing soil fertility because it enhances the physical, chemical and biological characteristics of the soil. It also provides nutrients to succeeding crops (45). Higher net production values were observed in all rice based cropping systems when 25 % of the recommended N dose of N was applied, either through FYM or by *in-situ* green manuring in rice (46). The residual effect of organic manures applied to the previous rice crop improved black gram yield compared to recommended NPK and untreated controls (47). Also the application of 75 % required NPK through fertilizers and 25 % N through poultry manure improved the growth characteristics, which enhanced the yield components resulted in a higher maize equivalent yield, however 100 % RDF with inorganic fertilizers produced the lowest yield (5). Higher concentration of micro and macro nutrients as well as its constant nutrient release from different sources could contribute to its good performance (48). Therefore, increasing the production and profitability is a major benefit of this approach, especially for small and marginal farmers (39).

Effect of nutrient uptake under BICCS

Nitrogen uptake was often higher in systems based on cotton, but systems based on maize exhibited much higher phosphorus and potassium uptake. Organic carbon increased by 16 % with FYM application in maize, while applying 100:50:50 NPK increased it by 21 %. The same treatments also significantly enhanced NPK uptake (49). In a long term experiment with maize - wheat system, combined application of 100 % NPK and FYM resulted in higher available N and P, while higher available K was observed with 100 % NPK alone compared to the control (50). Also the application of 100 % N resulted in a decline in available N, P and K from the initial values as compared to balanced application of 100 % NPK (51). The maize - potato - spring maize system closely followed the maize (cobs) + vegetable cowpea + sesbania - gram + gobhi sarson cropping system, which removed higher levels of NPK (9).

Effect of soil nutrient status under BICCS

Soil fertility and health are important for sustainable, higher and stable crop production. Beneficial microbes, groundwater and soil health all declined during the course of a multi-year wheat monoculture (52). For example, introducing nutrient demanding crops can reduce soil fertility, but applying organic amendments in that condition helps restore nutrient levels more effectively than relying solely on inorganic sources (5). Under these conditions inclusion of legumes in this system will enhance soil health by fixing atmospheric N in fields with low fertility (53). Supplying the 50 % recommended NPK through inorganic fertilizers + 50 % N through poultry manure for maize + cowpea + daincha system recorded the highest post-harvest available N. Additionally, the same system with 75 % of recommended NPK through fertilizers and 25 % of N through poultry manure produced the maximum K uptake (5). Meeting the crop's nutrient requirements, either entirely or partially through organic sources, boosts the microbial activity and causes the release of both native and inaccessible forms of nutrients which impacted the soil health (54).

Since maize is a heavy feeder crop, the residual effect of organic manures significantly increased grain production compared to treatments without manure. Among the organic sources, poultry manure outperformed FYM and urban garbage compost in improving grain, stover and protein yield of maize (28). Enhancing the cropping system with green manure crops or manures will improve soil nutrient availability. Also compared to fruit, cereal crop and agroforestry systems, the available NPK was greater under vegetable-based cropping systems (55). For fodder sorghum - cotton + onion + sunnhemp - lablab cropping sequence, the highest available nitrogen was observed, while the lowest was found in the sunflower - red gram - snake gourds cropping sequence (34). Compared to the rice - wheat cropping system, alternative systems such as groundnut + red gram (5:1) - wheat + sarson (9:1), maize + mash -peas (bed) + celery (furrows) and maize (for cobs) + vegetable cowpea + sesbania - chickpea + gobhi sarson showed higher availability of N and P. These findings conclude that alternative systems produced better outcomes in terms of accessible NPK by enhancing the microbiological status of the soil and hence improve soil health (9).

Effect of weed management under BICCS

Intercropping has the ability to suppress weeds because of its rapid ground cover; it not only suppressed weeds but also reduced weeding cost and gave additional yield (56). They suppress weeds better than sole cropping and thus provides an opportunity to utilize crops themselves as tools of biological weed management (57). Growing of green manure crops along with rice as intercrop suppresses weeds due to faster canopy cover. It has been reported that cowpea intercropping suppressed the weed infestation, weed population and weed density as compared with unweeded control (58).

Moreover intercrops produced the lowest density of grasses, sedges and broad leaved weeds in the cotton + black gram system which impacted their smothering efficiency. Their in-situ incorporation can add 40-50 kg/ha of nitrogen to the soil, while also enhancing weed suppression (59). Reduced weed growth in intercropping systems was due to early and rapid canopy formation, which minimized total weed biomass (60).

Effect of BICCS on energy use

Bio-intensive cropping not only increases the productivity and profitability but also saves the resources up to 50 % especially under small and marginal farming situation (39). The total energy requirement by rice - wheat cropping system was 28.66×10^3 mj/ha. The maize (furrow) + turmeric (bed) - wheat (bed) + linseed (furrow) system showed the highest energy input (50.30×10^3 mj/ha) and the higher energy inputs required for maize-based cropping systems might be due to the use of energy-richer inputs like seed and fertilizer respectively, in higher quantity. Similarly, the total energy output as computed from main product and by-product of different cropping systems varied from 360.24×10^3 to 1283.37×10^3 mj/ha. With a lower energy input (26.58×10^3 mj/ha), the fodder based cropping system, *viz.*, sorghum + cowpea (fodder) - wheat + mustard showed the highest total energy output (1283.37×10^3 mj/ha), energy-use efficiency (48.28) and energy output efficiency (6.35×10^3 mj/ha/day) over the prevailing rice - wheat cropping system due to its higher REY (9).

