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Dual cropping in rice: Integrating *Azolla*, dhaincha and legumes for sustainable rice production

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Abstract

Rice production systems are under increasing pressure to enhance productivity while conserving natural resources and maintaining long-term soil fertility. Dual cropping has emerged as a promising strategy for improving the sustainability of rice production through the integration of compatible companion crops. Common companion crops include *Azolla*, dhaincha (*Sesbania* spp.) and grain legumes. These systems improve the use efficiency of land, water and nutrients while reducing dependence on synthetic fertilisers. This review synthesises current knowledge on rice-based dual cropping systems, focusing on their ecological basis, agronomic performance and environmental benefits. The review analyses the impact of weather conditions, soil fertility, water use and cropping calendar on the efficient introduction of dual cropping systems. The advantages of such systems in enhancing nutrient recycling, soil health, soil microbial activity, weed and pest control and resource use efficiency are also discussed. Furthermore, the economic benefits, advancements in technology, existing limitations and potential research areas in rice + *Azolla*, rice + dhaincha and rice + legume systems are discussed. Evidence from recent studies shows that well-managed dual cropping systems improve crop productivity, enhance soil quality, reduce production costs and strengthen the sustainability of rice cultivation. Future research should focus on optimising crop combinations and planting schedules, precision nutrient and water management, long-term soil-health assessment and integration of remote sensing, internet of things (IoT), artificial intelligence (AI) and decision-support systems. Supportive policies, farmer training and improved access to quality planting material are also recommended to promote wider adoption.

Keywords: *Azolla*; dhaincha; dual cropping; legume-based cropping systems; *Oryza sativa*; resource-use efficiency; rice; *Sesbania* spp.; soil health; sustainable agriculture

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Introduction

Rice (*Oryza sativa* L.) is one of the world's most important staple food crops, providing more than half of the daily caloric intake for the global population, particularly in Asia. Rice is essential to ensure food security, especially in Asia where the cultivation of rice is intricately associated with the livelihood of millions of smallholder farmers. Some of the issues which have created challenges for sustainable rice productivity are population growth, reduced land availability for agriculture, climate change and resource conservation (1, 2).

Traditional rice cultivation often relies on monocropping, intensive irrigation and high inputs of fertilisers and pesticides. Although these practices have significantly increased crop yields, it has resulted in soil degradation, nutrient imbalance, loss of biodiversity and reduced adaptability to climatic changes. Crop diversification has therefore emerged as an important strategy for improving productivity and sustainability (3, 4).

Dual cropping is a diversification strategy in which rice is cultivated together with compatible crops or biological components to improve resource-use efficiency and overall system productivity. Diverse agricultural

cropping systems involve more ecological interactions among crops which result in efficient utilisation of light, water, nutrients and space. Diversified cropping practices in rice production are done using rice and other compatible crops or components such as *Azolla*, dhaincha (*Sesbania* spp.) and grain legumes such as green gram (*Vigna radiata* (L.) R.Wilczek) and black gram (*Vigna mungo* (L.) Hepper). These practices help in biological nitrogen fixation (BNF), soil organic matter management, microbial activities, weed control and reduced chemical fertiliser use (5).

The integration of *Azolla*, dhaincha and legumes into rice production has gained increasing attention because of its potential to improve soil fertility, nutrient cycling and crop productivity. Moreover, diversification of rice farming enhances the efficiency of water usage and helps adapt to climate change, as well as generates income for farmers (6). Dual cropping has emerged as a promising strategy for improving the productivity and sustainability of agricultural systems by enhancing land-use efficiency, resource utilisation and overall system resilience. Although numerous studies have independently evaluated rice-*Azolla*, rice-dhaincha and rice-legume systems, an integrated synthesis comparing their ecological functions, agronomic performance, environmental benefits and economic implications remains lacking. Accordingly, this review critically synthesises current evidence on rice-based dual cropping systems involving *Azolla*, dhaincha and legumes, with emphasis on their ecological mechanisms, agronomic performance, resource-use efficiency, environmental sustainability, economic viability and future research priorities.

Dual cropping in rice

Rice + *Azolla* system

Azolla utilisation is a low-cost solution with significant long-term environmental conservation and high potential for supplying fixed nitrogen (N) and other nutrients, including potassium (K^+), sulphur (S), magnesium (Mg^{2+}) and phosphorus (P). Adopting and using *Azolla* correctly will improve N use efficiency, minimising N-loss and reducing reliance on synthetic N fertilisers. Additionally, due to its high growth rate, *Azolla* enhances soil organic carbon organic carbon, raising microbial biomass and enhancing nutrient cycling (7). Application of *Azolla* as basal inoculation, dual inoculation, or their combination improved rice performance, with combined basal and dual inoculation providing the greatest nitrogen contribution (8). By increasing nitrogen use efficiency and reducing nutrient losses, dual cropping with *Azolla* can boost grain yield by up to 30 % (9).

Dual cropping with *Azolla* has been demonstrated to promote CH_4 oxidation and lower CH_4 emissions by up to 40 % in flooded rice habitats when compared to urea-based fertilisation (10). In a constantly flooded rice field planted with rice, the sole application of *Azolla filiculoides* as green manure and its subsequent growth as a cover successfully boosted rice grain production to levels comparable to those for recommended inorganic N application. Integrated application of *Azolla* with supplemental inorganic nitrogen during the establishment year ensures adequate nutrient availability throughout crop development (11).

Azolla is a rapidly growing aquatic fern that contributes to climate-resilient and sustainable agriculture. The *Azolla* plant helps enhance soil fertility and reduces the dependency on artificial fertilisers through atmospheric nitrogen fixation via a symbiotic relationship with *Anabaena azollae* (12). *Azolla* can partially substitute chemical fertilisers while maintaining comparable rice yields under appropriate management practices. For instance, crop yields equal to those of 100 % N application using 60 kg of urea per hectare have been realised through the use of 60 kg of *Azolla* N and 30 kg of urea N (13). Overall, available evidence demonstrates that rice + *Azolla* systems improve nitrogen-use efficiency, soil fertility, microbial activity, weed suppression and greenhouse gas mitigation while maintaining or increasing grain yield. Their effectiveness, however, depends on environmental conditions, *Azolla* biomass production, P availability and appropriate field management.

