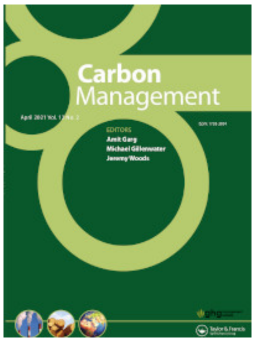

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Impact of varieties and organic nutrient sources on productivity, soil carbon stocks and energetics of rice-ratoon system in Eastern Himalayas of India

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ABSTRACT

Cultivation of rice (*Oryza sativa* L.) varieties having ratooning potential under adequate organic nutrient sources (ONSs) could improve system productivity, soil organic carbon (SOC) stock and energy use efficiency in the eastern Indian Himalayas. A 6-year study was conducted to evaluate the impact of four varieties (Shahsarang-1, Lampnah, IR-64 and Krishna Hamsha) under five ONSs [pig manure (PM), farmyard manure (FYM), vermicompost (VC), *in situ* paddy straw (PS) recycling and farmers' practice] on productivity, soil health and energetics of a rice-ratoon system in a mid-hill (950 m asl) subtropical climate. Organic manures were applied on an N-equivalent basis. The 6-year average grain yield of main rice was significantly highest for Shahsarang-1 (4.40 Mg ha^{-1}) followed by IR-64. Shahsarang-1 (2.58 Mg ha^{-1}) and IR 64 also produced higher ratoon crop yields, leading to higher total annual productivity (main + ratoon crops) than other varieties. Rice grown with PM produced the highest average rice productivity of main crop, followed by FYM. The highest total N, P and K uptake by the rice was obtained under PM followed by FYM. After six cropping cycles, the maximum SOC stock and available N and P were observed under PM, whereas available K was highest under PS recycling. The highest gross energy output, net energy and energy intensity were registered with PM, whereas energy use efficiency and energy productivity were the highest under control. Thus, cultivation of either Shahsarang-1 or IR-64 using PM/FYM is appropriate for enhancing productivity, soil health and conservation of energy in the study region and similar eco-regions elsewhere.

KEYWORDS
Soil carbon; soil fertility; hill ecosystem; energy use efficiency; sustainability

Introduction

Demand for rice (*Oryza sativa* L.) in India is increasing every year. The requirement will about 1121 Tg by 2025 [1], and by 2050 it will be 137.3 Tg [2]. Albeit the use of conventional farming (CF) practices (i.e. synthetic chemical-based agriculture) has increased productivity, it has also undermined some ecosystem services, and has challenged the sustainability of the production system [3]. Consequently, organic farming (OF) is increasingly gaining worldwide acceptance for safe and healthy food production [4,5]. The promotion of environmental, economic and soil sustainability by OF has been reported by many studies [6,7]. At the same time, there is a rise in demand for organic rice, due to increasing awareness and income levels [8,9]. Rice is the principal food crop of the northeastern region (NER) of India (popularly known as the eastern Indian Himalayas) comprising the states of Arunachal Pradesh, Assam, Tripura, Meghalaya, Mizoram, Nagaland, Manipur and Sikkim, spread over a geographical area of about 26.3 M ha. The crop is cultivated in an area of about 3.5 M ha in the NER, with an average productivity of 2 Mg ha^{-1}. The reason for such low productivity is the non-adoption of high-yielding varieties, and poor agronomic practices such as inadequate nutrient management and establishment practices, among many others [10]. The rice-ratoon system (i.e. regrowth from stubble after harvest) has great potential in the hills of NER, as after the harvest of summer/rainy season rice, it is not possible to cultivate a second crop of rice due

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to the early onset of winter, which is detrimental to spikelet fertilization and grain filling [Munda [58]]. Ratooning promotes recycling of biomass (stubble), saves time for nursery management and transplanting, reduces cost of cultivation and may give up to 60% of the grain yield of the main crop of rice [11].

Organic agriculture products are preferred by consumers due to their superior quality and nutrition relative to chemical farming products [8]. The NER of India has numerous advantages for conversion to an organic food production system, such as minimal use of fertilizer (<12 kg ha^{-1}) and agrochemicals, plentiful availability of plant biomass including forest litter and livestock-excreta-based organic manure, and favorable climatic conditions for growing a wide range of crops [9]. The estimated availability of organic manure in the NER is about 8.7 Mg ha^{-1}, which is a feasible quantity to allow the entire NER region to undertake OF [12].

OF seems to be more appropriate than CF for a hill ecosystem as it considers important aspects like sustainability of natural resources, environmental protection and conservation [9]. Organic manures, apart from containing good amounts of major nutrients (NPK), also contain diverse micronutrients, especially boron, copper, iron, sulfur and zinc, and a fair quantity of growth-promoting substances. Crops remove varying amounts of nutrients from soil, and to replace the harvested nutrients, organic amendments rich in nutrients must be added to soil. Rice produced in the NER of India, particularly with an organic tag, has a vast export potential because of its wider acceptability. In India, the area under organic rice is increasing due to increasing health consciousness and also the premium price and growing demand in the international market [10]. Hence, organic rice has a vast potential to achieve premium price and environmental sustainability.

Significant improvements in soil physico-chemical and biological properties have been reported in several OF studies [9,13,14]. OF enables ecosystems to better adjust to the effects of climatic variability and change, and also improve soil properties [9]. These studies indicated that under unfavorable conditions like drought, crops grown under OF systems perform better than those grown under CF [15].While there are a few reports that OF systems are less profitable than those under CF, higher profitability from OF is also reported by many researchers [Das [74]] [16]. Higher levels of soil organic carbon (SOC), available nitrogen (N), soluble phosphorus (P) and microbial activity have been reported from soils managed with OF than from those under CF [9]. In comparison to CF, OF has potential benefits in enhancing soil structure and biodiversity, and protecting th environment and improving soil quality [9,17], food quality and safety [9] while also procuring a premium price [18]. Increases in crop yields under OF during the first few years have been attributed to gradual improvements in soil properties, such as the capacity of the soil microbial community to mineralize nutrients [19]. Thus, OF has the potential to attain sustainability of agricultural production systems [20–22]. The application of mineral fertilizer is costly, especially for small and marginal farmers, and gradually leads to environmental degradation. Hence, organic residue and manure recycling is becoming an increasingly important aspect of environmentally sound, sustainable production systems [23]. There is an ongoing search for agronomic improvements to optimize farming systems under various organic management plans, and suitable plant types are needed to realize their potential [24]. Despite the potential benefits of OF in terms of better soil health and quality of produce, maintenance of high yields is one of the major challenges [3]. Identification of suitable cultivars responsive to OF, along with adequate nutrient management, is the key to realizing the potential of farming in any agro-ecosystem. Modern cultivars have been mostly selected by plant breeders under CF systems and they may not perform well under OF systems where they are grown in a stressed environment without the addition of external inputs, which is entirely different from the environment in which they were selected [25]. Similarly, not all sources of organic manure may produce similar results in terms of agronomic productivity, soil health, economics, energy use efficiency, etc. This is mainly due to varying rates of decomposition of biomass, nutrient concentrations, availability, cost, etc. under site-specific conditions.

