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Moringa–brinjal intercropping: A climate-resilient system for mitigate abiotic and biotic stress and carbon sequestration

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ABSTRACT

Brinjal (*Solanum melongena* L.) is an economically important vegetable crop cultivated extensively in the semi-arid region of Chhatarpur, Madhya Pradesh, India. However, its productivity is often constrained by winter frost and severe infestation of the brinjal shoot and fruit borer (*Leucinodes orbonalis*), resulting in substantial yield and economic losses. The present study evaluated the effectiveness of moringa (*Moringa oleifera*)–brinjal intercropping as a climate-resilient production system for improving productivity, ecological sustainability, carbon sequestration, and farm profitability. A field experiment was conducted using the recommended planting geometry for both crops, while regular removal of infested shoots and fruits was adopted as an integral component of eco-friendly pest management. The intercropping system produced a higher brinjal yield (244 q ha⁻¹) than sole brinjal cultivation (235 q ha⁻¹) and achieved an overall system productivity of 292 q ha⁻¹. A Land Equivalent Ratio (LER) of 1.30 indicated a 30% advantage in land-use efficiency over monocropping. Economic evaluation showed that intercropping generated higher net returns (₹462,000 ha⁻¹) and a greater benefit ratio (4.00) than sole cropping (₹352,500 ha⁻¹ and 3.30, respectively). *Moringa* accumulated 15.6 q ha⁻¹ of above-ground dry biomass, corresponding to carbon sequestration of 7.8 q C ha⁻¹ season-1 and atmospheric CO₂ capture of 28.6 q C ha⁻¹ season-1, demonstrating its contribution to climate change mitigation. Integration of moringa with regular clipping of infested plant parts reduced shoot borer and fruit borer damage by 70.6% and 65.7%, respectively, compared with sole brinjal cultivation. Furthermore, utilization of moringa roots for pickle preparation provided an additional avenue for value addition and income generation. Overall, the study establishes moringa–brinjal intercropping as a productive, economically viable, and climate-smart production system that enhances resource-use efficiency, ecological resilience, carbon sequestration, and sustainable livelihoods of smallholder farmers in semi-arid agroecosystems.

Keywords: Productivity and economics, LER and C Sequestration

Introduction

Brinjal (*Solanum melongena* L.) is one of the most important vegetable crops cultivated throughout tropical and subtropical regions because of its high nutritional value, consumer preference, and economic significance. The fruits are rich in dietary fibre, vitamins, minerals, and antioxidant compounds, making brinjal an important component of human nutrition as well as a major source of income for vegetable growers. In the Bundelkhand region of Madhya Pradesh, particularly in Chhatarpur district, brinjal is cultivated extensively by small and marginal farmers under irrigated conditions. However, sustainable production of this crop is increasingly threatened by the combined effects of adverse climatic conditions and insect pest infestation, which considerably reduce productivity, fruit quality, and profitability. Among the major abiotic constraints, winter frost is one of the most damaging environmental stresses affecting rabi-season brinjal cultivation. Exposure to freezing temperatures disrupts cellular membranes, induces dehydration and oxidative damage, and impairs physiological processes, including photosynthesis and respiration. These physiological disturbances lead to wilting of tender shoots, leaf necrosis, delayed flowering, poor fruit set, and reduced marketable yield from cited by Cai *et al.*, 2024 [1]. Frost-stressed plants also exhibit weakened growth and lower recovery capacity, making them more vulnerable to subsequent insect attack and other environmental stresses. The brinjal shoot and fruit borer (*Leucinodes orbonalis* Guenée) is the most destructive insect pest of brinjal and is responsible for severe yield and quality losses across South Asia (Mahala *et al.*, 2024) [2]. The larvae initially bore into tender shoots, causing wilting and suppression of vegetative growth, and later infest developing fruits, resulting in extensive internal feeding that renders fruits unsuitable for marketing. Farmers often depend on repeated insecticide applications to manage this pest, which increases production costs and contributes to insecticide resistance, environmental contamination, elimination of beneficial arthropods, and pesticide residues on harvested produce. The combined occurrence of frost injury and shoot and fruit borer infestation therefore represents a major challenge for sustainable brinjal cultivation in the