Rice + dhaincha system

Green manuring with *Sesbania aculeata* Pers. replaced 25 % of the N fertiliser requirement, improved post-harvest soil quality and increased economic returns, residue production and biological yield compared with sole chemical fertilisation (14). Green manure and rice straw (GMS) co-incorporated with 40 % N reduction successfully increases soil fertility, sustains rice yield and improves nutrient use efficiency, confirming its promise as a sustainable substitute for traditional methods (15). Growing dhaincha alongside rice and then incorporating it reduced the amount of N fertiliser needed for the current crop by 25 % without compromising production (16). Yield, nitrogen use efficiency (NUE) and nitrous oxide (N_2O) emissions are enhanced by replacing part of the chemical N fertiliser with green manure. Partial substitution of chemical N fertiliser with green manure increased grain yield and NUE while reducing N_2O emissions (17).

The cultivation of *Sesbania* resulted in increased cadmium (Cd) retention in rice roots, decreased rhizosphere pH, increased activity of rice roots and increased formation of iron plaque. The reduced accumulation of Cd in rice grains was due to aggressive competition for soil Cd by *Sesbania* roots and shade effect by *Sesbania* leaves (18). Treatment consisting of *Sesbania* + 50 % N was more efficient compared to sole green manures, which implies that while decomposition of green manure has not reached its maximum yet, there is some fertiliser supplementation that provides easy availability of nitrogen at the beginning of crop growth period. High productivity and efficiency observed in combined treatment can be mainly attributed to this synchronisation (19). The incorporation of green manure in situ improved soil fertility, increased grain yield and increased the concentration of 2-acetyl-1-pyrroline (2-AP) in the grain of the aromatic rice that was subsequently

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grown. The use of leguminous green manure *in situ* decreased soil bulk density and increased total organic carbon content and N availability. Consequently, the application of leguminous green manure increased N uptake by plants and partial factor productivity of N fertiliser (PFPN) (20). Furthermore, rice + dhaincha systems consistently reduce N fertiliser requirements by 25–50 %, improve soil fertility and NUE, enhance grain yield and mitigate greenhouse gas emissions. Their performance depends on biomass production, decomposition rate, incorporation timing and synchronisation of N release with crop demand.

Rice + legume system

Short-duration food legumes such as mung bean (*V. radiata*), black gram (*V. mungo*), cowpea (*Vigna unguiculata* (L.) Walp.), pea (*Pisum sativum* L.), chickpea (*Cicer arietinum* L.), grass pea (*Lathyrus sativus* L.) and lentil (*Lens culinaris* Medik.) are well suited for intensifying rice-fallow systems because of their short growth cycle and low external input requirements. They offer a valuable opportunity to utilise residual soil moisture in rice fallow (21). Furthermore, they are most suited for rice fallows due to their unique characteristics, which include BNF, deep root morphology, the ability to create surface spread in standing rice fields and to restore soil fertility (22). Soil carbon (C) and N dynamics are sustained by rotating legumes with cereal crops and incorporating their crop residue into the soil. Integration of legumes and green manures into nutrient-intensive rice-based systems improves soil structure, increases grain yield and profitability, enhances N availability and reduces fertiliser requirements for subsequent crops (2).

When compared to the rice-wheat control, legume-based rotations specifically, rice-faba bean and rice-hairy vetch significantly increased rice growth and yield. The yield was enhanced by rotating rice with faba beans and rice with hairy vetch. With increases in spring crop biomass, these rotations also showed improved biomass production efficiency. Improvements in soil nutrients were noted, especially in electrical conductivity, potassium (K) and available N (12). Under conservation tillage, adding short-duration legumes like lentils and peas in the winter and green gram, black gram, or French beans in the summer can increase cropping intensity to 300 %, improve soil health and system productivity and income. The addition of legumes to rice-based systems significantly improved the soil's organic carbon, available N and microbial characteristics (23). Involving legumes in agricultural production systems through increased efficiency of non-leguminous crops, reduction in weeds, fixation of atmospheric N, C storage in soil, climate adaptation and biodiversity conservation ensures food and livelihood security and also reduces the adverse effects on the environment (24). Nutrient relationships are often enhanced through the practice of intercropping of cereals and legumes by improving their nitrogen levels and overall nutrition. Legumes improve nitrogen availability through BNF, complementary root interactions, rhizosphere processes and mycorrhizal associations, benefiting neighbouring cereal crops (25). Collectively, these studies demonstrate that legumes contribute not only to BNF but also to improved soil quality, diversified production systems, enhanced resource-use efficiency and greater resilience of rice-based farming systems. Their multifunctional role makes them an integral component of sustainable agricultural intensification. A comparative overview of the major characteristics, benefits and limitations of rice + *Azolla*, rice + dhaincha and rice + legume systems is presented in Table 1 (26–32). The overall conceptual framework illustrating the interactions among rice, companion crops, resource-use processes and sustainability outcomes is presented in Fig. 1.

Table 1. Comparative performance of rice-based dual cropping systems involving *Azolla*, dhaincha and legumes

Parameter	Rice + *Azolla*	Rice + dhaincha (*Sesbania* spp.)	Rice + legumes (green gram/black gram)
Nitrogen contribution	Biological N fixation through the *Azolla*–*Anabaena* association; can provide an appreciable supplementary N source and improve N-use efficiency. Contribution varies with biomass production and incorporation.	Strong N contribution through biological N fixation. *S. rostrata* has been reported to fix ≥ 267 kg N ha^{-1} under favorable conditions, with part transferred to rice and part retained in soil.	Legumes fix atmospheric N through *Rhizobium* symbiosis. N contribution is generally moderate and depends on legume biomass, nodulation and duration of association.
Yield improvement	Generally increases or maintains rice yield when used with appropriate fertiliser N. Recent co-cultivation studies reported 6.2–8.3 % higher rice yield.	Can substantially increase rice yield when used as green manure. *S. rostrata* incorporation increased rice grain yield compared with the unfertilised control in field experiments.	Improves overall system productivity through complementary resource use and provides an additional legume harvest. Rice-green gram systems can achieve high rice-equivalent yield and nutrient-use efficiency.
Soil organic carbon	Adds readily decomposable organic biomass and can increase soil organic C; *Azolla* compost has also shown enhanced soil C sequestration.	Adds a large quantity of green biomass and enhances soil organic matter and nutrient availability after incorporation.	Legume residues contribute organic C and stimulate soil microbial activity; integrated rice-green gram management has been reported to increase soil organic carbon.
Weed suppression	High. Floating *Azolla* forms a surface mat that reduces light penetration and	Moderate–high. Rapid biomass production and incorporation	Moderate. Legume ground cover can compete with weeds and improve