The decomposition and mineralization of SOM is influenced by many factors, including chemical composition and the molecular structure of organic matter (OM), or the biomass such as the C:N ratio [26], the physical protection of OM within soil aggregates [27] and the soil biological activity [28]. Considering the fact that accumulation/mineralization of SOM is a slow process [29], the relative importance of organic amendments for SOC build-up should be evaluated in long-term

Table 1. **NPK and micronutrient concentration in different organic sources.**

Organic sources	Carbon content (%)	N (%)	P_2O_5 (%)	K_2O (%)	Fe (ppm)	Cu (ppm)	Zn (ppm)	Mn (ppm)
Farmyard manure	17.3 ± 1.90	0.72 ± 0.11	0.29 ± 0.05	0.61 ± 0.04	3250 ± 17.5	57 ± 6.90	315 ± 7.16	281 ± 9.25
Vermicompost	11.6 ± 1.70	0.90 ± 0.17	0.38 ± 0.04	0.70 ± 0.08	8618 ± 35.6	61 ± 7.10	328 ± 9.62	345 ± 9.86
Pig manure	9.92 ± 0.93	0.93 ± 0.18	0.34 ± 0.04	0.63 ± 0.04	1657 ± 53.6	49 ± 5.10	420 ± 79.5	98.7 ± 8.73
Paddy straw	51.72 ± 5.67	0.75 ± 0.10	0.23 ±	0.66 ± 0.04				
Rock Phosphate		–	18.0	–	–	–	–	–

Note: ± indicates standard deviation from the mean.

experiments. Hence, there is an urgent need to identify efficient varieties and organic nutrient-supplying sources for improving productivity, soil health and efficient energy management in the NER region. Therefore, the present study was planned to test the hypothesis that the cultivation of rice varieties having ratooning potential under organic nutrient management could increase the productivity, soil health, carbon stock and energy efficiency relative to that of single rice cropping under farmers' usual management practice. The specific objectives of the study were to identify suitable rice varieties for ratooning to enhance system productivity, and to assess the impact of organic sources of nutrients and the rice-ratoon system on soil properties, SOC stock and energy use efficiencies.

Materials and methods

Experimental details

A field experiment under an OF production system was conducted at the lowland Agronomy Farm of ICAR Research Complex for NEH Region, Umiam, Meghalaya, India (25°30′N latitude, 91°51′E longitude and 950 m asl) during early *kharif* (May to October) and the winter season (November to the first fortnight of January) from 2007 to 2013. Soil samples were collected from the 0–15 cm layer before initiation of the study. The soil of the experimental field was a sandy loam in texture and had low pH (5.1), high SOC (19.8 g kg^{-1}), low available N (195 kg ha^{-1}) and P (4.4 kg ha^{-1}) and moderate K (240 kg ha^{-1}). The experimental site (Umiam) is under a subtropical climate. The 6-year mean minimum and maximum temperature ranged from 9.2 to 20.4 °C and from 24.1 to 29.1 °C, respectively, with a mean total rainfall of 1695 mm during the cropping season. The rainfall temperature patterns during the study period are presented in Supplementary Figures S1–S3.

The experiment was laid out in a split plot design. The five organic nutrient sources (ONSs), laid out in the main plots, were farmyard manure (FYM), vermicompost (VC), pig manure (PM), paddy straw (PS) and control. Four rice varieties (vars.) were laid out in subplots: IR-64, Shahsarang-1, Lampnah and K. Hamsha. The average nutrient concentrations in the different ONSs used in the study are presented in Table 1.

Organic manures were applied on an N-equivalent basis, and P requirement was supplemented through input of rock phosphate. The state-recommended amounts of N, P_2O_5 and K_2O for rice are 80:60:40 kg ha^{-1}. All treatment combinations were replicated thrice. Three 30-day-old seedlings were transplanted per hill at a spacing of 20 × 15 cm. Well-decomposed FYM, VC and PM, along with the rock phosphate, were applied about 15 days prior to transplanting and mixed with the soil during field preparation. The PS was applied 1 month before the field preparation and was also incorporated into the soil. No fertilizer or manure was applied in the control plot. The main rice crop was transplanted (25-day-old seedlings, 2–3 seedlings $hill^{-1}$ and 20 × 15 cm spacing) during the first fortnight of May and harvested during the end of September, and stubble was managed to obtain a ratoon crop to increase system productivity. For ratooning, harvesting of the main rice (early-*kharif*) crop was done at about 10 cm above ground level, leaving at least one active node intact. Only 50% of the nutrients applied to the main crop (i.e. 40 kg N and 30 kg P_2O_5 ha^{-1}) were supplied to the ratoon crop through the respective ONSs during weeding, and the ratoon rice crop was harvested in mid-December.

Pest management

Weeds in rice were managed by two hand weedings at 25 and 50 days after transplanting (DAT), and one mechanical weeding with a rotary-weeder (cono-weeder) at 40 DAT. For the ratoon crop only one hand weeding was carried out, within a week after the main rice crop harvest. Soil-borne pathogens and insect pests were managed by applying neem (*Azadirachta indica*) cake at 150 kg ha^{-1} with the last plowing every year and mixed into the soil. Neem oil at 3 mL L^{-1} (a product of neem) and Derisom 2.5 mL L^{-1} (a product of *Deris indica*) of water were also sprayed at the flowering stage and again 15 days after the first spray as a preventive measurefor control of insect pests and diseases.

Plant sampling

Panicles in 1 m^2 were counted to determine the number of panicles m^{-2}. Plants were separated into straw and panicles, and the latter were threshed manually. Grain and straw yields were determined on the basis of the net plot area within each plot, and grain yield was reported at 14% moisture content. The weight of 1000 grains for each treatment was also recorded. Production efficiency and harvest index (HI) were calculated using the following equations:

$$\text{Productivity efficiency}\ \left(\text{kg ha}^{-1}\text{day}^{-1}\right) = \frac{\text{Grain yield}\ \left(\text{kg ha}^{-1}\right)}{\text{Total duration of the crop (in days)}}$$

$$\text{Harvest Index (HI)} = \frac{\text{Grain yield}}{\text{Biological (Grain + straw) yield}}\ \text{x}\ 100$$

Plant analysis

Plant samples were obtained at harvest and oven dried at 72 °C for 48 h, then ground and sieved through a 20 mm mesh sieve. Total N content was determined using the Kjeldahl method [30]. Determination of the P and K contents was also made from the finely ground plant samples which were digested in diacid (nitric acid + perchloric acid). Total P content was determined by the vanadate-molybdate method [31]. The K content in the nitric perchloric acid digestate of the sample was estimated using a flame photometer (Corning Limited, Nalstead, England) with a K filter [32]. Nutrient uptake by the crop (grain + straw) was estimated by multiplying the N, P and K concentration of the economic parts and straw/stover with their respective yield in kg ha^{-1} and summing the two values.

Soil analysis

Soil samples (one sample from each plot) were collected using a soil auger at 0–15 cm and 15–30 cm soil depth after six cropping cycles, in January 2013. A composite soil sample was also obtained prior to establishment of the experiment in 2007. Samples were air dried in the shade, gently ground, sieved through 2 mm mesh and analyzed for soil physical and chemical properties. Soil texture was determined by the hydrometric method [33]. The soil pH was determined by the glass electrode method [34], and the SOC concentration was determined by Walkley and Black method [35]. Soil available N was determined by the alkaline potassium permanganate method [36], P by the Bray and Kurtz No. 1 method [31] and K by the ammonium acetate method [37]. The soil microbial biomass carbon (SMBC) was determined by the ethanol-free chloroform fumigation extraction method (38) using a constant (Kc) value of 0.45 [39]. Soil dehydrogenase enzyme activity (DHA) was estimated using the procedure given by Tabatabai [40], by reducing 2, 3, 5-triphenyl tetrazolium chloride [41].

