PLANT SCIENCE TODAY
Vol 13(2): 1-10
https://doi.org/10.14719/pst.11644

eISSN 2348-1900

RESEARCH ARTICLE

Sustainable rice production in low-SOM soils: The case for green manure adoption

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Received: 06 September 2025; Accepted: 05 February 2026; Available online: Version 1.0: 18 March 2026; Version 2.0: 01 April 2026

Cite this article: Ferdous J, Mousumi SMJA, Fardus J, Anne IM, Jui AF, Mukta TA, Mim NJ, Hosenuzzaman M, Kibria MG, Hoque TS, Hoque MA and Hossain MA. Sustainable rice production in low-SOM soils: The case for green manure adoption. Plant Science Today. 2026; 13(2): 1-10. https://doi.org/10.14719/pst.11644

Abstract

In intensive rice-based rotations, reliance on high rates of chemical fertilisers (CF) often results in low nutrient-use efficiency and attendant environmental risks. To evaluate the potential of organic amendments (OAs) to mitigate these issues, we conducted a Boro–Fallow–Transplanted Aman (T. Aman) field trial for two years (2022–2024), with 7 treatments: an unfertilised control; farmer-practice CF; full recommended dose (RD) of CF; and 4 treatments combining 75 % RD of chemical fertiliser with farmyard manure (FYM), poultry manure (PM), compost, or green manure (dhaincha). Dhaincha was cultivated during the fallow interval, while all OAs were applied at T. Aman, with residual effects assessed in the subsequent boro season. All combined OA + 75 % RD treatments produced comparable grain yields (3.01–6.33 t ha^{-1}), each delivering 50–52 % higher grain and 47–50 % higher straw yields than the unfertilised control. Notably, the green manure treatment achieved the highest nutrient uptake and post-harvest soil carbon stocks, boosting soil organic carbon by 12–26 % relative to the control. These findings demonstrate that integrating moderate chemical inputs with targeted organic amendments, especially green manure, can maintain or enhance rice productivity while improving soil fertility and reducing dependence on CF.

Keywords: crop yield; green manuring; integrated nutrient management; nutrient uptake; *Sesbania rostrata*; soil carbon stock; soil fertility

Introduction

Sustainable agriculture is central to achieving the 2030 Agenda for Sustainable Development, particularly the goal of zero hunger. In Asia, rice (*Oryza sativa* L.) serves as a staple food and the need to increase rice production to meet future food demands is critical, as population growth pressures intensify. However, continuous rice cultivation depletes soil fertility, threatening long-term sustainability. The application of soil organic matter (SOM) is a promising approach to maintaining soil fertility, as SOM acts as a nutrient reservoir. In Bangladesh, soils typically contain less than 1.5 % SOM, with many areas reporting levels below 1.0 %, exacerbating soil fertility issues (1). The depletion of SOM is a significant constraint on crop production, reducing yields and agricultural sustainability (2). Intensive cultivation of high-yielding rice varieties, combined with the imbalanced use of chemical fertilisers (CFs), has accelerated soil nutrient depletion. Urea, which supplies nitrogen (N), is the most widely used CF, constituting nearly 70 % of nitrogen applications (3). The misuse of chemical fertilisers has resulted in soil degradation, reduced fertility and environmental pollution, including water and air contamination. Moreover, excessive CF application contributes to greenhouse gas emissions and negatively impacts soil health by reducing microbial activity, leading to a buildup of heavy metals and soil compaction (4). Therefore, improper nutrient management is a significant contributor to the yield gap in rice production.

The high cost of chemical fertilisers, coupled with their environmental drawbacks, has generated interest in using organic fertilisers as alternative nutrient sources. Organic fertilisers, such as cow dung (CD), compost, green manure, poultry manure (PM), farmyard manure (FYM) and vermicompost, offer multiple benefits (3). These organic sources can enhance soil organic matter, improve soil structure and increase nutrient availability over time (5, 6). Unlike CFs, organic amendments release nutrients slowly, promoting long-term soil fertility and reducing environmental damage. A widely recommended solution for sustainable rice production is integrated nutrient management (INM), which combines organic and chemical fertilisers. This approach optimises the benefits of both types of fertilisers: chemical fertilisers provide readily available nutrients, while organic amendments improve soil structure and increase SOM. Green manure, particularly dhaincha (*Sesbania rostrata* Bremek. & Oberm), is commonly used as a nitrogen-fixing plant that is incorporated directly into the soil after cultivation. This green manure supplies essential nutrients like nitrogen, phosphorus and sulfur and improves soil health, enhancing crop yield and soil fertility (7, 8). Green manuring is widely practiced in many rice-growing countries in Asia and has consistently shown positive effects on soil quality and crop productivity (9, 10). Earlier studies focused on the use of green manure mainly to enhance soil organic matter and soil properties (9). However, limited attention has been given to evaluating whether green manure can partially substitute CF without compromising rice yield. This forms the key knowledge gap addressed in our research. Specifically, we investigated whether *S. rostrata* green manure can enable a reduction in CF application while maintaining comparable yields in rice-based systems. Importantly, this experiment was conducted across 4 consecutive cropping seasons to ensure robust and reliable conclusions.

Sustainable agriculture is vital for achieving global food security, particularly in rice-dependent regions like Asia. In Bangladesh, declining soil fertility due to continuous rice cultivation and excessive chemical fertiliser use poses a major threat to long-term productivity. Incorporating organic amendments through integrated nutrient management offers a promising solution to restore soil health and sustain rice yields (11). Researchers reported that a 2.9–18.3 % increase in grain yield for rice grown with a combination of organic and chemical fertilisers compared to CF-only treatments (12). Similarly, others found that applying dhaincha or cow dung in combination with 70 % NPKS fertilisers substantially enhanced grain yield compared to using NPKS fertilisers alone (13). These results suggest that organic amendments can reduce dependence on CFs while maintaining or even increasing crop productivity. The integrated use of inorganic fertilisers with organic sources is essential for ensuring sustainable rice production and soil fertility. This balanced approach addresses the drawbacks of over-reliance on chemical fertilisers, promoting improved soil health and long-term agricultural sustainability. By adopting INM strategies that combine organic amendments with optimal CF doses, rice-dependent regions like Bangladesh can enhance food security while preserving soil quality. Thus, integrating organic and chemical fertilisers is key to achieving sustainable agriculture and meeting future food demands. Based on this gap, we hypothesised that incorporating green manure together with a reduced rate of CF would sustain crop yield while improving soil health. Accordingly, the specific objectives of this study were to: i. evaluate the effects of organic and inorganic fertiliser combinations on crop growth, yield and nutrient uptake and ii. improve soil fertility and crop productivity using organic amendments and green manuring in conjunction with balanced fertiliser management. Therefore, our study provides new insights for Bangladesh and the wider Asian region by moving beyond the traditional concept of green manure as solely a source of soil organic matter. Instead, we propose green manuring as a strategy for optimising fertiliser inputs, simultaneously improving soil quality and sustaining crop productivity.