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	suppresses germination and growth of aquatic weeds.	improve soil fertility and can indirectly reduce weed competitiveness, although its main benefit is N enrichment rather than direct weed control.	canopy closure, but suppression depends strongly on legume density and spatial arrangement.
Methane reduction	Potentially high. Rice + *Azolla* can reduce CH_4 emissions by modifying dissolved oxygen and soil redox conditions. Recent research reported 2.9 –13.2 % CH_4 reduction under different irrigation regimes.	Variable. Incorporation of fresh *Sesbania* biomass may actually increase CH_4 production because readily decomposable organic C stimulates methanogenesis. Therefore, dhaincha should not be described as inherently methane-reducing.	Variable/uncertain. Effects depend on residue management, flooding and decomposition. Legume residues may increase CH_4 when incorporated under anaerobic conditions, although reduced fertiliser use may provide indirect climate benefits.
Economics	Potentially economical because it can partially substitute for fertiliser N and may reduce weed-control requirements; however, multiplication, maintenance and incorporation require labor.	Economically attractive where seed and biomass production are feasible because it supplies substantial N and organic matter; establishment and incorporation require additional time and labour.	Attractive because farmers obtain an additional legume crop and may improve overall land productivity and nutrient-use efficiency. However, competition with rice and additional management can reduce profitability in some situations.
Major limitations	Requires standing water, adequate P and suitable temperature; biomass management can be labor-intensive; excessive growth may interfere with rice management.	Requires sufficient time before rice establishment; biomass incorporation requires labor/machinery; rapid decomposition can temporarily affect CH_4 emissions.	Competition for light, water and nutrients may occur; synchronisation of rice and legume growth is important; N fixation can be limited by poor nodulation, soil constraints and nutrient deficiencies.
Suitability	Best suited to flooded rice fields with suitable temperature and water availability; particularly useful where reducing fertiliser N and weeds is a priority.	Best suited as pre-rice green manure in irrigated lowland rice where sufficient time is available for biomass production and incorporation.	Suitable for rice–legume dual/sequence systems where farmers want additional grain/seed production, improved nutrient cycling and greater system productivity.
Reference	(26–28)	(29–31)	(32)

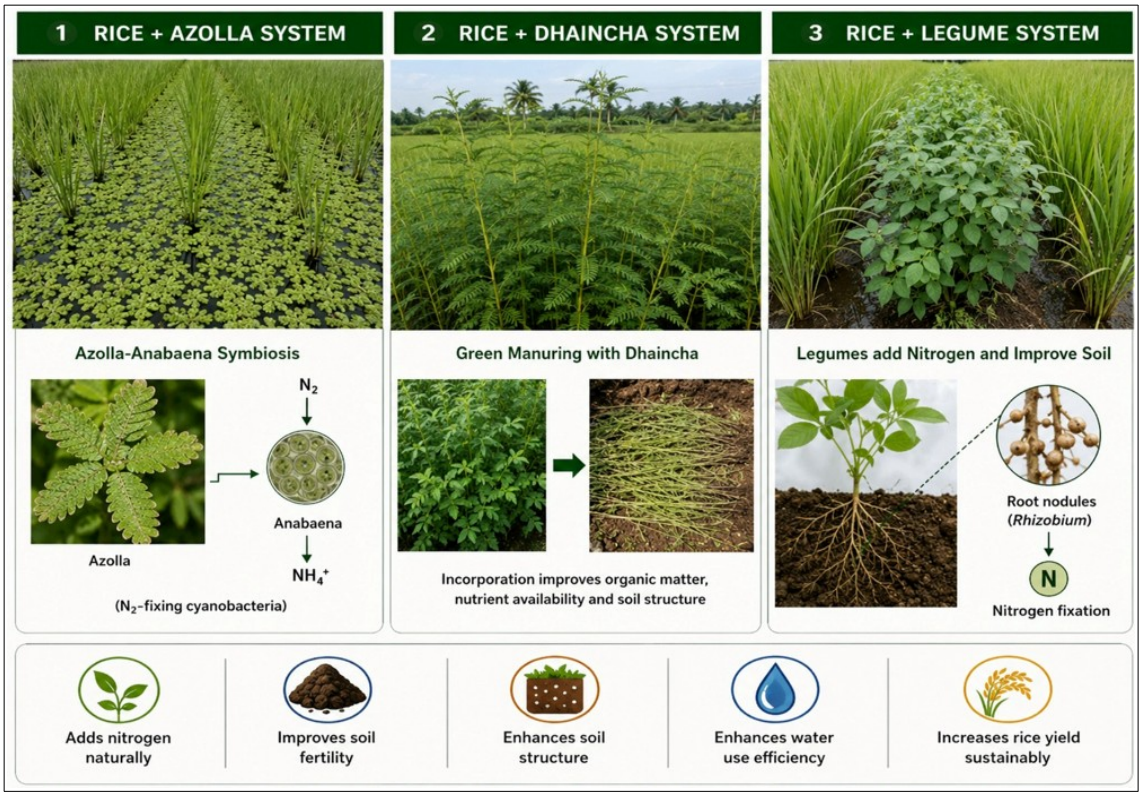


Fig. 1. Conceptual model of rice-based dual cropping systems for sustainable production.

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Agroecological basis of dual cropping

The effectiveness of the dual cropping practice in a rice production system is greatly influenced by the relationship between climatic conditions, soil, water availability and the farming methods adopted. These agroecological factors determine the compatibility of component crops and influence productivity, resource-use efficiency and long-term sustainability. Dual cropping as opposed to monoculture seeks to maximise the utilisation of natural resources through the integration of crops which complement each other ecologically.