Soil bulk density (ρ_b) was determined from core samples (5.8 cm diameter and 5.4 cm length) obtained from the 0–15 cm and 15–30 cm soil layers using a manually driven core sampler [42]. The SOC stock was calculated using ρ_b as follows [43]:

$$\begin{aligned}\text{SOC stock}\ \left(\text{Mg ha}^{-1}\right) &= \text{SOC concentration}\ (\%)\\ &\quad \text{x}\ 10^{-2}\text{x bulk density}\ \left(\text{Mg m}^{-3}\right)\\ &\quad \text{x depth (m) x}\ 10^4\text{m}^2\text{ha}^{-1}\end{aligned}$$

Economics

The gross returns were considered the total income from the produce of grain and straw yield based on prevailing price. Net return, benefit–cost ratio and economic efficiency were calculated with the use of the following equations:

$$\begin{aligned}\text{Net return}\ \left(\text{ha}^{-1}\right) &= \text{Gross return}\ \left(\text{ha}^{-1}\right)\\ &\quad -\text{cost of cultivation}\ \left(\text{ha}^{-1}\right)\end{aligned}$$

$$\text{Benefit cost ratio} = \text{Gross return}\ \left(\frac{\text{ha}^{-1})}{\text{Cost of cultivation}\ \left(\text{ha}^{-1}\right)}\right.$$

$$\text{Economic efficiency}\ \left(\text{ha}^{-1}\text{day}^{-1}\right) = \text{Net return}\ \left(\frac{\text{ha}^{-1})}{\text{Total duration of the crop (in days)}}\right.$$

Energetics

Energy input and output were calculated by converting all inputs (i.e. labor, seeds, organic manures, bio-pesticides) and outputs (i.e. grain, straw) into energy units (MJ) [44,45], as indicated in Table 2. Energy equivalents for all inputs were summed to provide an estimate of the total energy input. Biomass was computed as the sum of the yield of

Table 2. Energy equivalents of inputs and outputs in agricultural production.

Particulars	Equivalent energy (MJ unit^{-1})	Particulars	Equivalent energy (MJ unit^{-1})
Inputs		Pesticides (neem oil), L	120
Adult man (man-h)	1.96	Chemicals requiring dilution at the time of application, kg	120
Woman (man-h)	1.57	Chemicals not requiring dilution at the time of application, kg	10
Farmyard manure (kg)	0.3	Outputs	
Vermicompost (kg)	0.5	Rice grain, kg	14.7
Pig manure (kg)	0.7	Rice straw, kg	12.5
Rice seed (kg)	14.7		

Source: Devasenapathy et al. [44]; Tuti et al. [45].

Table 3. Yield attributes of main rice (rainy season) as influenced by varieties and organic nutrient sources (average of 6 years).

Varieties	Panicle m^{-2}	Panicle length (cm)	Panicle weight (g)	Grains filling %	Grain per panicle	Test weight (g)	Maturity (in days)	Dry matter hill^{-1}
IR-64	193.1	19.8	4.18	82.32	168.27	29.60	145.47	49.66
Shahsarang-1	180.6	20.6	4.34	83.56	177.89	29.65	154.27	51.47
Lampnah	177.9	20.3	4.24	82.17	175.59	29.76	151.60	52.54
K.Hamsa	193.8	20.5	4.16	81.18	171.85	28.53	149.60	49.49
SEM (+)	4.3	0.27	0.02	0.45	1.10	0.35	0.44	0.90
LSD ($p = 0.05$)	12.4	0.67	0.067	1.32	3.22	1.04	1.27	2.64
Organic nutrient sources								
Farmyard manure	188.6	20.88	4.34	82.43	179.63	29.62	151.17	54.63
Vermicompost	185.7	20.35	4.29	82.25	173.65	29.24	150.25	51.67
Pig manure	191.4	20.73	4.44	84.48	183.18	29.86	148.92	57.96
Paddy straw	186.2	20.52	4.19	81.90	169.98	29.58	149.50	48.16
Control	179.8	19.22	3.87	80.48	160.58	28.64	151.33	41.53
SEM (+)	3.2	0.23	0.056	0.33	0.91	0.23	0.28	0.91
LSD ($p = 0.05$)	10.5	0.78	0.016	1.15	3.15	0.80	0.97	3.15

LSD: Least significant difference; NS: Not significant; SEM: Standard error of mean.

grain and by-products (straw/leaves/stalk). Energy output from the product (grain) was calculated by multiplying the production amount and its corresponding energy equivalent. Energy outputs from by-product were estimated by multiplying the amount of by-product and its corresponding energy equivalent.

The net energy return was computed as the difference between the gross output energy produced and the total energy required to obtain it (input energy). The following equations were used to compute the energy parameters [[46]:

$$\text{Net Energy} = \text{Energy output}\left(\text{MJ ha}^{-1}\right) - \text{Energy input}\left(\text{MJ ha}^{-1}\right)$$

$$\text{Energy profitability (PE)} = \frac{\text{Net energy return}\left(\text{MJ ha}^{-1}\right)}{\text{Input energy}\left(\text{MJ ha}^{-1}\right)}$$

$$\text{Energy profitability (EP)} = \frac{\text{Crop economic yield}\left(\text{kg ha}^{-1}\right)}{\text{Energy input}\left(\text{MJ ha}^{-1}\right)}$$

$$\text{Energy use efficiency (EUE)} = \frac{\text{Energy output}\left(\text{MJ ha}^{-1}\right)}{\text{Energy input}\left(\text{MJ ha}^{-1}\right)}$$

$$\text{Energy intensiveness}\left(\text{MJha}^{-1}\right) = \text{Energy input}\left(\text{MJha}^{-1}\right)/\text{Cost of cultivation}\left(\$\text{ha}^{-1}\right)$$

$$\text{Energy intensity in physical term}\left(\text{MJ kg}^{-1}\right) = \frac{\text{Total input}\left(\text{MJ ha}^{-1}\right)}{\text{Total output (grain + straw)}\left(\text{kg ha}^{-1}\right)}$$

$$\text{Energy intensity in economic term}\left(\text{MJ Rs}^{-1}\right) = \frac{\text{Gross energy output}\left(\text{MJ ha}^{-1}\right)}{\text{Cost of cultivation}\left(\$\ \text{ha}^{-1}\right)}$$

Carbohydrate equivalent and carbon output

The economic yield of rice was converted into the equivalent value of carbohydrate (kg ha^{-1}) as per the procedure suggested by Gopalan *et al.* [47]. Carbon output was calculated based on plant biomass production under different sequences and considering an average 44% carbon content in biomass [48].