Effect of BICCS on greenhouse gas (GHG) emission

Depending on various management techniques, such as the application of chemical fertilizers or manures, agricultural soils may turn into a net source or sink of greenhouse gases (61). Furthermore, the quantity and chemical composition of manures added to soil can be adjusted to modify greenhouse gas emissions. Cumulative CO_2 emission was generally strongly correlated with soil organic carbon (SOC) content because SOC and soil microbial activity can significantly increase the number of substrates for soil microbes (62). Utilizing animal manure or practicing organic farming can increase soil carbon sequestration, turning the soils into net CO_2 sinks (63). This prevents CO_2 from escaping into atmosphere while simultaneously enhancing soil fertility and structure. The SOC gains were higher (40 %) when manure application was coupled with inorganic fertilizer than when manure application was done alone. The largest SOC rise was observed with the application of FYM, cattle and pig manure (64).

When chemical N fertilizer was applied, soil N_2O emissions were almost two times higher than the organic manure (65). Conversely, the gradual release of nitrogen from organic manures increases plant availability while lowering the possibility of excessive nitrogen runoff and subsequent N_2O emission. In pulse-based systems, additional organic matter from leaf fall and root biomass might accumulate to form humus, which would then improve soil porosity and aeration in compacted soil (66). The amount of water-filled pore space was decreased, since it stabilizes microbial carbon and reduces CO_2 emissions.

While pigeon pea based cropping sequence was more efficient at increasing available NPK, rice based cropping sequence with RDF + FYM was more successful in improving soil carbon density and stock as well as sequestering CO_2 (67). Additionally, cropping systems based on agroforestry have a greater capacity to sequester carbon from the soil. Thus, agroforestry based cropping systems need to be promoted in order to adapt to the changing climate and lessen its effects (55).

Effect of BICCS on economics

By implementing a cropping strategy that is profitable and economically feasible, farmers can overcome their concerns about increased per hectare productivity and income per unit area within a certain time frame. Resource use efficiency is a crucial factor to take into account when evaluating the sustainability of a cropping system in the current period of diminishing land, water and energy resources (68). Due to the higher market price for pulses, it was found that the intercropping system produced an equivalently greater seed cotton yield compared to sole crop (69).

The integration of vegetable crops with field crops yields higher returns when compared to different cropping systems. Onion - cotton - maize cropping system showed higher economic efficiencies, with net returns of Rs.561/ha/day and production efficiency was also higher with these systems since they feature cash ensuring crops that yield higher returns (34). A system will produce better net returns and B: C if its productivity is higher and its cultivation costs are lower. The intercropping system of maize + cowpea + daincha, applied with 75 % recommended NPK through fertilizers + 25 % N through poultry manure achieved higher gross return, net return and B:C ratio. A comparable performance was observed with 50 % recommended NPK through fertilizers + 50 % N through poultry manure in the same system (70).

When compared to the current rice - wheat cropping system, the net returns from basmati rice and maize farming systems were found to be higher (12). Furthermore, when millets were intercropped with pulses like sorghum + cowpea (2:2), the net return and B:C ratio (2.77) were noticeably higher than the sole crop (71). Also, castor + foxtail millet (2:4) and castor + proso millet (2:4) recorded the highest net return and B: C ratio when compared to sole castor crop (72). Due to increased planting diversity and intensity to address the rising food insecurity scenario, or to make greater investments to support farming enterprises, farmers involved in bio-intensive system have been able to produce additional revenue from their farms which is a promising sign for sustainable means of subsistence (4) (Table 1).

Conclusion

The exploration of bio-intensive complementary cropping systems presents a promising avenue for synergizing agricultural production with conservation efforts. This comprehensive review reveals that integrating diverse crops in complementary arrangements not only enhances soil fertility and pest management but also fosters biodiversity conservation and resilience against environmental stresses. The benefits of bio-intensive complementary cropping systems extend beyond yield enhancement; they encompass ecological sustainability and economic viability within agricultural landscapes. By capitalizing on natural ecological processes and the synergies between plant species, farmers can mitigate the negative impacts of monoculture farming while promoting long-term soil health and biodiversity conservation. However, realizing the full potential of bio-intensive complementary cropping systems requires concerted efforts across various cropping systems, nutrient management, energy use, water management, land configuration, weed management and greenhouse gas emissions. An efficient water management practice improves the water use efficiency while lowering total water use and lessening the effects of water scarcity. Inclusion of leguminous crops and organic amendments improves the nutrient cycling which contributes to better soil health and reducing resilience on synthetic fertilizers. Building robust agro-ecosystems, diverse cropping patterns lower the risk of yield loss, enhance biodiversity and stabilize yields. Moreover, reduced overall energy consumption leads to more sustainable and energy-efficient farming operations, contributing to lower greenhouse gas emissions and mitigating effects of climate change. By embracing this holistic approach, we can cultivate a more sustainable and equitable system that nourishes both people and the planet for generations to come.

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Authors' contributions

GS prepared the manuscript. SPM, SSP and other authors reviewed and suggested improvements in the manuscript and guided in writing the manuscript.

Compliance with ethical standards

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

Ethical issues: None

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

During the preparation of this work, the authors used Paraphrasing AI and 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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Table 1. Economic performance of various cropping systems

Cropping systems	B:C	Economic performance	Reference
Bt cotton + green gram (1:3) - Pearl millet	1.91	Higher net returns than other ratios	(14)
Sole Maize	2.66	Highest net return and B:C than mono cropping	(73)
Maize + soybean (2:6)	3.57		
Sole sorghum	2.98	Inclusion of fodder to meet the fodder needs with higher net return	(74)
Sorghum + guinea grass	7.03		
Maize + Indian mustard	1.00	More advantageous than mono cropping and other intercropping system	(75)
Double cropping maize and lentil	1.91		

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