Climatic requirements

Climate is one of the primary factors determining the success of rice-based dual cropping systems. Rice requires warm temperatures, adequate solar radiation and sufficient water throughout most of its growth cycle. For the incorporation of companion crops such as *Azolla*, dhaincha and short duration leguminous crops, there is a need to align the process well depending on the level of rainfall, temperature and photoperiod. Regions with extended growing seasons and adequate rainfall are suitable for dual cropping since they will provide sufficient time for the growth of the two crops. Planning of the planting and harvesting period has been found to enhance efficiency and reduce climatic risks (33).

Soil fertility and suitability

Although fertile soils support higher productivity, dual cropping is also used to restore soil fertility in degraded rice ecosystems. Properly irrigated rice which are capable of holding high levels of moisture, have moderate fertility and contain adequate levels of organic material may be able to support other crops. Biological nitrogen fixation, organic matter and better nutrient cycle through the incorporation of organic green manures such as dhaincha and leguminous plants contribute towards increasing soil fertility. In a similar manner, *Azolla* facilitates BNF in addition to increasing organic C content in the soil through decomposition processes (4).

Water management strategies

Water management is key for sustainability in dual cropping systems based on rice. Although traditional lowland rice is grown under flooded conditions, many companion crops require different soil moisture regimes. Irrigation scheduling, drainage and water harvesting are some tools that help ensure proper soil moisture conditions in favour of both crops. Efficient use of water through better irrigation management practices also helps prevent water loss while building resistance against drought and erratic rainfalls (33). Companion crops improve water-use efficiency by increasing soil organic matter, enhancing infiltration, reducing evaporation and improving soil structure.

Cropping calendar and seasonality

A proper cropping schedule is essential to ensure the full potential of dual cropping. The use of short-duration rice varieties and accompanying plants allows farmers to make proper use of their available time periods without affecting the next crops. Alignment of the crop development phases with seasonal rainfall and temperature allows minimising competition between crops and avoiding crop failures. Studies on double cropping demonstrate that the appropriate scheduling of the planting and harvesting periods improves land use efficiency and promotes sustainable intensification of rice-based farming systems (34).

Overall, successful implementation of rice-based dual cropping systems depends on the interaction among climate, soil, water availability and crop management. Site-specific adaptation of these agroecological factors is essential to maximise productivity, NUE and long-term sustainability.

Benefits of dual cropping

Long-term studies have demonstrated that incorporating green manure into double rice cropping systems significantly improves crop productivity and soil quality (Fig. 2) (35). The chemical, physical and biological characteristics of the soil were significantly improved by *Sesbania sesban* (L.) Merr. crops. Green manures also suppress weeds, reduce pest and disease incidence and decrease soil erosion. By lowering the need of chemical pesticides and fertilisers, enhancing soil qualities, minimising soil erosion and stopping nitrate and other chemical inputs from seeping into surface and groundwater, *S. sesban* is crucial for environmental sustainability (3). For intensive rice systems, sesbania green manuring combined with 75 % of the recommended dose of fertilisers is a more sustainable, resource-efficient and productive nutrient management approach. Compared to monocropping rice, intensifying rice fallows by rotating short-duration pulses and oil seeds crops is comparatively more economic, energy-efficient, water-smart and sustainable (36). In nutrient-exhaustive rice-based cropping systems, the use of green manures, pulses and other leguminous crops preserves nitrogen fertiliser for subsequent crops, boosts grain yield and profitability, lowers soil pH and enhances soil structure (2).

Introducing pulses and green manures can enhance soil structure, increase fertility and lower the prevalence of pests. The introduction of summer/pre-kharif crops and the integrated application of fertilisers, such as organic, inorganic and biofertilisers, can enhance soil health and fertiliser usage efficiency in rice-based cropping systems (37). The intercropping of legumes is well-known for enhancing the solubility of P along with the availability of N and P through BNF. Apart from the above processes, the root exudates and microbial activities and increased soil organic matter have an essential contribution in nutrient cycling of major and minor nutrients like potassium (K), calcium (Ca), magnesium (Mg), zinc (Zn), iron (Fe) and boron (B). Improved nutrient cycling reduces nutrient deficiencies and supports sustainable crop growth. The cropping of legumes and cereals in one piece of land will help in increasing the K level by mineral weathering through organic acids secreted

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by the roots (38). *Azolla* improves the growth of rice due to its capacity to facilitate soil moisture retention, temperature regulation and weed removal. *Azolla* increases the processes of photosynthesis, tillering, rooting and chlorophyll production. *Azolla* and rice grown together have been found to have a 48 % increase in root mass (39). Although most studies consistently report improvements in soil fertility and productivity, the magnitude of these benefits varies with climate, soil type, cropping sequence and management practices. Therefore, site-specific recommendations are essential for maximising the effectiveness of dual cropping systems.

Resource use efficiency

Legume intercropping enhances climate resilience and farm profitability by improving resource-use efficiency while promoting natural suppression of pests, diseases and weeds (40). Compared to incorporating rice residue, the rice-based system with sesbania green manuring had a greater water-use efficiency. The improved production of rice and subsequent rabi crops as well as effective soil moisture conservation led to increased water-use efficiency and utilisation by crops treated with green manuring (36). Nitrate leaching can be avoided and N gaseous emissions can be decreased by combining green manures with chemical N fertilisers. The composition and functionality of soil microbial communities are also enhanced by the application of green manure. Green manures enhance nitrogen uptake by improving root development, regulating rhizosphere processes, promoting soil aggregation and increasing N transport within plants, thereby improving nitrogen-use efficiency (41). Apart from improving the soil structure and organic C accumulation, legume-based farming practices have other benefits, such as increased water use efficiency. The improved aggregation and soil porosity help in water penetration and retention in soils, hence improving water utilisation by plants in both rainy and dry seasons. Improved microbial activity is always an outcome of improved soil physical properties. This increases mineralisation and hence the nutrient availability (42).