Materials and Methods

Experimental site

The experiment was conducted at the Soil Science Field Laboratory (24° 71.59’ N latitude and 90° 42.50’ E longitude) of Bangladesh Agricultural University (BAU), Mymensingh. The dominant soil type was non-calcareous floodplain soil under Agro-Ecological Zone (AEZ) 9, known as Old Brahmaputra Floodplain (14). The experimental area belongs to a sub-tropical climate, which is characterised by high temperature, high humidity and high rainfall in the pre-monsoon (April–September) and a scanty rainfall associated with moderately low temperature during winter (October–February). Before experiment set up the soil was collected at 15 cm depth. The soil was silt loam in texture having pH 6.29 and the other initial properties are presented in Table 1.

Table 1. Initial soil properties of the experimental soil

Characteristics	Unit	Value
Bulk density	g cc^{-1}	1.23
pH		6.70
Organic matter	%	1.10
Total N	%	0.09
Olsen P	ppm	4.10
Extractable K	meq 100 g^{-1} soil	0.091
Extractable S	ppm	17.0

Experimental design and crop management

During 2022–2024 a rice-based cropping system (rice-fallow-rice) was practiced in this study. This experiment was started at monsoon season of 2022. Late monsoon to early winter season and mid-winter to pre-monsoon season was occupied by Transplanted Aman (T. Aman) (1st & 3rd crop) and boro rice (2nd & 4th crop) growing seasons, respectively. In the fallow period (at monsoon) dhaincha (*S. rostrata)* was cultivated in the land and incorporated into the soils ~ 15 days before transplanting of T. Aman rice. The experiment was laid out in a randomised complete block design (RCBD) with three replications, the experiment was continued for 2 years. There were seven treatments where T0 had neither chemical or organic nutrient source, T1 was planned by following the farmers’ practice, T2 had full amount of recommended dose (RD) of NPKSZn fertiliser (1) but no organic source and T3, T4, T5 and T6 had FYM, PM, compost and dhaincha, respectively, as organic source with combination of 75 % RD of NPKS chemical fertilisers (Table 2). Manures viz., compost, PM were used in this study. Cow dung was collected from Dairy Farm, PM from Poultry Farm of BAU. Manures at 15 % moisture basis was added to the first crop in each crop cycle. The 2nd crop received only

Table 2. Amount of organic and inorganic sources of nutrients in the different treatments

Treatment	T. Aman						Boro				
	N	P	K	S	Zn	Manure	N	P	K	S	Zn
			(kg ha^{-1})			(t ha^{-1})			(kg ha^{-1})		
T0	0	0	0	0	0	0	0	0	0	0	0
T1	72	12	60	8	1.4		144	21	60	8	1.5
T2	80	15	65	10	1		150	20	65	10	1
T3	54	9	45	6	1.05	5	108	15.75	45	6	1.05
T4	54	9	45	6	1.05	3	108	15.75	45	6	1.05
T5	54	9	45	6	1.05	10	108	15.75	45	6	1.05
T6	54	9	45	6	1.05	Dhaincha	108	15.75	45	6	1.05

T0 = control (fertiliser); T1 = farmers’ practice; T2 = 100 % recommended dose (RD) of chemical N, P, K, S, Zn fertiliser; T3 = 75 % RD of NPKSZn with FYM; T4 = 75 % RD of NPKSZn with PM; T5 = 75 % RD of NPKSZn with compost; T6 = 75 % RD of NPKSZn with green manure.

chemical fertilisers.

The land was prepared by repeated ploughing and cross ploughing (4 times) with a power tiller followed by laddering. Manures were applied to their respective plots before ten days of transplanting. A full amount of P, K, S and Zn fertilisers were applied as basal during final land preparation. Urea was applied in three equal splits at 15 days after transplanting (DAT), 30 DAT and 45 DAT. Forty-days-old seedlings of BRRI dhan29 and 35-days-old seedlings of Binadhan-17 were transplanted in boro and T. Aman rice respectively. Weeding and other management practices were performed as and when required. T. Aman did not need irrigation due to sufficient rainfall but in boro, irrigation was done whenever required.

Crop harvesting and sample preparation

At maturity, the crops were harvested from 1 m^2 area of each plot. The samples were threshed and weighed after air drying for grain and straw yields. Some portions of samples were dried at 65 °C until constant weight and grinded into fine powder by using a ball mill grinder (PM4100) and stored for chemical analysis. Grain and straw yields and plant parameters were recorded. Various growth and yield characters of the crop for each plot were recorded. The characters included plant height (cm), number of tillers plant^{-1}, number of filled and unfilled grains spike^{-1}, panicle height (cm), 1000-grain weight, crop yield (kg m^{-2}; then converted to t ha^{-1}). The plant samples from every plot were chemically analysed for N, P, K and S concentrations.

Soil sample collection

Three soil samples before and after each crop cultivation were randomly collected from each replication sites at a depth of 0–15 cm using an auger and then mixed to get a composite soil sample for chemical analysis of soil properties. The soil samples were air dried at room temperature, grinded and sieved through a 2 mm sieve. Chemical and physical soil analyses were done on the separates pass through 2 mm mesh only. In the second year, before dhaincha cultivation and after boro rice harvest soils from experimental sites were collected by using core sampler to determine bulk densities of the soils.

Chemical analysis

The bulk density of the soil was determined by following the core sampling method (15). The Walkley and Black method was used to determine SOM content of the soils (15). The pH of the soils was determined by glass electrode method. Nitrogen in the digest was estimated by distillation with 10 N NaOH followed by titration of the distillate trapped in H_3BO_3 indicator solution with 0.01 N H_2SO_4 using the Kjeldahl method (16). The P, K and S determination HNO_3-H_2O_2 digestion procedures were followed (17). The K concentration in the acid digest was determined by flame photometer (18). The amount of P in the digest was determined calorimetrically (19) and the S determined turbidimetrically (20).