Statistical analysis

The experimental data pertaining to each parameter of study over the 6 years were pooled and statistically analyzed using analysis of variance (ANOVA), and their significance was tested by "F" test [49]. The significance of the treatments was evaluated using the *t*-test. The standard error of the mean (± SEM) and critical difference (CD) at 5% probability ($p = 0.05$) were worked out for each character studied to evaluate differences between treatment means. Differences between treatment means that were higher than their respective CD values were considered significantly different.

Table 4. Grain yield (Mg ha^{-1}) of main rice (rainy season) as influenced by varieties and organic nutrient sources.

Varieties	2007–2008	2008–2009	2009–2010	2010–2011	2011–2012	2012–2013	Mean
IR-64	4.32	4.12	4.36	4.20	4.03	4.35	4.23
Shahsarang-1	4.51	4.23	4.58	4.33	4.16	4.56	4.40
Lampnah	4.20	4.19	4.06	4.24	4.13	4.41	4.21
K.Hamsa	4.00	3.96	3.86	3.76	3.94	3.86	3.90
SEM (+)	0.03	0.02	0.01	0.01	0.04	0.05	0.02
LSD ($p = 0.05$)	0.08	0.06	0.04	0.04	0.11	0.12	0.07
Organic nutrient sources							
Farmyard manure	4.50	4.38	4.63	4.27	4.33	4.55	4.44
Vermicompost	4.26	4.15	4.32	4.12	4.17	4.39	4.24
Pig manure	4.67	4.49	4.71	4.47	4.40	4.69	4.57
Paddy straw	4.25	4.09	4.03	4.18	4.24	4.36	4.19
Control	3.57	3.54	3.42	3.60	3.19	3.49	3.47
SEM (+)	0.04	0.03	0.05	0.02	0.04	0.05	0.03
LSD ($p = 0.05$)	0.11	0.09	0.15	0.06	0.14	0.14	0.10

LSD: Least significant difference; NS: Not significant; SEM: Standard error of mean.

Results

Yield attributes

Pooled data for the 6 years with respect to growth and yield attributes (Table 3) of rice indicated that the variety Shahsarang-1 produced by far the tallest plant (51.7 cm) and greatest panicle length (20.7 cm) relative to the other treatments. The test weight was higher for Lampnah (29.8 g) and panicle m^{-2} was higher for K. Hamsha (193.8) compared to the other varieties. Among ONSs, the maximum plant height (51.5 cm), panicle m^{-2} (191.4), panicle length (20.7 cm) and test weight (29.9 g) were observed under PM compared to those for other nutrient sources. The growth and yield attributes of rice under FYM, VC and in situ recycling of PS were on par with each other and remained significantly superior to those for the control.

Grain yield

The pooled average grain yield (6 years) of rice was significantly higher with var. Shahsarang-1 (4.40 Mg ha^{-1}) than those for the other treatments (Table 4). The productivities of var. Lampnah and IR-64 were on par with each other, but were significantly higher than that of var. K. Hamsha. Among the ONSs, PM was the most efficient in terms of higher average productivity, followed by FYM. On average, rice productivity under PM, FYM, VC and PS was 30.8, 28.0, 22.2 and 20.7% higher, respectively, than that for the control.

Straw yield and harvest index

The straw yields were significantly higher in var. Lampnah, followed by Shahsarang-1, compared to other varieties in all 6 years of the study. The average straw yield over the 6 years was also the maximum with Lampnah (6.15 Mg ha^{-1}) followed by Shahsarang-1 (5.7 Mg ha^{-1}). The straw yield of Lampnah was 19, 14 and 7% higher than that for K. Hamsha, IR-64 and Sahsarang-1, respectively. Among ONS treatments, the maximum rice straw yield was recorded for PM, followed by FYM and VC (Figure 1). The percentage increase in straw yield under PM, FYM, VC and PS was 17.7, 15.3, 12.5 and 11.10%, respectively, over the control. HI was the maximum for IR 64, followed by Shahsarang-1. Among ONSs, HI was the maximum for FYM followed by PM (Figure 2).

Rice-ratoon yields and total system yields

Rice-ratoon yield data was recorded only for the two consecutive years of 2009–2010 and 2010–2011. The pooled data for the 2 years (Figure 3) revealed that the maximum ratoon crop yield (2.6 Mg ha^{-1}) was obtained with Shahsarang-1 compared to the other varieties. The percentage share of the ratoon crop yield relative to their main crop yields were 36.6, 36.5, 35.8 and 31.7% for vars. Shahsarang-1, IR-64, Lampnah and K. Hamsha, respectively. Total system productivity was the highest for Shahsarang-1 and its ratoon, followed by IR 64 and Lampnah and their ratoon crops. Among ONSs, the maximum ratoon yield was recorded under FYM (2.7 Mg ha^{-1}) and PM (2.7 Mg ha^{-1}). These two ONSs also yielded higher total system productivity than that obtained with other sources.

Nutrient uptake

The average nutrient uptake data over 6 years revealed that among the four varieties, Lampnah had significantly higher total N, P and K uptake, followed by Shahsarang-1 (Figure 4). However, the total uptake levels by Lampnah and Shahsarang-1 were on par with each other. Total uptake of N and K was 17.3% and 15.0% higher, respectively, with Lampnah/Shahsarang-1 than Krishna Hamsha. P uptake was 25.6% higher for Sahsarang-1

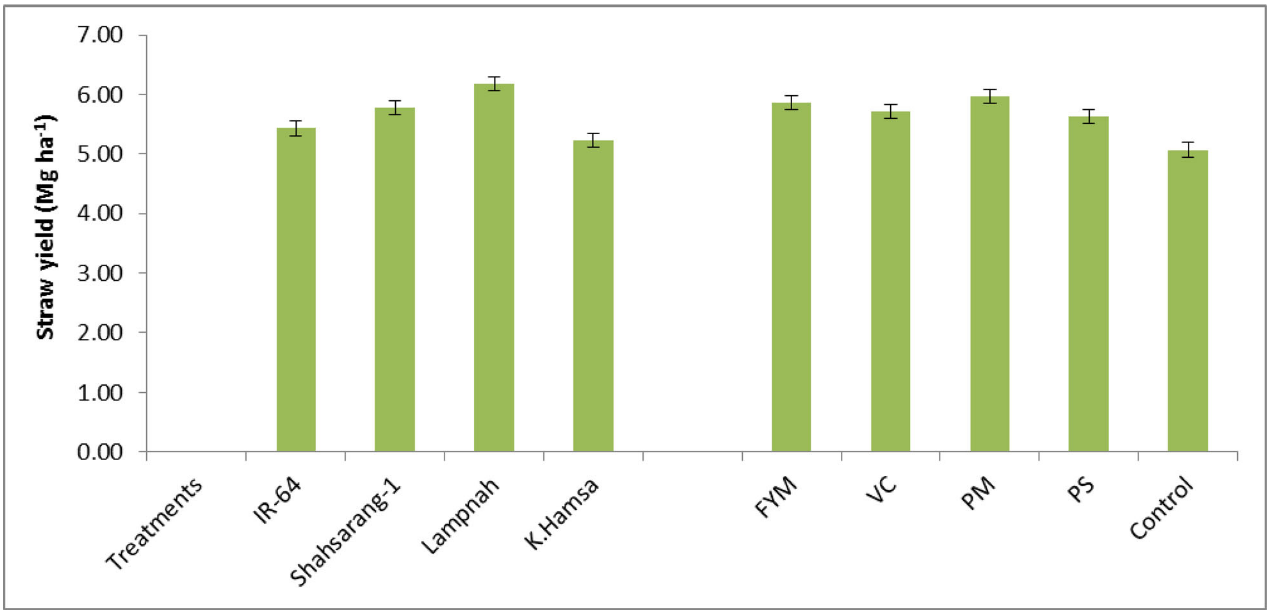

Figure 1. **Rice straw yield as influenced by varieties and organic nutrient management sources (vertical bars represent least significant difference at $p = 0.05$).**