Water use is improved by *Azolla* due to its ability to cover the water surface reducing evaporation. The vegetative layer plays a role in controlling water temperature, prevents the development of algae and creates favourable environment for growing rice. After the introduction of *Azolla*, increased biological activity of soil promotes better soil aggregation and nutrient retention, allowing more efficient water and mineral utilisation. Consequently, the integrated use of *Azolla* reduces adverse environmental effects of high fertiliser application rates, decreases production expenses and boosts grain output (43). Mung bean, urd bean, cowpea and lentil serve as water-efficient pulse crops in southern, eastern and northeastern India, whereas chickpea and lentil predominate in northern and central India. These legumes require substantially less irrigation than rice, reducing overall water demand in rice-based cropping systems (44). The increase in water use efficiency by 25 % is attained when legumes are inter-cropped with cereals through maximum water extraction from the environment and reduced soil evaporation, particularly during drought periods (45).

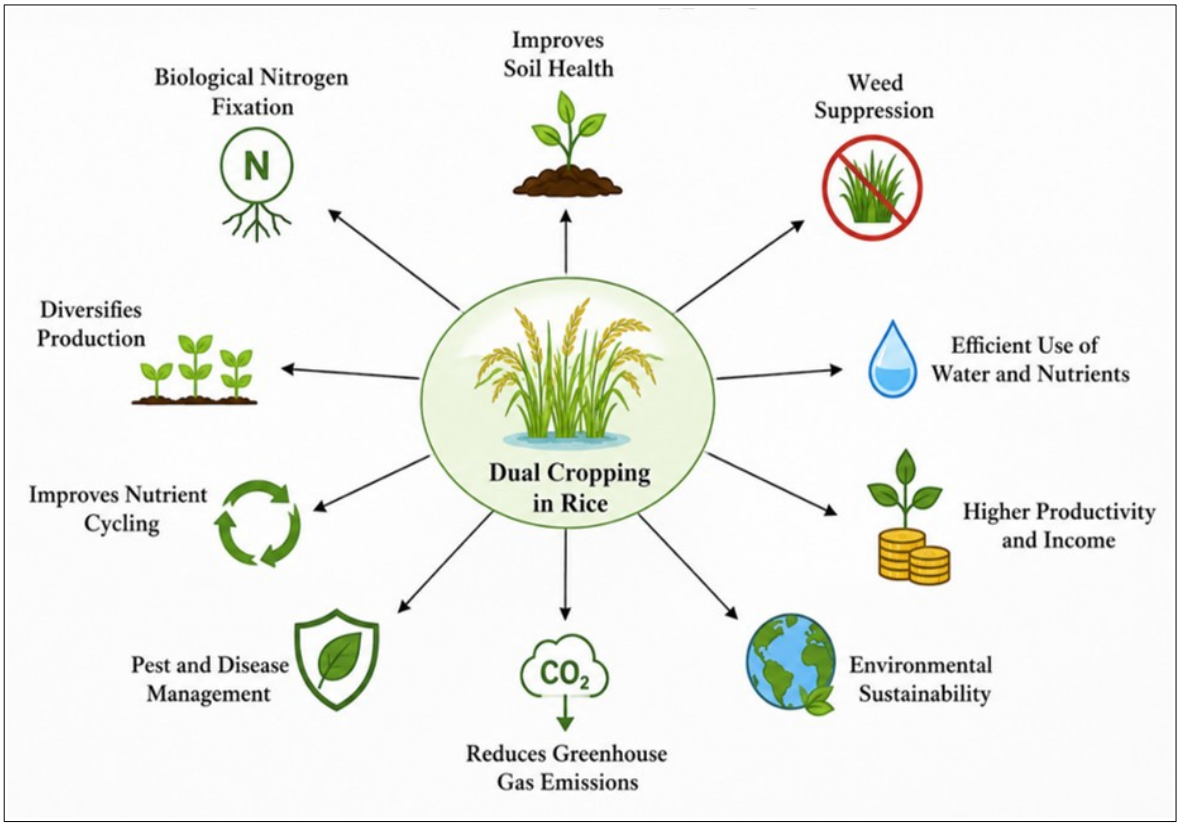


Fig. 2. Key benefits of dual cropping in rice.

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Impact on soil health and microbial activity

The co-cultivation of rice with *Azolla* enhanced nutrient cycling in the soil, altered the soil microbial ecology of the rhizosphere and improved soil quality by influencing bacterial populations. Compared with rice monoculture, *Azolla* incorporation altered phosphorus cycling while enhancing carbon and nitrogen cycling within the rhizosphere (46). *Azolla* can act as an accumulator of heavy metals from contaminated water, making it an effective phytoremediator. Due to factors like passive adsorption onto cell walls as well as metabolic absorption, living as well as dead biomass is equally efficient at removing the contaminants (47). Enzyme expression and transient peaks in microbial activity can be stimulated by increased rhizosphere exudation and labile C inputs from intensified rotations that include legumes, green manures and high-residue vegetables. However, the intensity, timing and persistence of those reactions are strictly controlled by residue quality, soil moisture regime and seasonal timing (48, 49). The integration of *Azolla*, dhaincha and legumes enhances nutrient cycling through BNF, biomass decomposition, nutrient mineralisation, rhizosphere interactions and microbial activity, thereby improving nutrient availability and uptake by rice (Fig. 3).

In rice cultivation systems, the use of green manure crops is possible because they acidify the soil, enhance its fertility, improve water retention and partly eliminate the need for N fertilisers. Green manures contribute to increased availability of other plant nutrients, raise organic matter content of soil and improve efficiency of mineral fertiliser application. Planting green manure, rape, or fallow during the winter enhanced the soil's C and N pools and increased rice productivity as compared to the traditional rice-wheat cropping method (50). Green manure improved soil pH, N availability, microbial biomass, bacterial diversity and beneficial microbial groups involved in C and N cycling, including Firmicutes, Actinobacteria and members of the phylum Glomeromycota (51). Agroecosystem performance can be rapidly improved by combining green manure with conservation tillage (reduced-tillage and no-tillage) techniques. In a semiarid agroecosystem, no-till cover crops gathered more microbial biomass C and available P and K in the 0–10 cm soil depth than intense tillage (52). The effects of rice-based dual cropping systems on key soil-health indicators, including soil organic carbon (SOC), nutrient availability, microbial activity and related soil properties, are summarised in Table 2 (10, 53, 54). Integration of *Azolla*, dhaincha and legumes enhances soil quality through improved nutrient cycling, increased microbial activity, greater organic matter accumulation and enhanced BNF, thereby supporting sustainable rice production.