Calculation

Crop yield was calculated by using the formula at 14 % grain moisture content:

Crop yield (t ha^{-1}) = [Fresh weight (kg) × (100 - % moisture) × 10000] / (100-14) × 1000]

After chemical analysis of soil, grain and straw samples, the nutrient contents were calculated. From the values of nutrient contents nutrient uptakes were calculated by the following formula:

Nutrient uptake (kg ha^{-1}) =[Nutrient content (%) × yield (kg ha^{-1})] / 100

Soil bulk density was determined by using the formula:

Bulk density (kg m^{-3}) = Mass of solid soil (kg)/Volume of total soil (m^3)

Carbon stock and carbon accumulation were calculated using following formula:

Carbon stock (t ha^{-1}) = Carbon concentration (%) × bulk density (kg m^{-3}) × depth (m) × area (m^2)

Carbon accumulation (t ha^{-1}) = Final carbon stock (t ha^{-1}) - Initial carbon stock (t ha^{-1})

Statistical analysis

Data were analysed statistically by analysis of variance (ANOVA). The significance of differences between mean values was evaluated by Duncan's Multiple Range Test. The software package "R", version 3.4.3 was followed for statistical analysis. Where $p<0.05$ was considered as the threshold value for significance.

Results

The experiment was conducted over 2 consecutive years, with T. Aman cultivated as the first crop and boro as the second crop in each year. This results section presents the data on yield and yield-contributing parameters, specifically focusing on the first-year data of T. Aman (2022) and the final-year data of boro rice (2024).

Plant height

In the present study, plant height was significantly influenced by the combined application of organic amendments with 75 % recommended dose (RD) of chemical fertiliser in both T. Aman

Table 3. Effects of chemical fertilisers and organic amendments on yield contributing parameters of Transplanted Aman rice (2022)

Treatments	Plant height (cm)	No. of effective tillers per hill	Panicle length (cm)	No. of grains per panicle	Thousand- grain weight (g)
T0	59.97±2.29c	8.00±0.53b	16.63±0.94b	51.67±3.4c	15.67±0.57b
T1	71.83±2.15b	13.67±0.59a	19.67±0.45a	117.67±4.23b	19.11±0.28a
T2	76.91±1.89ab	14.00±0.13a	20.88±0.39a	116.67±3.51b	19.28±0.35a
T3	80.39±2.28ab	14.33±0.13a	20.89±0.05a	120.00±2.29ab	20.60±0.48a
T4	82.49±1.67a	13.33±1.47a	21.23±0.41a	121.00±2.53ab	19.97±0.21a
T5	79.55±1.92ab	13.67±0.33a	21.13±0.16a	124.33±2.51a	19.67±0.82a
T6	80.39±1.39ab	14.67±0.27a	21.57±0.62a	127.33±1.52a	20.92±1.16a
Level of Significance	*	*	**	**	*

* and ** indicate significant at 5 % and 1 % level of probability, respectively. Mean ± SE with the same letters within the same column do not differ significantly.

Table 4. Effects of chemical fertilisers and organic amendments on yield contributing parameters of boro rice (2024)

Treatments	Plant height (cm)	No. of effective tillers per hill	Panicle length (cm)	No. of grains per panicle	Thousand- grain weight (g)
T0	76.00 ± 4.1b	11.00 ± 0.07b	19.33 ± 0.72b	89.7 ± 2.80b	23.57 ± 0.15a
T1	89.00 ± 2.2a	13.67 ± 0.54ab	21.00 ± 0.44ab	99.0 ± 4.21ab	23.7 ± 0.17a
T2	88.33 ± 0.8a	15.33 ± 0.85a	21.33 ± 0.36ab	103.3 ± 3.25ab	23.6 ± 0.2a
T3	91.00 ± 1.6a	15.67 ± 0.71a	21.33 ± 0.34ab	101.7 ± 3.58ab	24.0 ± 0.5a
T4	90.33 ± 0.8a	14.67 ± 0.53a	21.67 ± 0.17a	106.0 ± 2.22a	23.6 ± 0.26a
T5	90.00 ± 0.1a	14.33 ± 0.66a	20.67 ± 0.26ab	105.0 ± 3.96ab	24.15 ± 0.72a
T6	90.67 ± 1.5a	16.33 ± 0.98a	21.67 ± 0.36a	110.7 ± 2.38a	24.85 ± 0.89a
Level of Significance	**	**	**	*	ns

* and ** indicate significant at 5 % and 1 % level of probability, respectively. Mean ± SE with the same letters within the same column do not differ significantly.

(Table 3) and boro season (Table 4). In T. Aman, the shortest plants (60 cm) were observed in the control (T0), while the tallest plants (82 cm) were found in T4 treatment. Treatments T3, T5 and T6 also resulted in comparatively taller plants. Similarly, in the boro season, plant height was significantly influenced by nutrient management. The values ranged from 76 cm in T0 to 91 cm in T3. The tallest plants were recorded in T3, which was statistically similar to all other treatments except T0. The shortest plants were consistently recorded in control across both seasons, showing the positive impact of integrated nutrient application.

Number of effective tillers per hill

The number of effective tillers per hill showed a significant response to the combined application of organic and inorganic fertilisers. In T. Aman, the lowest number of tillers (8) was observed in the control (T0), while the highest (15) was recorded in T6 (Table 3). Treatments T1 to T5 also produced significantly more tillers compared to the control. Likewise, in the boro season, the number of effective tillers ranged from 11 in T0 to 16 in T6 (Table 4). The treatments T2 to T6 showed statistically similar results, all outperforming T0. These results suggest that the application of organic amendments in combination with reduced chemical fertiliser can match or exceed the performance of full chemical doses.

Panicle length

Panicle length varied significantly among the treatments, except for the control. In T. Aman, panicle length ranged from 17 cm in T0 to 22 cm in T6 (Table 3). Treatments T1 through T5 also resulted in significantly longer panicles compared to T0. In boro rice, panicle length ranged from 19 cm in T0 to 21 cm in T4 and T6, which were statistically identical and significantly longer than the control. The panicle lengths in T1, T2, T3 and T5 were also higher than T0 but not statistically different from each other (Table 4). These results highlight the beneficial role of nutrient combinations in improving panicle development.