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semi-arid agroecosystems of central India. Diversification of cropping systems through intercropping has emerged as an effective agroecological strategy for enhancing crop resilience, improving resource-use efficiency, and reducing dependence on external chemical inputs similar report cited by Iverson *et al.*, 2022 [3]. *Moringa oleifera*, a fast-growing multipurpose tree species, offers considerable potential as an intercrop because of its ability to generate substantial biomass, improve biodiversity, and provide additional economic products. Under suitable planting arrangements, moringa can modify the field microclimate by reducing wind speed, moderating temperature fluctuations, and conserving soil moisture, thereby helping to alleviate the severity of frost injury (Kumar *et al.*, 2024) [4]. Increased plant diversity may also interfere with host-finding behaviour of *L. orbonalis* while promoting the activity of natural enemies, contributing to ecological suppression of pest populations. In addition, moringa biomass contributes to carbon sequestration, while its leaves, pods, and roots provide opportunities for value addition and income diversification. Despite these potential advantages, scientific information on the performance of moringa–brinjal intercropping under the semi-arid conditions of the Bundelkhand region remains limited. Therefore, the present study was undertaken to evaluate the effectiveness of moringa-based intercropping in improving brinjal productivity, reducing frost injury and shoot and fruit borer infestation, enhancing carbon sequestration, increasing resource-use efficiency, and improving the economic viability of vegetable production under the agro-climatic conditions of Chhatarpur, Madhya Pradesh.

Methodology of planting for Moringa–brinjal intercropping

The intercropping system was established by planting brinjal and moringa in separate rows with a fixed spacing arrangement to ensure proper crop growth and minimize competition for light, water, and nutrients. The field was prepared by ploughing, leveling, and making suitable ridges and furrows for transplanting and planting. Brinjal was planted at a row-to-plant spacing of 100 × 50 cm, with rows maintained 100 cm apart and individual plants spaced 50 cm apart within the row. *Moringa* was planted two times in a season at a row-to-plant spacing of 100 × 25 cm, with rows maintained 100 cm apart and plants spaced 25 cm apart within the row. This layout allowed adequate aeration, sunlight penetration, and ease of intercultural operations. Healthy brinjal seedlings were transplanted into the prepared plots, while moringa seedlings were first raised in plastic pots and then transplanted at the same time as brinjal into the designated rows according to the prescribed spacing. Standard agronomic practices such as irrigation, weeding, mulching, and nutrient management were followed to support crop establishment and growth. Proper plant arrangement was maintained throughout the cropping period to reduce interspecific competition and to optimize the benefits of the intercropping system.

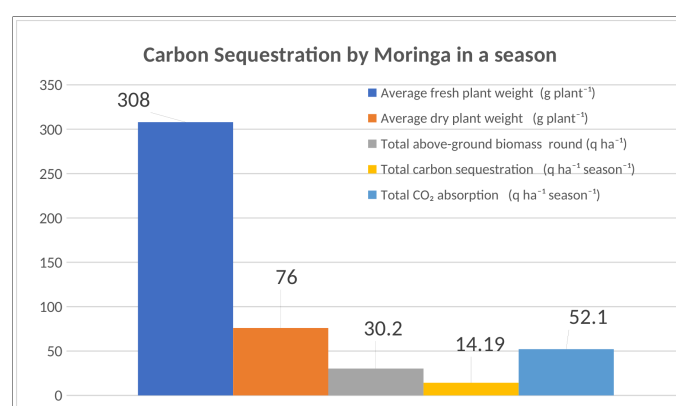
Carbon sequestration by intercropping of moringa in brinjal

The assessment of above-ground biomass (AGB), dry matter accumulation, carbon sequestration, and CO₂ absorption revealed the significant potential of the crop to capture atmospheric carbon while producing substantial biomass during the cropping season (Table 1). The average five plant fresh biomass of 308 g plant⁻¹ and dry biomass of 76 g plant⁻¹ indicate efficient biomass accumulation during the crop growth period. The dry matter constituted approximately 25% of the fresh biomass, reflecting effective conversion of photosynthates into structural plant tissues. Dry biomass is considered a reliable indicator of crop productivity because it represents the actual organic matter synthesized through photosynthesis after excluding