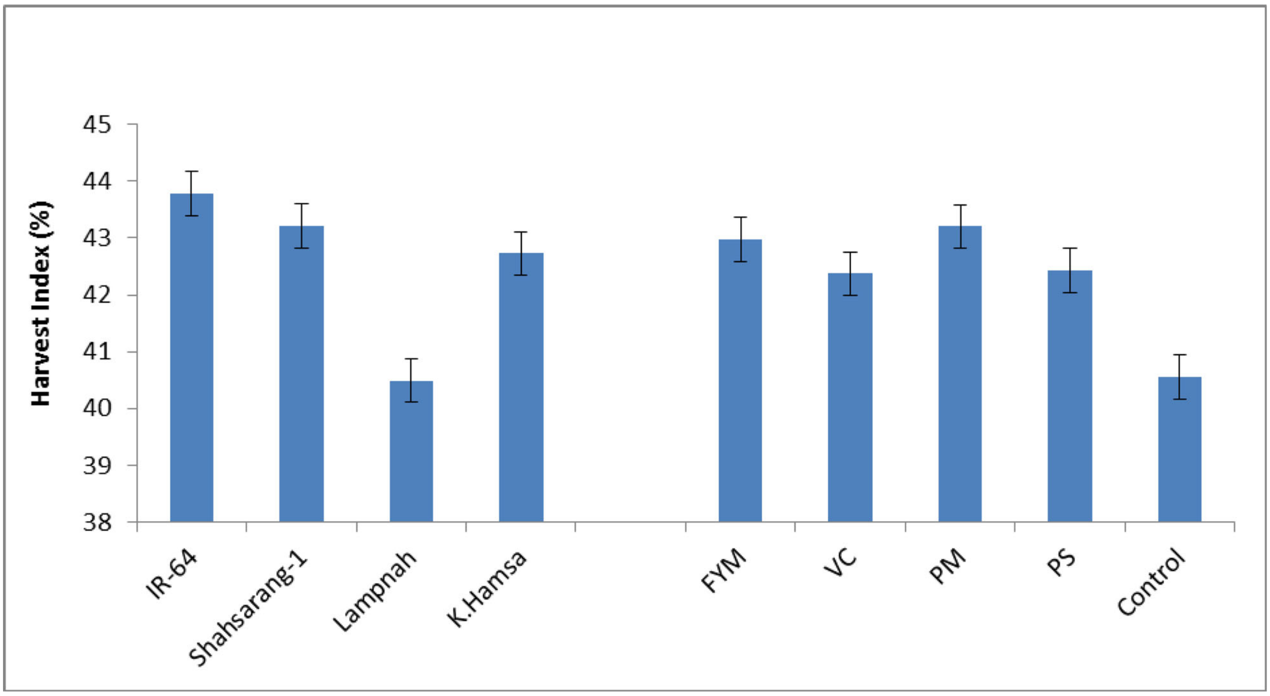

Figure 2. **Harvest index of rice as influenced by varieties and organic nutrient management sources (vertical bars represent least significant difference at $p = 0.05$).**

compared to K. Hamsha. Among ONSs, the highest total N, P and K uptake was recorded with PM followed by FYM. However, P uptake levels under FYM and PM were on par with each other. The total N, P and K uptake was 38.8, 46, 38% and 33.4, 68.6 and 32.7% higher under PM and FYM, respectively, compared to the control.

Soil fertility

After six cropping cycles, significantly higher available N (256.7 kg ha^{-1}) and P (24.6 kg ha^{-1}) were observed under PM compared to other ONSs (Table 5). Available K was higher under PS than under the other sources. On average, application of PM increased available N and P by 24.7, 9.42 and 26.7%, respectively, over the control after 6 years. Available K in soil under PS was 8.1% higher than that in the control soil. The maximum SMBC (372.7 μg g^{-1} dry soil) and DHA (12.7 μg g^{-1} dry soil) were observed under FYM followed by VC (μg g^{-1} dry soil and μg g^{-1} dry soil, respectively). These two sources had significantly higher SMBC than that for all other ONS. The DHA values under FYM and VC were significantly higher than for the control and PS, but remained on par with that for the PM.

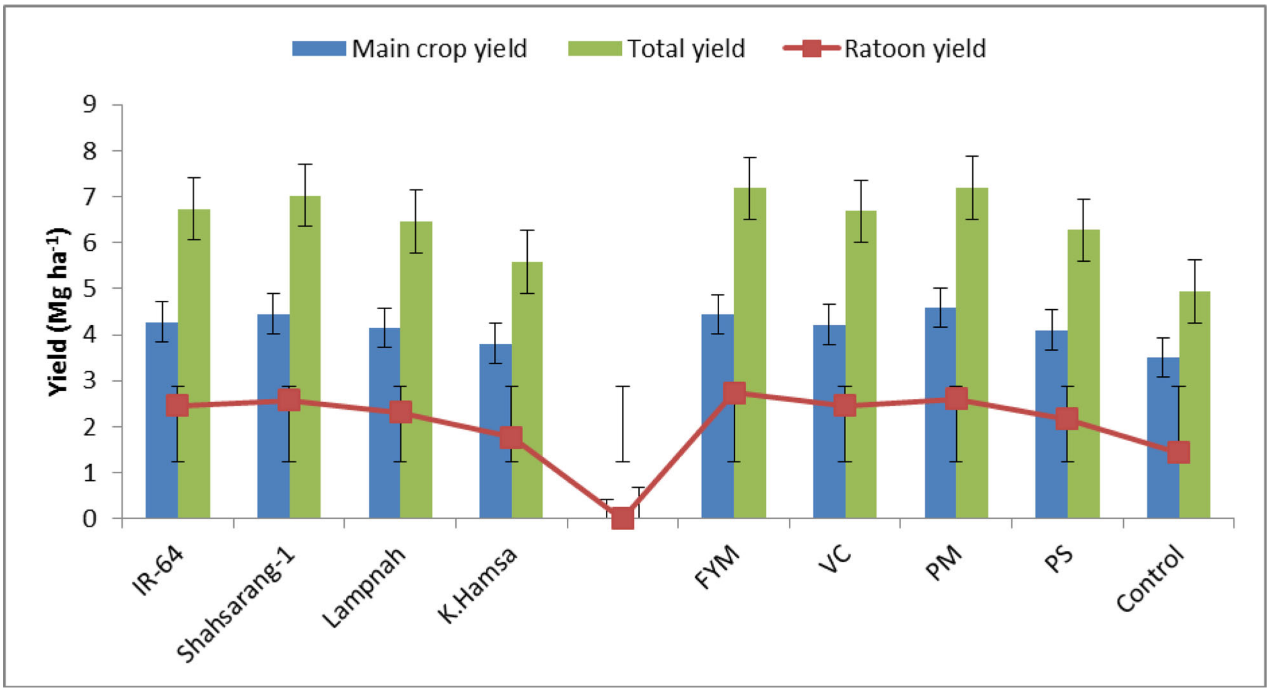

Figure 3. Rice main crop, ratoon, and total yields as influenced by varieties and organic nutrient sources (2-year average; vertical bars represent least significant difference at $p = 0.05$).