Number of grains per panicle

The number of grains per panicle was significantly influenced by the nutrient treatments in both cropping seasons. In T. Aman, the lowest number of grains was recorded in the control treatment T0, while the highest (127) was found in T6 (52) (Table 3). The treatments T4 and T5 also produced significantly higher grain numbers. Similarly, in boro rice, the number of grains per panicle ranged from 90 in T0 to 111 in T6 (Table 4). Treatment T6 was statistically superior to T0 and at par with T4. These findings indicate that integrated nutrient management is effective in enhancing grain settings.

Thousand-grain weight

The 1000-grain weight of rice was significantly affected by nutrient application in T. Aman, while differences in boro rice were statistically non-significant. In T. Aman, grain weight ranged from 15 g in T0 to 21 g in T6, with all treatments involving fertiliser application showing improved weights over the control (Table 3). In boro rice, although the variation was not statistically significant, the grain weight ranged from 24 g in T0 to 25 g in T6. All treated plots had higher values than the control, indicating a consistent positive effect of organic-inorganic combinations even when statistical significance was not observed (Table 4).

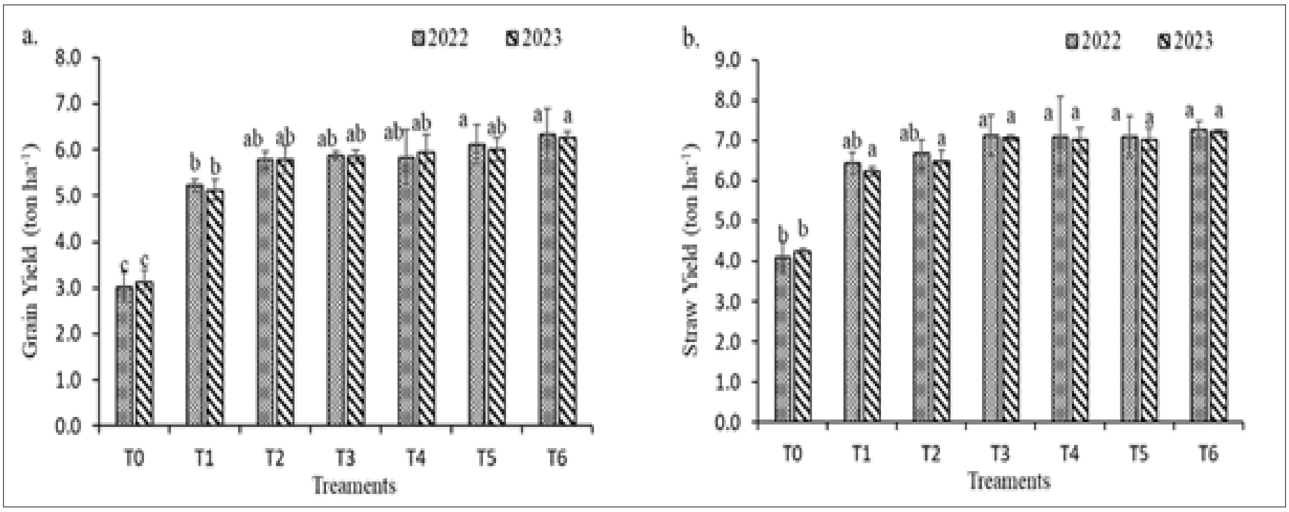

Fig. 1. Two-year mean ± SE (a) grain yield and (b) straw yield of T. Aman rice under different treatments; T1: Farmers' practice, T2: 100 % RFD chemical fertilisers (NPKSZn), T3: 75 % RFD (NPKSZn) + FYM (5 t ha^{-1}), T4: 75 % RFD (NPKSZn) + PM (3 t ha^{-1}), T5: 75 % RFD (NPKSZn) + compost (10 t ha^{-1}), T6: 75 % RFD (NPKSZn) + green manuring (Dhaincha). Bar represents mean ± standard error of mean and with different letters vary significantly (p<0.05) to each other.

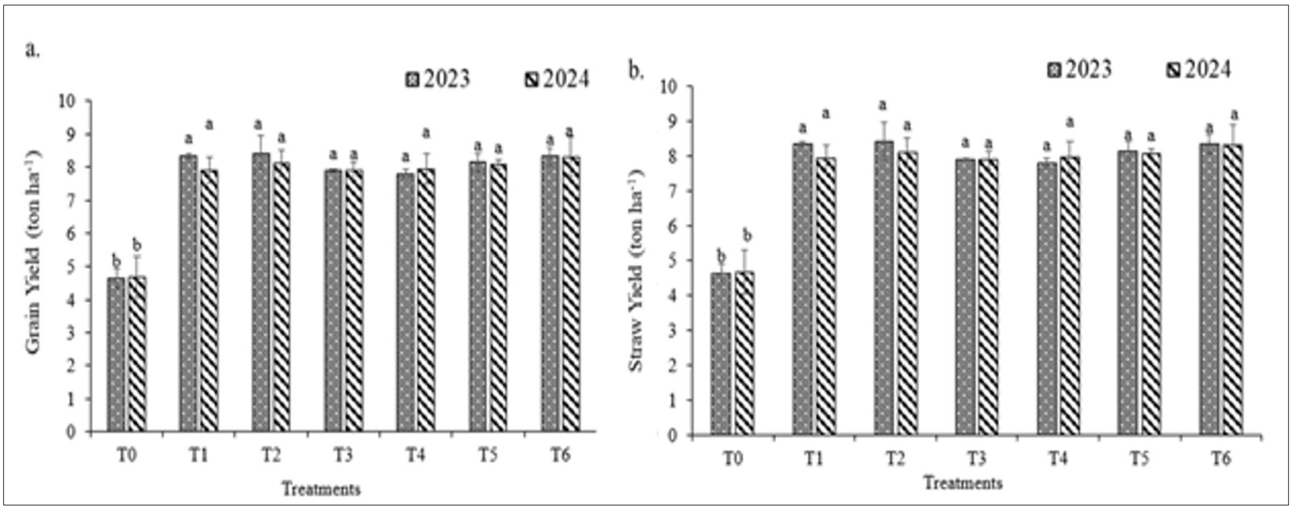

Fig. 2. Two-year mean ± SE (a) grain yield and (b) straw yield of boro rice under different treatments; T1: Farmers' practice, T2: 100 % RFD chemical fertilisers (NPKSZn), T3: 75 % RFD (NPKSZn) + FYM (5 t ha^{-1}), T4: 75 % RFD (NPKSZn) + PM (3 t ha^{-1}), T5: 75 % RFD (NPKSZn) + compost (10 t ha^{-1}), T6: 75 % RFD (NPKSZn) + green manuring (dhaincha). Bar represents mean ± standard error and with different letters vary significantly (p<0.05) to each other.