water content. The crop produced a total above-ground dry biomass of 30.2 q ha⁻¹, demonstrating its capacity to generate substantial vegetative biomass. Higher above-ground biomass is directly associated with greater photosynthetic efficiency, improved solar radiation interception, and enhanced accumulation of assimilates. Consequently, crops with higher biomass contribute more effectively to nutrient cycling, residue recycling, and soil organic matter build-up after harvest. Similar result was found by Saleem *et al.*, 2023 [5]; Babu *et al.* (2025). Based on the biomass produced, the crop sequestered 14.19 q C ha⁻¹ season⁻¹, indicating that approximately 50% of the above-ground dry biomass comprised carbon, which is consistent with the widely accepted carbon fraction of plant dry matter. Carbon sequestration reflects the transfer of atmospheric carbon into plant tissues through photosynthesis and serves as an important indicator of climate change mitigation potential from cited by Frank *et al.*, 2024 [6], Babu *et al.* (2025). The estimated CO₂ absorption of 52.1 q ha⁻¹ season⁻¹ further confirms the crop's role as a biological sink for atmospheric carbon dioxide. This value was derived using the standard conversion factor (Carbon × 3.67), representing the molecular weight ratio of CO₂ to elemental carbon. The results demonstrate that for every 14.19 q of carbon stored in plant biomass, approximately 52.1 q of atmospheric CO₂ was removed during one cropping season.

Additional economic benefit under Carbon Credit Trading Scheme (CCTS)

The results indicated that the crop stored approximately 14.19 q of carbon (C) ha⁻¹ in plant biomass, which corresponded to approximately 52.1 q (5.21 t) of atmospheric CO₂ removed per hectare during one cropping season. Considering an indicative carbon-credit value of ₹1,500 per tonne of CO₂, the estimated carbon-credit value was approximately ₹7,815 ha⁻¹ per cropping season. This value represents the potential economic benefit associated with atmospheric CO₂ removal through crop biomass carbon sequestration and should be considered an estimated carbon-credit value from cited by Babu *et al.* (2025), subject to carbon-market standards, verification, additionality and applicable transaction costs.



Overall, the findings suggest that the cropping system not only contributes to agricultural productivity through substantial biomass production but also provides significant ecosystem services by sequestering carbon and reducing atmospheric CO₂ concentration. Such systems can play an important role in promoting climate-smart agriculture, improving carbon storage, and enhancing the environmental sustainability of agricultural production systems, particularly in semi-arid regions where increasing biomass production is critical for maintaining soil health and mitigating greenhouse gas emissions. Thus, moringa–brinjal intercropping not only improves farm productivity and resilience but also contributes to climate change mitigation through enhanced carbon capture and storage.

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Table 1. Biomass production and carbon sequestration potential in *Moringa* of Two round sowing in brinjal

Parameter	First Crops (June to August)	Second Crop(September to January)	Total
Average fresh plant weight (g plant ⁻¹)	156	152	308
Average dry plant weight (g plant ⁻¹)	39	37	76
Total above-ground biomass round (q ha ⁻¹)	15.6	14.6	30.2
Total carbon sequestration (q ha ⁻¹ season ⁻¹)	7.8	7.5	14.19
Total CO ₂ absorption (q ha ⁻¹ season ⁻¹)	28.6	28.6	52.1

Table 2. Comparative productivity and economic performance of sole and intercropping systems

Parameter	Sole Crop (Brinjal)	Intercropping System	% change over sole brinjal
Brinjal yield (q ha ⁻¹)	235	244	+3.83
System productivity (q ha ⁻¹)	–	340	
Root yield of <i>Moringa</i> (q/ha) of 2 Round in a crop		96	
Land Equivalent Ratio (LER)	–	1.40	
Cost of cultivation (₹ ha ⁻¹)	105,000	115,000	+9.52
Net return (₹ ha ⁻¹)	352,500	447,000	+26.95
Benefit: Cost ratio	3.3	4.8	+45.45