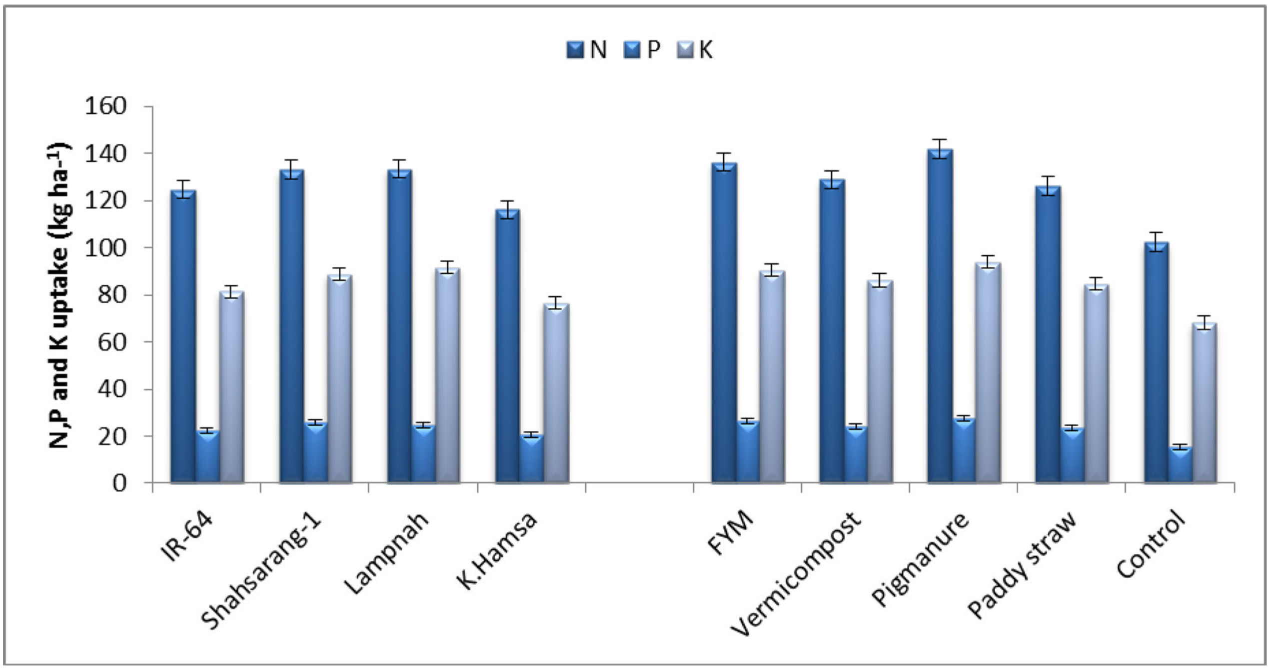

Figure 4. Effect of rice varieties and nutrient sources on nutrient uptake by rice (pooled over 6 years; vertical bars represent least significant difference at $p = 0.05$).

The impact of the different varieties on available K was significant after six cropping cycles (Table 5). Available K under IR-64 was significantly higher than that under Lampnah. The other varieties were similar to each other in terms of available K.

Soil C stock

After six cropping cycles, the SOC concentration was the highest in soil under PM (24.0 g kg^{-1}) followed by FYM (23.7 g kg^{-1}) (Table 6). In the 0–15 cm soil layer, soil ρ_b was significantly lower in plots treated with FYM and PM (1.24 Mg m^{-3}) compared to the control. Soil ρ_b under FYM, PM and VC was lower by 3.9, 3.9 and 3.1%, respectively, relative to the initial value after 6 years. Similarly, at 15–30 cm depth, ρ_b under FYM and PM remained lower than in other ONSs and the control. The SOC stock after 6 years ranged from 42.7 to 44.3 Mg ha^{-1} at 0–15 cm and from 42.41 to

Table 5. Soil parameters as influenced by rice varieties and organic nutrient sources after six cropping cycles (0–15 cm).

Treatments	Available soil nutrient status (kg ha^{-1})			SMBC (μg g^{-1} dry soil)	DHA (μg g^{-1} dry soil)
Varieties	N	P	K		
IR-64	248.4	23.1	236.9	288.1	12.15
Shasarang-1	245.2	21.7	234.6	285.5	11.22
Lampnah	244.2	20.9	233.3	283.4	10.86
Krishna Hamsha	247.8	22.3	235.8	286.5	11.53
SEM (±)	1.22	0.79	0.97	1.28	0.40
LSD ($p = 0.05$)	3.56	NS	2.83	NS	NS
Organic nutrient sources					
Farmyard manure	253.4	23.8	243.9	322.7	12.68
Vermicompost	243.4	23.3	232.9	316.9	12.44
Pig manure	256.7	24.6	244.0	302.2	11.81
Paddy straw	242.1	23.2	249.0	305.6	10.91
Control	236.2	15.1	206.6	281.9	9.36
SEM (±)	0.73	0.63	1.10	0.87	0.28
LSD ($p = 0.05$)	2.54	2.20	3.82	3.01	0.98
Initial	234.6	19.38	230.5	265.85	8.35

DHA: Dehydrogenase; LSD: Least significant difference; NS: Not significant; SEM: Standard error of mean; SMBC: Soil microbial biomass carbon.

Table 6. Soil parameters as influenced by rice varieties and organic nutrient sources after six cropping cycles.

Treatments	SOC (g kg^{-1})		Pb (Mg m$^{-3)}$		SOC stock (Mg ha^{-1})	
Varieties	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
IR-64	23.4	21.34	1.25	1.34	43.87	42.89
Shasarang-1	23.2	21.03	1.28	1.36	43.84	42.90
Lampnah	22.5	20.74	1.28	1.37	43.20	42.62
Krishna Hamsha	22.8	20.98	1.26	1.34	43.10	42.17
SEM (±)	1.1	0.98	0.011	0.01	0.25	0.22
LSD ($p = 0.05$)	NS	NS	NS	0.03	NS	NS
Organic nutrient sources						
Farmyard manure	23.6	21.49	1.24	1.32	43.90	42.55
Vermicompost	23.2	21.02	1.25	1.36	43.50	42.88
Pig manure	23.8	21.72	1.24	1.33	44.27	43.33
Paddy straw	23.0	20.98	1.26	1.37	43.47	43.11
Control	22.4	20..49	1.27	1.38	42.67	42.41
SEM (±)	0.5	0.48	0.011	0.01	0.31	0.29
LSD ($p = 0.05$)	1.3	1.25	0.037	0.03	0.81	0.76
Initial	21.9	19.08	1.29	1.39	42.38	41.28

LSD: Least significant difference; NS: Not significant; ρb: Bulk density; SEM: Standard error of mean; SOC: Soil organic carbon.