Crop yield

Grain and straw yields of both T. Aman (Binadhan-17) and boro (BRRI dhan29) rice were significantly influenced by different nutrient management treatments (Fig. 1, 2). The integration of organic amendments with reduced chemical fertiliser application resulted in higher productivity compared to control and conventional treatments. Across both the 2022 and 2023 seasons, every fertilisation regime (T1–T6) markedly outperformed the unfertilised control (T0) in both grain and straw production. In 2022, control plots yielded 3.0 t ha^{-1} of grain, whereas even the farmer's practice (T1) produced about 5.3 t ha^{-1}, a 77 % increase. Grain yields climbed further under the combined 75 % RD + organic treatments (T3–T6), reaching between 5.8 and 6.3 t ha^{-1} (a 93–110 % gain over T0). The green manure treatment (T6) delivered the largest boost, more than doubling control yields (Fig. 1a). In 2023, a similar pattern emerged: control grain yield (≈3.2 t ha^{-1}) rose to ~5.3 t ha^{-1} under T1 (+66 %) and peaked at ~6.3 t ha^{-1} under T6 (+97 %). Straw yields exhibited the same trend (Fig. 1b). In 2022, control plots produced about 4.3 t ha^{-1} of straw, while T1 yielded 6.1 t ha^{-1} (+42 %) and the 75 % + organic treatments ranged from 7.0 to 8.3 t ha^{-1} (a 63–93 % increase over T0). Again, T6 led with the highest biomass. In 2023, straw output rose from 4.4 t ha^{-1} in the control to 6.7 t ha^{-1} under T1 (+52 %) and 8.3 t ha^{-1} under T6 (+88 %). These results demonstrate that substituting a portion of the full chemical recommendation with organic amendments, especially green manure substantially and consistently increases both grain and straw yields, nearly doubling productivity compared to unfertilised soil and outperforming 100 % chemical fertilisation alone. Fig. 2 shows the two-year (2023–2024) response of boro rice to seven fertilisation regimes, expressed as (a) grain yield and (b) straw yield. Under the unfertilised control (T0), grain production was lowest, 4.5 t ha^{-1} in 2023 and 4.8 t ha^{-1} in 2024 (Fig. 2a) and straw yield similarly lagged at about 5.3 and 5.0 t ha^{-1}, respectively (Fig. 2b). In contrast, every fertilised treatment (T1–T6) boosted both grain and biomass substantially. Farmer's practice (T1) raised grain yield to 6.9 t ha^{-1} in 2023 and 7.2 t ha^{-1} in 2024, while straw climbed to 8.7 and 8.2 t ha^{-1}. The T2–T6 all produced grain in the 6.6–7.5 t ha^{-1}range and straw between 8.2–9.4 t ha^{-1}, with only minor year-to-year variation, but did not differ significantly from one another. This consistency across both seasons underscores that partial replacement of CF with organic inputs, whether FYM, PM, compost, or green manure, maintains high and stable rice productivity.

Total nutrient uptake

The uptake of key macronutrients, N, P, K and S by rice grain and straw was significantly influenced by the application of integrated nutrient management practices across both the T. Aman and boro seasons (Table 5). Overall, treatments that combined reduced chemical fertiliser doses with organic inputs substantially enhanced nutrient uptake compared to the control (T0) and farmer's practice (T1). Among the treatments, T6 (75 % of the recommended fertiliser dose, RFD, supplemented with green manuring using *S. rostrata*) consistently produced the highest uptake values for all four nutrients. In T. Aman rice, T6 resulted in the maximum N uptake in grain and straw (92 and 61 kg ha^{-1}, respectively), as well as the highest grain uptake of P (19 kg ha^{-1}), K (21 kg ha^{-1}) and S (6.3 kg ha^{-1}). Similar trends were observed in the boro season, with T6 again achieving the highest grain uptake for N (85.9 kg ha^{-1}), P (23.5 kg ha^{-1}), K (21.9 kg ha^{-1}) and S (21.9 kg ha^{-1}). Straw nutrient uptake also followed a comparable pattern. The T6 recorded the highest values for straw uptake of N (56.2 kg ha^{-1}), K (17.4 kg ha^{-1}) and S (135 and 17.4 kg ha^{-1} for T. Aman and boro, respectively), while P uptake in straw peaked in T3 (FYM-based treatment), suggesting a differential response of P mobilisation to organic amendments.

Post-harvest soil organic carbon and nitrogen

Post-harvest soil analysis revealed that soil organic carbon (SOC) was significantly influenced by integrated nutrient management practices, whereas TN did not vary significantly among treatments (Table 6). The highest SOC contents were recorded in the T4 treatment (75 % RFD + PM), being similar with T6 (75 % RFD + green manuring) in both the T. Aman and boro seasons, with values of 1.37 % and 1.46 %, respectively. In contrast, the lowest SOC values were observed in the control (T0) treatment, with 1.15 % and 1.19 % in the T. Aman and boro seasons, respectively. Treatments involving organic amendments, such as poultry manure (T4), compost (T5) and FYM (T3), also contributed to a marked improvement in SOC compared to chemical fertiliser only and farmer practice treatments (T1 and T2).