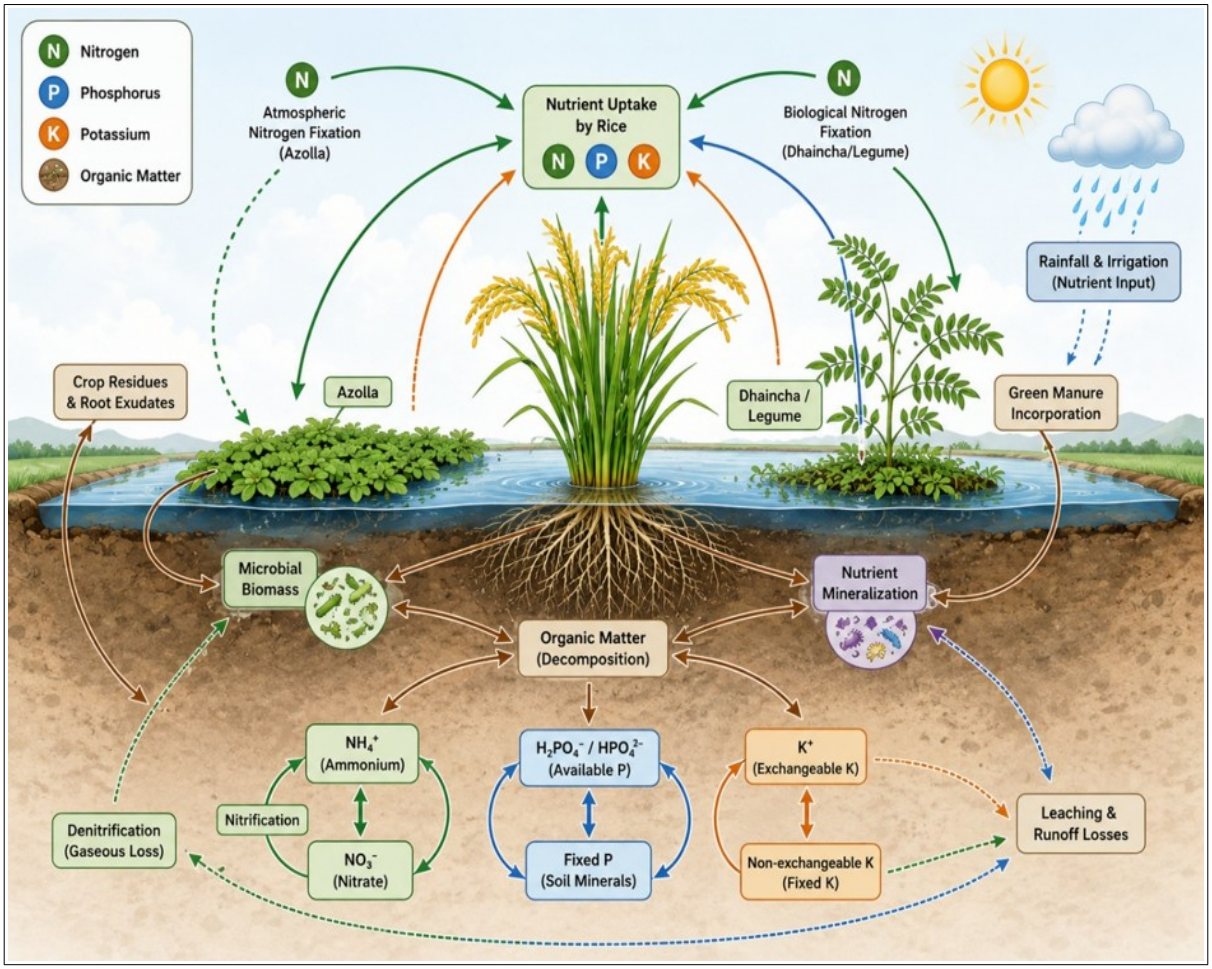


Fig. 3. Nutrient cycling and transformation in rice dual cropping systems.

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Table 2. Effects of dual cropping systems on soil

Dual cropping system	Rice + *Azolla*	Rice + Dhaincha (*Sesbania* spp.)	Rice + legumes
Soil organic carbon	Increase through biomass addition and decomposition	Increase substantially after incorporation of green biomass	Increase through legume residue incorporation
Available N	Increase due to biological N fixation	Increase through biological N fixation and decomposition	Increase through biological N fixation
Available P	Increase through improved nutrient cycling	Increase due to improved P availability and cycling	Increase due to enhanced nutrient cycling
Available K	Increase due to biomass decomposition and recycling	Increase through residue decomposition	Increase through residue decomposition
Soil microbial activity	Increase microbial biomass and activity	Increase microbial activity and soil biological processes	Increase microbial biomass and enzymatic activity
Soil structure/physical properties	Increase through biomass addition and decomposition	Improves aggregation, porosity and soil structure	Improves soil structure and aggregation
Overall effect on soil health	Improves soil fertility and nutrient cycling	Strong potential for improving soil fertility and organic matter	Enhances soil fertility and sustainability
Reference	(10)	(53)	(54)

Weed, pest and disease dynamics

Weeds are unwanted plants that compete with crops for light, water, nutrients and space, resulting in reduced crop growth and yield. They may also serve as reservoirs for insect pests and plant pathogens (55). Crop management practices-including crop rotation, tillage, residue management, mulching, balanced fertilisation and targeted agrochemical use-are essential for managing weed populations since different cropping systems have their own weed spectrum, diversity and difficulties in their management (56, 57). Studies have shown that *Azolla* effectively suppresses weed growth, reducing the density of grasses and broadleaf weeds either alone or when integrated with herbicide applications (58).