42.33 Mg ha^{-1} at 15–30 cm depth, compared to the antecedent stock of 42.4 and 39.78 Mg ha^{-1}, respectively. Among ONSs, SOC stock was significantly higher under PM, followed by FYM, compared to other sources. There was a slight increase in SOC stock even in soil under the control, compared to the initial level. The SOC stock in soils under PM, FYM, VC, PS and control was 1.89, 1.52, 1.12, 1.09 and 0.29 Mg ha^{-1} higher, respectively, than that of the initial stock in the 0–15 cm soil layer. In the 15–30 cm soil layer, the respective increases in the SOC stock were 2.05, 1.27, 1.60, 1.83 and 1.13 Mg ha^{-1}, above the initial stock values.

The SOC stock was not significantly influenced by variety. However, the SOC stock under IR-64 and Shahsarang-1 was slightly higher than that observed under the other two varieties after 6 years.

Carbohydrate equivalent and carbon output

The average data over 6 years (Figure 5) revealed that the maximum carbohydrate equivalent (3132.8 kg ha^{-1}) was produced by Sahsarang-1, followed by IR-64 (3011.76 kg ha^{-1}), and the minimum was produced by by K. Hamsha (2776.80 kg ha^{-1}). Carbon output was highest with Lampnah (2706 kg CO_2eq ha^{-1}), and lowest with K. Hamsha (2274.8 kg CO_2eq ha^{-1}), compared to the other varieties. Among the ONSs, the maximum carbohydrate equivalent (3253.8) and carbon output (2609.2) were recorded with PM and the minimum were recorded with the control (2470.6 and 2217.6). FYM, VC, PM and PS produced 28.0, 22.2, 31.7 and 20.8% higher carbohydrate equivalent, respectively, relative to the control. Similarly, carbon output was 15.3, 12.5, 17.7 and 11.1% higher under FYM, VC, PM and PS, respectively, than for the control.

Economics

Among rice varieties, Shahsarang-1 produced higher net returns and a higher benefit:cost (B:C) ratio compared to other rice varieties (Table 7). The maximum production efficiency (29.0 kg ha^{-1} day^{-1}) and economic efficiency (\$2.6 ha^{-1} day^{-1}) were recorded with IR 64 and

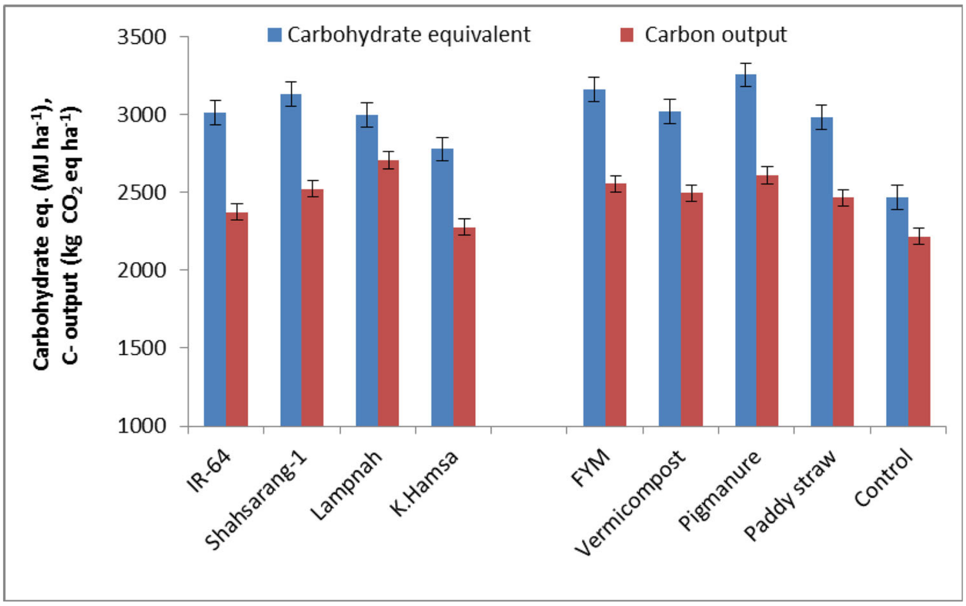

Figure 5. Effect of rice varieties and nutrient management on carbohydrate equivalent and carbon output by rice crop (6-year average; vertical bars represent least significant difference at $p = 0.05$).

Table 7. Economics of treatments as influenced by varieties and different organic nutrient sources (average of 6 years).

Treatments	Net return (\$ ha^{-1})	Benefit: cost ratio	PE (kg ha^{-1} day^{-1})	Economic efficiency (\$ ha^{-1} day^{-1})
Varieties				
IR-64	294.3	1.72	28.96	2.03
Shahsarang-1	330.4	1.80	28.68	2.14
Lampnah	307.9	1.75	28.29	2.03
K.Hamsa	232.8	1.58	25.71	1.56
SEM (±)	10.5	0.03	0.43	0.074
LSD ($p = 0.05$)	32.2	0.09	1.27	0.216
Organic nutrient sources				
Farmyard manure	327.9	1.77	29.60	2.17
Vermicompost	240.9	1.50	28.87	1.60
Pig manure	381.4	1.97	30.77	2.56
Paddy straw	254.9	1.57	27.87	1.70
Control	252.1	1.75	23.03	1.67
SEM (±)	9.73	0.02	0.39	0.063
LSD ($p = 0.05$)	33.7	0.08	1.35	0.220

LSD: Least significant difference; NS: Not significant; PE: Production efficiency; SEM: Standard error of mean. 1 US\$ = Indian Rupee (INR) 71.

Shashsarang-1, respectively, compared to the other rice varieties. This trend was attributed to the shorter growth duration of IR-64 and its comparable yield with other varieties. In terms of ONSs, PM produced the highest net return (\$381.4 ha^{-1}), B:C ratio (2.0), production efficiency (30.8 kg ha^{-1} day^{-1}) and economic efficiency (\$2.6 ha^{-1} day^{-1}), followed by FYM.

Energetics

Energy analysis is the tool used to judge the efficiency of treatments. Energy analysis of the pooled data for 6 years (Table 8) indicated that thedifferent treatments required different levels of total energy input. Among the rice varieties, higher gross input energy, net energy, EUE, energy productivity and EI were recorded with Lampnah and Shahsarang-1 than for the other varieties. Greater input energy was required for PS than for all other ONSs. Among the ONSs, the maximum energy output (141,701.60 MJ ha^{-1}), net energy (134,843.7 MJ ha^{-1}), and EI (5.08 MJ Rs^{-1}) were also observed under PM, whereas EUE (34.1) and energy productivity (1.04 kg MJ^{-1}) were higher under the control. Energy intensiveness and EI in physical terms were higher with PS than in other treatments.

Discussion

The growth and productivity of a crop are determined by the interaction effects of its genetic potential, environment and management practices. Thus, varieties differ in their performance in a given ecosystem under a particular set of management practices. Varieties like Shahsarang-1 and

Table 8. Energetics as influenced by varieties and different organic nutrient sources (average of 6 years).