Table 5. Integrated effects of nutrient management on N, P, K and S uptake (kg ha^{-1}) in rice

Nutrients	Treatments	T. Aman		Boro	
		Grain	Straw	Grain	Straw
N	T0	26.96 ± 0.58g	25.24 ± 0.02g	31.56 ± 0.01e	23.24 ± 0.00g
	T1	55.69 ± 0.58f	39.63 ± 0.02f	64.1 ± 0.02f	37.53 ± 0.02f
	T2	58.51 ± 0.58e	45.26 ± 0.02e	68.9 ± 0.03e	44.61 ± 0.01e
	T3	82.24 ± 0.57c	47.95 ± 0.03d	77.3 ± 0.04d	46.76 ± 0.03d
	T4	74.51 ± 0.04d	55.70 ± 0.01b	70.99 ± 0.12b	52.97 ± 0.02b
	T5	85.81 ± 0.01b	51.65 ± 0.01c	82.96 ± 0.05c	50.81 ± 0.01c
	T6	92.2 ± 0.13a	92.2 ± 0.13a	85.95 ± 0.48a	56.24 ± 0.03a
Level of significance		**	*	***	*
P	T0	6.17 ± 0.01f	4.85 ± 0.02g	6.38 ± 0.01f	4.56 ± 0.02g
	T1	11.16 ± 0.04e	7.61 ± 0.02e	10.85 ± 0.03e	6.67 ± 0.01e
	T2	12.02 ± 0.02d	7.44 ± 0.01f	12.23 ± 0.02d	8.05 ± 0.01f
	T3	14.17 ± 0.03c	10.05 ± 0.01a	14.38 ± 0.01c	11.32 ± 0.02a
	T4	14.17 ± 0.03c	9.29 ± 0.01d	15.76 ± 0.01c	9.01 ± 0.01d
	T5	15.55 ± 0.06b	9.50 ± 0.01c	17.99 ± 0.00b	9.96 ± 0.01c
	T6	19.41 ± 0.05a	9.72 ± 0.01b	23.52 ± 0.02a	10.58 ± 0.02b
Level of significance		*	*	*	*
K	T0	5.58 ± 0.01g	8.59 ± 0.01g	4.65 ± 0.01f	61.2 ± 0.01g
	T1	13.19 ± 0.01f	13.86 ± 0.01f	6.23 ± 0.01e	101.87 ± 0.04f
	T2	14.87 ± 0.01e	15.24 ± 0.02e	6.98 ± 0.02c	119.78 ± 0.03e
	T3	17.52 ± 0.01c	16.63 ± 0.01c	7.01 ± 0.01c	123.05 ± 0.02c
	T4	16.79 ± 0.01d	17.14 ± 0.01b	6.45 ± 0.03d	126.27 ± 0.01d
	T5	20.23 ± 0.01b	16.34 ± 0.01d	7.31 ± 0.01b	130.03 ± 0.02b
	T6	21.01 ± 0.02a	17.72 ± 0.01a	7.85 ± 0.02a	136.31 ± 0.03a
Level of significance		**	*	*	*
S	T0	3.01 ± 0.01f	59.35 ± 0.01g	4.88 ± 0.01g	8.34 ± 0.00g
	T1	5.23 ± 0.01e	105.94 ± 0.01f	14.77 ± 0.02f	12.39 ± 0.02f
	T2	5.80 ± 0.01c	110.90 ± 0.02e	16.38 ± 0.00e	13.1 ± 0.01e
	T3	5.87 ± 0.02c	119.26 ± 0.02d	16.95 ± 0.01c	15.69 ± 0.00c
	T4	5.54 ± 0.03d	122.63 ± 0.02c	16.85 ± 0.01d	17.35 ± 0.01b
	T5	6.13 ± 0.01b	125.97 ± 0.01b	21.45 ± 0.01b	15.46 ± 0.01d
	T6	6.33 ± 0.01a	135.12 ± 0.01a	21.98 ± 0.02a	17.49 ± 0.01a
Level of significance		**	*	**	*

*, ** and *** indicate significant at 5 %, 1 % and 0.1 % level of probability respectively. Mean ± SE with the same letters within the same column do not differ significantly.

Table 6. Effects of chemical fertilisers and organic amendments on total nitrogen and soil organic carbon of soil

Treatments	Total N (%)		SOC (%)	
	T. Aman	Boro	T. Aman	Boro
T0	0.11	0.12 d	1.15 d	1.19 d
T1	0.11	0.13 c	1.18 c	1.33 c
T2	0.12	0.13 c	1.18 c	1.43 b
T3	0.12	0.14 b	1.36 b	1.36 c
T4	0.12	0.15 a	1.37 a	1.46 a
T5	0.11	0.13 c	1.36 b	1.40 b
T6	0.12	0.15 a	1.37 a	1.42 ab
Level of significance	ns	***	***	***

* and ** indicate significant at 5 % and 1 % level of probability respectively. Mean ± SE with the same letters within the same column do not differ significantly.

Table 7. Effects of chemical fertilisers and organic amendments on soil organic carbon stock in post-harvest soil

Treatments	Initial soil			Final soil			SOC accumulation (t ha^{-1})
	SOC (%)	BD (g cc^{-1})	SOC stock (t ha^{-1})	SOC (%)	BD (g cc^{-1})	SOC stock (t ha^{-1})	
T0	1.18	1.24	21.95	1.19	1.22	21.78	-0.18 ± 0.01d
T1	1.18	1.24	21.95	1.33	1.14	22.74	0.80 ± 0.03c
T2	1.18	1.24	21.95	1.43	1.06	22.73	0.79 ± 0.05c
T3	1.18	1.24	21.95	1.36	1.11	22.64	0.70 ± 0.04 b
T4	1.18	1.24	21.95	1.46	1.09	23.87	1.92 ± 0.02a
T5	1.18	1.24	21.95	1.40	1.13	23.73	1.78 ± 0.6a
T6	1.18	1.24	21.95	1.42	1.15	27.08	2.55 ± 0.9a

Mean ± SE with the same letters within the same column do not differ significantly.

Soil organic carbon stock

The SOC stock in post-harvest soil was significantly affected by the application of integrated nutrient management treatments (Table 7). Treatments that incorporated organic amendments in combination with reduced chemical fertilisers substantially improved SOC stock compared to control and chemical only treatments. The highest SOC accumulation was recorded under the T6 treatment (75 % RFD + green manuring), with an increase of 2.55 t ha^{-1}, followed closely by T5 (75 % RFD + compost), which showed a gain of 1.78 t ha^{-1}. Both values were significantly higher than the control (T0), which experienced a net loss of SOC (–0.18 t ha^{-1}), indicating depletion of soil organic matter under unfertilised conditions. Similarly, T1 (farmers' practice) and T2 (100 % RFD) showed modest gains (0.80 and 0.79 t ha^{-1} respectively), but these increases were substantially lower than those achieved with organic inputs. Notably, T4 (PM) also resulted in a significant increase (1.92 t ha^{-1}), highlighting the efficiency of high-quality organic sources in restoring SOC. These findings emphasise that the integrated application of organic and inorganic nutrient sources; especially green manuring and compost, plays a pivotal role in C sequestration in rice-based cropping systems. Such practices not only enhance soil quality and fertility but also contribute to climate change mitigation through long-term C stabilisation in agricultural soils.