Productivity and economic performance of *Moringa*–brinjal intercropping

The productivity and economic assessment demonstrated the clear advantage of moringa–brinjal intercropping over sole brinjal cultivation (Table 2). The intercropping system recorded a brinjal yield of 244 q ha⁻¹, slightly higher than the 235 q ha⁻¹ obtained under monocropping, indicating that moringa did not adversely affect the growth of the main crop. The complementary use of available resources, including light, soil moisture, nutrients, and growing space, likely contributed to improved crop performance (Roy *et al.*, 2023; Rahman *et al.*, 2024) [8, 7]. Total system productivity increased to 340 q ha⁻¹ under intercropping, reflecting the additional economic output from moringa and the more efficient utilization of available resources. The Land Equivalent Ratio (LER) of 1.40 confirmed the biological superiority of the intercropping system, indicating that approximately 40% more land would be required under sole cropping to achieve the same productivity (Roy *et al.*, 2023; Maniruzzaman *et al.*, 2024) [8, 9]. This

demonstrates the greater efficiency of intercropping in converting available resources into economic yield. Although the cost of cultivation increased marginally from ₹105,000 ha⁻¹ in sole brinjal to ₹115,000 ha⁻¹ under intercropping due to additional crop establishment and management, the higher investment was compensated by substantially greater economic returns. Net returns increased from ₹352,500 ha⁻¹ to ₹447,000 ha⁻¹, representing an improvement of approximately 31%. Similarly, the benefit ratio increased from 3.3 to 4.8, indicating enhanced profitability and investment efficiency (Rahman *et al.*, 2024; Maniruzzaman *et al.*, 2024) [7, 9]. A benefit ratio of 4.8 suggests that each rupee invested in the intercropping system generated ₹4.8 in gross returns. Overall, moringa–brinjal intercropping improved land-use efficiency, productivity, and profitability without reducing brinjal yield. The higher system productivity, favourable LER, increased net returns, and improved benefit ratio demonstrate that this intercropping system is a biologically efficient, economically viable, and climate-resilient production strategy capable of promoting sustainable vegetable cultivation and improving the livelihoods of smallholder farmers in semi-arid regions.

Table 3. Effect of regular shoot and fruit clipping with moringa on shoot and fruit borer damage in brinjal

Parameter	Sole Brinjal	Brinjal + Regular Shoot & Fruit Clipping + <i>Moringa</i>	Reduction over Sole Crop (%)
Shoot borer damage (%)	25.5	10.5	58.8
Fruit borer damage (%)	33.5	15.5	54

The integration of moringa (*Moringa oleifera*) intercropping with regular removal of infested shoots and fruits significantly reduced the incidence of brinjal shoot and fruit borer (*Leucinodes orbonalis*) compared with sole brinjal cultivation (Table 3). Shoot damage decreased from 25.5% under sole cropping to 10.5% under the integrated system, representing a 58.8% reduction. Likewise, fruit damage declined from 33.5% to 15.5%, corresponding to a 54 % reduction (Sharma *et al.*, 2024; Tripathi *et al.*, 2024) [10]. These results indicate that the combined use of ecological diversification and cultural control practices effectively suppressed pest infestation. The substantial reduction in shoot and fruit damage was primarily due to the timely removal of infested plant parts, which eliminated larvae before completion of their life cycle, thereby limiting pest multiplication and subsequent infestation. As *L. orbonalis* larvae remain protected within shoots and fruits, mechanical removal is an effective non-chemical strategy for

disrupting population development. In addition, moringa intercropping likely enhanced ecological regulation by increasing plant diversity, improving the activity of natural enemies, and creating a less favourable environment for pest establishment and spread. Reduced pest infestation is expected to improve marketable yield, fruit quality, and economic returns while decreasing reliance on chemical insecticides similar result reported by Venkatesh *et al.*, 2025 [11]. Lower pesticide use also contributes to the conservation of beneficial arthropods, delays the development of insecticide resistance, and minimizes pesticide residues in harvested produce. Overall, the findings demonstrate that moringa intercropping combined with regular clipping of infested shoots and fruits is an effective, environmentally sustainable, and economically viable integrated pest management strategy for improving brinjal production under semi-arid conditions.