Rice yield was greatly increased and insect outbreaks were decreased when integrated agricultural system components were introduced. Furthermore, green manure, *Azolla* farming systems showed reduced pest occurrences and increased insect pest control efficacy, richness, diversity and evenness indices (59). Legumes like *Glycine max* (L.) Merr. and *V. radiata* improve soil fertility and agrobiodiversity, promoting resilient and environmentally friendly rice production systems, while companion crops like *Azolla pinnata* assist fix N and reduce weeds. Microbial-based biofertilisers like *Pseudomonas fluorescens, Burkholderia pyrrocinia, Trichoderma* species and *Bacillus thuringiensis* (Bt), as well as bioactive plant-based compounds like pesticides and botanical extracts like neem, ginger and garlic extract, have shown notable effectiveness in lowering pest damage and increasing rice yields (60). Host preference, damage and population densities of major rice pests were significantly reduced by green manures. Not only did the application of green manures enhance the formation of flavonoids and alkaloids and trigger defence-related genes but also contributed to the induction of synergistic activation of induced systemic resistance in rice. Along with increased soil functionality (N/C cycling), the green manures also increased some taxa beneficial for plants (Arbuscular mycorrhizal fungus (AMF): *Rhizophagus irregularis*; N-fixing bacterium: *Bradyrhizobium erythrophlei*, *Pseudolabrys* sp.) (61).

Climate change adaptation and sustainability

Global demand for rice is projected to increase substantially owing to population growth, urbanisation and changing dietary patterns. At the same time, changing climate patterns, food security will become an issue because of the increased demand. Conversely, rice production itself contributes significantly to global greenhouse gas emissions. Precision farming, biofertilisers, climate-resilient rice varieties, irrigation technology, C and methane mitigation techniques and mechanisation technologies are examples of cutting-edge net-zero and climate-resilient technologies that both benefit the environment and the economy (62). The development of heat, drought, flood and salinity tolerant strains of rice through the use of advanced breeding practices is an example of what can be done to enhance resilience. Drones and remote sensing technologies fall under the category of precision agriculture technologies and serve to make optimal use of the inputs due to data driven decisions. Water savings are achieved through such sustainable practices as direct seeding of rice, intermittent irrigation and the System of Rice Intensification. Climate-smart agricultural practices, including conservation agriculture and diversified cropping systems, improve resilience to climatic variability. The adaptive capacity can be improved by guaranteeing that farmers have access to climate services, finance and insurance (63).

Azolla reduces the impact of climate change through C sequestration as it consumes carbon dioxide (CO_2) while growing and keeps it stored within its biomass. *Azolla* can be used for rice farming as it improves the structure of soil and conserves water and increases production of rice; hence it is an important part of climate smart agriculture. Either integrate it into a discussion of

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plant physiological responses or omit it, as it does not directly support the section's theme (64). More specifically, where climate change is concerned, legumes are critical for sustainable farming due to their role in ensuring healthy soils and nitrogen cycling, C sequestration and salinity tolerance. The deep root systems of legumes help in increasing SOC and soil structure stability. Moreover, through rhizobacteria, legumes ensure efficient nitrogen transformations (65). The emissions of the three primary greenhouse gases are also significantly impacted by green manure. The effects of green manure on greenhouse gas emissions depend largely on residue quality, particularly the C : N ratio. Low C : N residues generally reduce methane (CH_4) emissions but may increase N_2O emissions, whereas integrated residue and fertiliser management can reduce overall greenhouse gas emissions from rice fields. In addition to suppressing weeds and lowering herbicide residues in paddy fields, green manure enriches and transfers certain heavy metals including Cd, lead (Pb) and Zn, improving the soil (66).

Climate-resilient rice systems can further strengthen adaptation to drought and flood stress through improved water management, tolerant cultivars and diversified cropping. Alternate wetting and drying (AWD), intermittent irrigation and direct-seeded rice can conserve water during drought periods, while improved drainage, flood-tolerant varieties and timely water management can reduce crop losses under excess rainfall and temporary submergence. These practices also influence the greenhouse-gas balance of rice fields. Periodic drainage generally suppresses CH_4 formation by reducing prolonged anaerobic conditions, although excessive drying or inappropriate N management may increase nitrous oxide (N_2O) emissions. Therefore, balanced water and N management is essential for reducing the overall C footprint rather than targeting a single greenhouse gas. Integrated management of water, N, residues and suitable cultivars can lower greenhouse-gas emissions while maintaining rice productivity (67, 68). In addition, biomass inputs from legumes, *Azolla* and other organic resources can contribute to soil C sequestration through the accumulation and stabilisation of soil organic matter. Thus, climate-smart rice production should integrate adaptation and mitigation practices that improve water-use efficiency, soil carbon storage and resource-use efficiency while sustaining productivity and farm profitability (69).

Economic analysis of dual cropping systems

Incorporating crops like lentils, mustard, rapeseed and garden peas during the rabi season, along with black gram and sesbania as green manuring crops during the summer, can effectively diversify a rice-based cropping system. Under rainfed medium-land conditions in Assam, the rice-garden pea-dhaincha sequence recorded the highest profitability among the evaluated rice-based cropping systems, highlighting the importance of location-specific crop diversification (70). In comparison to upland rice interplanted with mung bean, rice interplanted with peanuts produced the maximum rice grain yield of 2.8 t ha^{-1} and the largest gross margin when the optimal rice seeding rate of 60 kg ha^{-1} (drilled in a furrow) was used (71). Higher net returns and a benefit-cost (B : C) ratio were seen in rice + dhaincha intercropping, possibly as a result of notable improvements in grain and straw yields (72).

The dual cropping of rice (with *Sesbania* + 100 % recommended dose of nitrogen [RDN]) generated the highest net benefit and B : C ratio. This advantage resulted from lower crop establishment costs and the efficient incorporation of *Sesbania* biomass. This system is like that of (rice + *Azolla*) + 100 % RDN. Both the dual crops improve not only the soil properties but also contribute nutrients such as N for sustainable agriculture (73). Mechanical incorporation of dhaincha with cono weeder resulted in higher productivity of rice and dhaincha than either manual incorporation or incorporation using cono weeder along with manual operation. Mechanical incorporation of rice and dhaincha by cono weeder resulted in higher net gain and higher energy ratio from economic and energetics aspects (74). Integrated use of *Sesbania*, *Azolla* and appropriate weed management increased grain yield and economic returns compared with sole direct-seeded rice (58). Collectively, these studies indicate that the economic advantages of dual cropping arise from higher productivity, lower fertiliser requirements, improved resource-use efficiency and reduced weed management costs. However, profitability varies with crop combinations, management practices and regional agroecological conditions. Table 3 provides a comparative overview of the economic performance of rice + *Azolla*, rice + dhaincha and rice + legume systems, emphasising their potential to increase system productivity, reduce input costs and improve net returns and benefit-cost ratios.