Discussion

Yield response

The grain yield parameter is a valuable tool for judging the combined impact of organic and inorganic fertilisers on rice. The results showed that the combined use of organic and inorganic fertiliser had a beneficial effect on the yield component characteristics such as plant height, panicle length, number of effective tillers hill^{-1}, grains panicle^{-1}, thousands grain weight, grain yield and straw yield of both T. Aman rice and boro rice. In the first crop, the highest values of yield parameters were observed in T6, similarly, in second crop the highest yield parameters were observed in both T4 and T6 treatments. Aligning to the findings, the maximum grain in T. Aman rice was achieved from the application of 70 % NPKS fertilisers +4 t ha^{-1} dhaincha (21). The results also revealed that the grain yield increased by 50 to 52 % over control, depending on the treatments. In comparison to sole fertiliser treatment, integrated use of manure with fertilisers increased grain yields in boro and T. Aman rice by an average of 8.3–33.8 % and 2.9–18.3 %, respectively (12). In line with our results, researchers conducted an experiment and revealed that the highest grain yield during the boro season was obtained by the application of 100 % NPKS, which was statistically equal to the yield produced by the application of 70 % NPKS + PM (6.57 t ha^{-1}) (22). The added organic amendments may supply nutrients to the plants for their growth to maintain proper yield.

In the first crop, the yield was highest in T6, since the incorporated dhaincha easily decomposed and released nutrients, promoting vegetative growth and higher grain production. Nearly 90 % of the organic N in the fresh residue of green manure may be mineralised within one month after incorporation into the soil due to the low C: N ratio in N- fixing plants like dhaincha (23). Green manure manages agricultural pests, lessen erosion, control weeds and provides habitat for beneficial microbes, in addition to enhancing the health and fertility of the soil (24). Poultry manure, compost, FYM, on the other hand, is rich in a variety of nutrients, including N, P and S as well as micronutrients but it is more stable than the fresh green manure. It improves the physical structure of the soil and encourages root growth, which results in higher nutrient uptake and increases rice yield (25). Organic fertilisers release nutrients slowly through microbial mineralisation as opposed to inorganic fertilisers, which ensure nutrient availability in the grain-filling stage of crops and even in the following crop (26). The dhaincha green manure treatment (T6) consistently produced the highest yield parameters in both T. Aman and boro rice, indicating its potential for sustaining productivity across consecutive years. This stability is largely due to the rapid mineralisation of its low C: N residues, releasing up to 90 % of organic N within a month of incorporation, which aligns with peak crop nutrient demands. Beyond immediate yield gains, dhaincha improves soil organic matter, structure and microbial activity, enhancing nutrient cycling and resilience to seasonal variability. By simultaneously supporting high yields and maintaining soil fertility, dhaincha-based integrated nutrient management offers a sustainable alternative to sole chemical fertilisation in rice systems.

Nutrient uptake

Nutrient uptake (N, P, K and S) by the rice grains of Binadhan-17 (T. Aman) and BRRI dhan29 (boro) was significantly influenced by different organic manure and inorganic fertiliser treatments. In both cases the highest nutrient uptake by rice grain was recorded in T6 treatments. The other organic manure (PM, FYM) in combination with 75 % chemical fertiliser also contributed to higher nutrient uptake over T0 (control) and T1 (100 % NPKSZn) treatments. Other researchers also stated that use of green manure along with fertiliser resulted in the highest nutrient (N, P and K) uptake in rice (27). The increase in nutrient uptake might be due to the higher availability of these nutrients through additional supply and prolific root system of green manure crops, resulting in higher absorption of water and nutrients. Mechanistically, the superior performance of the *S. rostrata* (dhaincha) green-manure treatment arises from rapid, well-timed N release from low-C: N residues, additional biological N inputs from stem- and root-nodulated symbioses and cumulative improvements to SOC formation pathways, aggregation and P availability that together enhance nutrient uptake. Dhaincha residues have a low C: N and decompose quickly, synchronising N supply with rice demand during early to mid-tillering thus in first year T6 had higher performance than other treatments. Recent syntheses show that legume green manures typically mineralise most of their N within 2–4 weeks after incorporation as it contributes additional N via biological N fixation, aligning with the crop's first N uptake peak, which improves N use efficiency and yield stability. Beyond N supply, dhaincha drives SOC gains through microbially mediated pathways. Green manuring has been shown to increase SOC over time in paddy systems. Dhaincha also improves phosphorus nutrition, another lever behind greater nutrient uptake by stimulating rhizosphere organic acids and P-solubilising microbes, which mobilise inorganic and organically bound P and increase labile P pools available to rice. Recent studies show green manure additions elevate bioavailable P and microbial P cycling in perennial and paddy systems. Finally, integrating green manure with a reduced CF rate improves N use efficiency and can cut nutrient losses relative to sole CF use (26, 27). When organic and inorganic fertilisers were applied together, nutrient uptake and subsequent utilisation efficiencies appeared better and more satisfying (26, 28). The slow decomposition of organic fertilisers and the prolonged availability of nutrients contribute to the maintenance of the soil's nutritional balance. Many results revealed that organic manure is the source of N, P, K, Ca, Mg and S that can improve the soil fertility status and the grain crops can uptake more of these nutrients (29, 30). Treatments (T3–T5), which involved the application of FYM, PM and compost in combination with 75 % RFD, also significantly improved nutrient uptake over the control and conventional fertiliser application. The enhanced nutrient uptake observed under these treatments may be attributed to improved microbial activity, increased nutrient mineralisation and enhanced synchronisation between nutrient release and plant demand. These findings highlight the efficacy of integrating organic inputs such as green manure or compost with reduced rates of chemical fertilisers in improving the availability and uptake of multiple essential nutrients. Such practices not only enhance nutrient use efficiency but also contribute to sustainable intensification in rice-based cropping systems.