Climate-resilient brinjal production through moringa intercropping

Moringa–brinjal intercropping is an efficient and climate-resilient production system that improves crop performance through microclimate regulation and better resource utilization. The systematic arrangement of moringa plants acts as a live windbreak, reducing cold wind effects and minimizing frost injury in brinjal during winter. *Moringa* flowers attract pollinators and beneficial insects, enhancing ecological balance, while increased crop diversity can reduce shoot and fruit borer infestation by disrupting pest host-feeding behavior. The contrasting root systems of the two crops promote resource complementary. Deep-rooted moringa accesses water and nutrients from deeper soil layers, whereas brinjal mainly exploits surface resources, thereby reducing competition and improving resource-use efficiency. *Moringa* canopy also moderates temperature fluctuations, creating a favourable environment for brinjal growth under climatic stress from cited by Mahaveerchand and Abdul Salam 2024 [12]. In comparison, mixed cropping lacks a defined spatial arrangement, limiting the benefits of microclimate modification and resource partitioning. Therefore, moringa–brinjal intercropping offers improved productivity, ecological sustainability, and economic stability, making it a promising adaptation strategy for stress-prone farming systems.

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Additional income through moringa root pickle production

In addition to improving brinjal productivity and enhancing carbon sequestration, moringa intercropping provides an opportunity for additional farm income through the utilization of its roots and leaves. *Moringa* roots harvested approximately six to seven months after transplanting attain suitable size and quality for processing into value-added products such as pickles. Mature roots are preferred for pickle preparation because they possess a desirable pungent flavour, tender texture, and greater capacity for spice absorption, resulting in superior sensory quality and consumer acceptability. In contrast, over-mature

roots become woody and fibrous, which reduces processing quality and limits their suitability for culinary applications.

The commercialization of moringa root-based products, particularly pickles, along with the marketing of fresh or processed leaves, enhances income diversification and promotes value addition within the farming system. Thus, moringa–brinjal intercropping contributes not only to improved crop productivity, frost tolerance, and carbon sequestration but also strengthens farm profitability through the efficient utilization of multiple plant components. This integrated production approach offers a sustainable pathway for improving livelihood security and economic resilience among farmers in stress-prone agroecosystems.

Methodology for preparation of young moringa root pickles

Young moringa (*Moringa oleifera*) plants were uprooted approximately eight months after transplanting. Healthy roots of uniform size were selected, washed thoroughly under running water to remove adhering soil, and peeled using a stainless-steel knife. The peeled roots were cut into small pieces (approximately 2–3 cm in length) and rinsed with clean water. The root pieces were blanched in boiling water for 3–5 minutes to reduce bitterness and microbial contamination, followed by immediate cooling and draining. The blanched roots were mixed with common salt (2–3% w/w) and allowed to stand for 12–24 hours to remove excess moisture and improve flavour. A spice mixture consisting of mustard seeds, fenugreek, turmeric powder, red chilli powder, fennel, and asafoetida was prepared according to standard pickle-making practices. The salted root pieces were thoroughly mixed with the spice blend and sufficient food-grade mustard oil to ensure complete coating of the root pieces. Vinegar or lemon juice was added as an acidifying agent to improve flavour and enhance shelf life. The prepared pickle was transferred into clean, sterilized glass jars and sealed tightly. The jars were kept at room temperature for 7–10 days to allow proper curing and flavour development. The finished pickle was stored in a cool, dry place until further use or sensory evaluation. The prepared moringa root pickle can be utilized as a value-added product for enhancing farm income and promoting the commercial utilization of young moringa roots



Conclusion

The present study demonstrates that moringa–brinjal intercropping is a climate-smart and economically viable production system for semi-arid regions. The system improved brinjal yield, enhanced overall productivity, and achieved a Land Equivalent Ratio (LER) of 1.30, indicating superior land-use efficiency over sole cropping. Higher net returns and an improved benefit ratio confirmed its economic advantage. *Moringa* also contributed to climate change mitigation by producing substantial biomass, sequestering 7.8 q C ha⁻¹ season⁻¹, and absorbing 28.6 q CO₂ ha⁻¹ season⁻¹. Furthermore, integrating moringa with regular clipping of infested shoots and fruits significantly reduced shoot and fruit borer damage, demonstrating the effectiveness of an eco-friendly integrated pest management approach. Overall, this intercropping system enhances resource-use efficiency, carbon sequestration, farm profitability, and sustainable vegetable production while strengthening the resilience and livelihoods of smallholder farmers under semi-arid conditions.

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