Table 3. Economic benefits of major dual-cropping systems in rice

Dual-cropping system	Rice + *Azolla*	Rice + Dhaincha	Rice + Legumes
Additional economic output	Additional value through improved rice productivity and biomass production	Mainly contributes indirectly through improved rice productivity and soil fertility rather than a separate marketable grain	Provides additional marketable grain such as green gram or black gram
Cost-saving potential	Potential reduction in N-fertiliser requirement and weed-control costs	Can reduce expenditure on N fertiliser through biological N fixation and green-manure incorporation	Biological N fixation and potential reduction in fertiliser requirement

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Income / profitability advantage	Better returns may result from improved resource-use efficiency and reduced external inputs	Improved soil productivity can provide longer-term economic benefits and reduce dependence on external inputs	Higher system productivity, diversified farm income and improved land-use efficiency
Major economic constraint	Cost of establishment, multiplication and periodic maintenance of *Azolla*	Additional labour and field operations required for establishment and incorporation	Additional seed, labour and crop-management costs; profitability depends on legume yield and market price
References	(9, 10, 75)	(54)	(22, 75)

The economic performance of dual cropping systems should be assessed not only from grain yield but also from the cost of cultivation, labour requirement, fertiliser use, net return and B : C ratio. Although the inclusion of a companion crop may increase initial expenditure for seed, sowing and field operations, the additional cost can be offset by higher combined output, reduced fertiliser demand and lower expenditure on weed management. Systems involving *Sesbania* or *Azolla* may provide an economic advantage through biological N inputs, thereby reducing dependence on externally supplied N fertiliser. Labour requirements may increase where companion crops require additional establishment, biomass incorporation or harvesting, whereas mechanised operations can reduce this constraint. Net returns and B : C ratios are influenced by input prices, labour costs, crop yields and market prices of the companion crop. Over the long term, repeated incorporation of organic biomass and improved soil fertility may reduce external input requirements and support sustained productivity. Therefore, long-term profitability of dual cropping depends on the balance between additional cultivation costs and the economic benefits obtained through additional produce, fertiliser savings, improved resource-use efficiency and improved soil fertility.

Future perspectives

The success of rice based dual cropping systems in the future would depend upon their adaptation to local environment, objectives of cultivation and limitations Dual cropping systems such as rice + *Azolla*, rice + dhaincha and rice + legume have demonstrated positive effects on soil fertility, nutrient cycling, weed suppression and reduced input requirements. These benefits contribute to improved productivity and sustainability. However, the performance of these systems varies depending on climatic conditions, soil properties, water availability and management practices. Long-term, site-specific investigations are required to evaluate these systems under variable seasonal and climatic conditions. In addition, advances in digital agriculture provide new opportunities to enhance the efficiency and resilience of these systems. Artificial intelligence (AI)-based crop management, integrated with decision support systems, can assist farmers in selecting suitable crop combinations, optimising sowing schedules and improving field-level management based on weather, soil and crop information.

Further studies should focus on improving selection of companion crop, its timing of planting and incorporation of biomass along with nutrient dynamics, which would facilitate efficient incorporation of these systems in modern rice cultivation. Further investigation is required to evaluate the effect of dual cropping systems on soil microflora, C sequestration, emission of greenhouse gases such as CH_4 and NO_2. Modern methods including molecular approaches, precision agriculture, remote sensing and decision support systems can facilitate this task. Modern technologies, including molecular approaches, precision nutrient management, remote sensing, Geographic Information Systems (GIS), drone-based crop monitoring and internet of things (IoT)-based sensors, can support continuous monitoring of crop performance, soil moisture, nutrient availability, weed infestation and environmental conditions, enables timely and site-specific management interventions while improving resource-use efficiency.

Another critical aspect is economic and social feasibility. There is a high probability that the adoption of these systems will increase when they are profitable, practical and supported by effective extension services. Future research should therefore include cost-benefit analysis, labour requirements and risk management to ensure that recommendations are economically viable and suitable for farmers. In parallel, breeding programmes should focus on developing rice varieties and companion crops with compatible growth characteristics, improved nutrient-use efficiency and greater tolerance to biotic and abiotic stresses, thereby enhancing the stability and productivity of rice-based dual cropping systems. Supportive policy interventions, including investments in digital agriculture infrastructure, improved access to quality seeds and biofertiliser inoculants, farmer training programmes and strengthened extension services, will be equally important for promoting large-scale adoption. On the whole, interdisciplinary research integrating agronomy, soil science, ecology, agricultural economics and climate science will be essential for developing resilient and sustainable rice-based dual cropping systems.

Conclusion

Dual cropping represents a practical strategy for sustainably improving rice-based farming systems. With the integration of crops like *Azolla*, dhaincha (*Sesbania* spp.) and legumes in the farming systems along with rice cultivation, farmers would be able to utilise their natural resources in a more effective manner without much dependence on synthetic fertilisers. All the combinations

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of crops contribute to the production system in a different way. For example, *Azolla* is known to increase biological nitrogen fixation (BNF) and suppress weeds, dhaincha increases soil fertility due to its contribution of green manure, while legumes increase soil fertility and contribute to crop diversification.

Moreover, dual cropping also provides environmental benefits, such as reduced greenhouse gases, better water and nutrient management, as well as increased climate change adaptation potential. These systems further improve farm profitability through higher productivity, lower external input requirements and improved resource-use efficiency. While promising outcomes have been found in numerous studies, the effectiveness of dual cropping techniques differs based on climatic conditions, soil quality and agricultural practices. Consequently, further research needs to be conducted to optimise techniques and assess their broader application. Overall, rice-based dual cropping offers a scientifically sound and environmentally sustainable approach to achieving productive, resilient and climate-smart rice production. Continued research, supportive policies and effective extension programs will be essential to realise its full potential for sustainable agricultural development and global food security.

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Authors' contributions

GK contributed to literature collection and drafted the manuscript. SE provided overall guidance for corrections and improvements. GA, MP and AP contributed to literature collection and formatting. All authors contributed equally to revising the manuscript. All authors have read and approved the final 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 ChatGPT to improve editing and grammatical refinement of manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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