Soil response

Integrated nutrient management exerts multifaceted benefits on soil health, extending beyond mere nutrient supply to encompass structural, chemical and biological enhancements. In the present study, the T6 treatment; comprising combined green manuring and inorganic inputs significantly elevated SOC stocks while simultaneously reducing bulk density, indicative of improved soil aggregation and pore connectivity. These physical improvements likely arise from increased inputs of organic residues through root and litters depositions that stimulate the formation of microbial extracellular polymeric substances (EPS), which act as binding agents for soil particles and enhance soil tilth and water infiltration (31). Contemporary SOM paradigms increasingly recognise the primacy of microbial transformation over the humification of resistant plant materials. Scientists demonstrated that microbial necromass particularly fungal-derived residues, constitutes a dominant fraction of persistent SOM, with stabilisation governed by microbial growth efficiency and substrate quality (32). Complementing this, some researchers underscored that microbial carbon use efficiency (CUE) and matrix stabilisation are foundational to the resilience of SOM pools, leading to the accrual of mineral-associated organic matter (MAOM) that underpins long-term C sequestration (33, 34). The fresh litters of *Sesbania* spp. may undergo rapid decomposition and the MAOM mostly formed from microbial derived necromass, restricting further rapid loss and retained in soil as SOM, therefore, present unevenly within soil layers. The observed decline in bulk density under organic amendments can be mechanistically linked to enhanced aggregate stability and increased pore volume, facilitated by the organic amendments, increased fungal hyphae, resulting from both physical enmeshment by soil microbes and biochemical binding by microbial EPS. Field data revealed that soils receiving organic manure exhibited bulk density reductions up to 15 %, concomitant with SOC increases of 11–80 % in the 0–15 cm depth (35, 36). The spongy nature of organic amendments may decrease the soil bulk density and increased porosity, however, in T0 the bulk density may reduce due to the root deposition in soil in the four cropping seasons over two years. The lower bulk density not only facilitates root proliferation and gas exchange but also augments water-holding capacity, thereby supporting plant growth under variable moisture regimes. Despite these marked SOC gains, total soil N remained statistically unchanged across treatments (0.11–0.12 %), likely reflecting N losses through volatilisation, leaching and denitrification inherent in flooded rice systems (3, 36), as well as transient microbial immobilisation during residue decomposition, however the N uptake was higher in the plots with organic amendments, especially green manure. The bacteria located in the stem of *S. rostrata* and fixes atmospheric N. The litter of the plant mixed with the soil and may be due to low C: N ration they undergo decomposition rapidly and the organic N may convert into different forms of the N and lost into the environment. Therefore, the remaining microbial derived SOM are mostly responsible for forming MAOM, which is quite stable and may not be detected in analysis. Future investigations should quantify microbial biomass C and N, the microbial quotient and enzyme activities (e.g., β-glucosidase, phosphatase) to elucidate the microbial processes driving nutrient dynamics under INM. To advance understanding of INM's role in agroecosystem sustainability, we recommend: (i) integrating metagenomic and functional gene analyses (e.g., nifH, amoA) to link microbial N cycling traits with agronomic performance; (ii) establishing long-term monitoring sites across diverse edaphoclimatic zones to track SOM pool dynamics and crop productivity over successive cropping cycles; (iii) assessing microbial CUE under varying amendment regimes to refine predictions of MAOM formation; (iv) coupling empirical data with process-based models (e.g., DAYCENT, APSIM) to simulate nutrient fluxes, SOM stabilisation and greenhouse gas emissions; and (v) conducting life cycle assessments to quantify the economic and environmental trade-offs of INM versus conventional fertilisation. Collectively, these interdisciplinary and multi-scalar approaches will validate and optimise INM strategies for climate-resilient, sustainable rice production. Integrated nutrient management (INM) with green manure (T6) significantly improved soil health by increasing soil organic carbon (SOC) stocks and reducing bulk density, indicating enhanced aggregation and pore connectivity. These benefits are driven by organic residue inputs from roots and litter, which stimulate microbial extracellular polymeric substance (EPS) production, improving tilth and water infiltration. Modern SOM theory highlights the central role of microbial transformation, with microbial necromass-especially fungal-derived-forming stable MAOM crucial for long-term C sequestration. Rapid decomposition of low C: N *Sesbania* spp. litter contributes to this process. Organic amendments enhanced aggregate stability, fungal growth and porosity, with field data showing up to 15 % bulk density reduction and 11–80 % SOC increases in the topsoil (37). While total soil N remained unchanged due to losses and microbial immobilisation in flooded systems, N uptake was higher in organically amended plots. Sesbania's N-fixing bacteria and rapid litter mineralisation contribute to nutrient supply, though some N is lost (38). Future research should quantify microbial biomass and enzyme activities, apply metagenomics, conduct long-term monitoring, assess microbial carbon use efficiency, model nutrient and SOM dynamics and evaluate life cycle impacts to optimise INM for climate-resilient rice production.

Conclusion

This study demonstrates that integrating green manure with a 25 % reduced rate of currently suggested chemical fertiliser rate can maintain high rice productivity while improving soil health, providing a viable pathway toward more sustainable nutrient management in Bangladesh and similar subtropical rice systems. For farmers, adopting INM-particularly dhaincha-based green manuring-offers a practical strategy to reduce fertiliser dependence, lower input costs and support long-term soil fertility. Future work should examine the economic feasibility of INM at farm scale, quantify long-term SOC stabilisation mechanisms and incorporate microbial and functional genomic analyses to better link soil biological processes with nutrient dynamics and yield stability. Long-term monitoring and modelling efforts (e.g., APSIM, DAYCENT) will further clarify how INM influences SOM pools and greenhouse gas emissions across seasons. These steps will strengthen evidence-based recommendations for climate-resilient rice production and inform policy toward reduced fertiliser use without compromising food security.

Acknowledgements

The authors gratefully acknowledge the partial financial support provided by Bangladesh Agricultural Research System (BAURES) to conduct this research work.

Authors' contributions

TSH, MAH[1] and MH conceived the study and developed the methodology. JF[1], SMJAM, JF[2], IMA, AFJ, TAM and NJM conducted the research and collected the data. JF[1] performed the data analysis. JF[1], TSH and MGK prepared the original draft of the manuscript. JF[1], TSH, MAH[1], MAH[2] and MGK contributed to writing, reviewing and editing the manuscript. TSH, MGK and MAH[1] supervised the study. All authors read and approved the final version of the manuscript [JF[1] –Jannatul Ferdous, JF[2]–Jannatul Fardus, MAH[1] –Md. Anamul Hoque and MAH[2] –Mohammad Anwar Hossain].

Compliance with ethical standards

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

Ethical issues: None

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Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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