Treatments	Energy input ($\times 10^3$ MJ ha^{-1})	Output energy ($\times 10^3$ MJ ha^{-1})	Net Energy ($\times 10^3$ MJ ha^{-1})	EUE	EP (kg MJ^{-1})	Energy profitability	Energy intensiveness	Energy intensity	
								Economic term (MJ INR^{-1})	Physical term (MJ kg^{-1})
Varieties									
IR-64	25.24	129.72	104.48	19.61	0.63	18.61	0.81	4.42	2.61
Shahsarang-1	25.24	137.24	112.00	20.72	0.66	19.72	0.81	4.67	2.48
Lampnah	25.24	140.13	114.89	21.23	0.64	20.23	0.81	4.77	2.43
K.Hamsa	25.24	121.94	96.70	18.55	0.59	17.55	0.81	4.17	2.77
SEM (±)	0.021	1.50	1.50	0.28	0.011	0.80	0.0036	0.06	0.039
LSD ($p = 0.05$)	0.062	4.38	4.39	0.83	0.032	2.45	NS	0.18	0.116
Organic nutrient sources									
Farmyard manure	7.26	138.99	131.73	19.15	0.62	18.15	0.24	4.57	0.70
Vermicompost	5.36	133.45	128.09	24.91	0.79	23.91	0.16	3.94	0.54
Pig manure	6.86	141.70	134.84	20.66	0.67	19.66	0.25	5.08	0.65
Paddy straw	103.36	132.52	29.16	1.28	0.04	0.28	3.24	4.15	10.52
Control	3.36	114.61	111.25	34.14	1.04	33.14	0.14	4.79	0.39
SEM (±)	0.007	1.40	1.39	0.03	0.013	0.23	0.024	0.052	0.061
LSD ($p = 0.05$)	0.026	4.83	4.82	0.79	0.047	0.79	0.74	0.018	0.21

EI: Energy intensiveness; EP: Energy productivity; EUE: Energy use efficiency; LSD: Least significant difference; NS: Not significant; SEM: Standard error of mean.

Lampnah are developed by crossing local rice lines with high-yielding varieties from other parts of the world. The suitability of varieties like Shahsarang-1 and Lampnah in terms of higher growth and yield attributes, relative to other varieties, in a hill ecosystem has been previously reported [11].

Organic manures vary in terms of their nutrient concentrations as well as their physical properties [9]. Readily biodegradable materials make better nutrient sources [50,51]. Some manure may have high nutrient concentrations but may not provide the required nutrition to the associated crop due to their slow release [51]. Better crop performance under PM may be due to its higher nutrient concentrations (Table 1) relative to that in other organic sources such as FYM and crop residues [Kumar [87]] [52]. Similar or higher productivity of crops with PM to that of inorganic fertilizers was previously reported [53,54]. The differential effects of diverse organic manure types on rice productivity, including ratoon crops, may be due to varied nutrient concentrations and nutrient release patterns of organic manure.

The relatively higher N, P and K contents in PM might have led to its higher crop productivity, including that of the ratoon crop, relative to the other ONSs. FYM contains less N and P than PM does, but to supply an equivalent amount of N and P a greater volume of FYM was applied than PM, which might have improved the soil physical properties leading to better nutrient availability to the crop. This might be the reason for the higher ratoon crop yield under FYM than under VC, PS etc. [Das [74]]. Myint et al. [55] reported that rice yield and N availability of low-fertility soil increased with continuous application of organic manure. The effect of OM application on crop productivity depends mainly on the kind and amount of OM used. Surekha [56] reported a gradual increase in grain yield with the use of organic manure over a period of time. The PM was reported to be effective in increasing the yields of cereals and other crops relative to other manures [52,57]. Yield parameters (Table 3) and yields (Table 4; Figure 3) of crops are primarily due to their genetic attributes. However, management practices may influence yield parameters and yields owing to the availability of resources such as water, light, nutrients, etc. In the present study, varieties and management practices also significantly influenced yield parameters (Table 3), including the grain (Table 4; Figure 3) and straw yields of both the main and ratoon crops (Figure 1). The suitability of Lampnah and Shahsarang-1 for OF at mid-attitudes in the eastern Himalayas has been previously reported [9]. The higher ratoon yields of Shahsarang-1 (Figure 3) might be due to its better regrowth and tillering ability relative to the other varieties. Varietal differences in ratoon yields were previously reported by other researchers [58,59] [Santos *et al.* 2003].

A meta-dataset of 362 studies conducted globally indicated that crops grown with OF had yields on average 20% lower than those managed by CF [60]. In another meta-analysis, yields under OF were reported to be 19% lower than those under CF [61,62]. However, these studies indicated that the yield gaps with OF varied significantly among crops and regions. For specific crops, growing conditions and management practices, yields of crops grown with OF were similar to those grown with the CF production system [63]. In the present study, the productivity of early *kharif* (rainy season) rice (Table 4) was similar to that obtained under CF practices by Das et al. [9].

The nutrient uptake is directly correlated with yield and biomass production of grain and straw and the concentrations of nutrients within them, because the dominating factor is productivity. Thus, higher N, P and K uptake in the present study was obtained with PM (Figure 4) than in the treatments with other ONSs. Increases in the concentration of N, P and K in the plant due to soil application of PM have been previously reported [53]. Decomposition of OM releases macro- and micronutrients to the soil, which become available to plants, resulting in higher nutrient uptake [64].

Kumar et al. [10] reported an enhancement in SOC content by 11.8% with the application of 100% of the recommended N and P through FYM and rock phosphate, compared to the initial value after three cropping cycles. Continuous applications of organic amendments like PM, FYM and VC have been previously reported to improve the SOC, available P and K in soil, thereby sustaining soil health [9,17,65]. A number of long-term experiments comparing CF and OF practices have documented an increase in OM/SOC under OF-managed soils [66]. It was also reported that OF and low-input farming practices led, after 4 years, to an increase in the SOC content, soluble P, exchangeable K, pH and reserve pool of stored nutrients, and that the soil maintained a relatively stable EC level [67,68]. The increase in SOM following the application of organic manure and the adoption of OF management practices is a slow but steady process based on climate, yet it influences the long-term soil fertility and productivity [67]. An increase in the SOC content can improve crop yields through increased nutrient supply [69].

The contribution of OM of different quantities and volume by the different rice varieties also contributed to variation in the soil fertility (Table 5), especially in the available K. However, the varieties did not influence the SOC stock, which might instead have been influenced by variations in soil ρ_b. Different genotypes have varying abilities in terms of nutrient acquisition and biomass production [70], which on recycling into soil may affect soil properties like SOC, available K and others [71]. The effects of ONS and genotypes on SOC stocks depend on climate, soil conditions and other management practices. The soil microbial population (Table 5) was enhanced by continuous application of nutrients through diverse ONSs, as indicated by the higher SMBC and DHA relative to control and antecedent levels. Use of organic amendments is known to improve soil biological properties [69] and plant nutrient uptake [72] due to their role in nutrient cycling, with direct effects on crop yield [69] and with ultimate enhancement of agricultural sustainability [73].

Lower soil ρ_b (Table 6) under various ONSs might be attributed to an improvement in SOC due to the application of different organic manures. Lower ρ_b in soils treated with FYM, when applied on an N-equivalent basis, was attributed to the greater OM content in FYM (due to its bulky nature) compared to other sources. A decrease in ρ_b under OF has been reported by many researchers [11,17,74].

The SOC content is the outcome of a balance between mineralization and inputs of biomass-C [75]. Thus, cultural practices that increase C inputs (i.e. FYM, composting and incorporation of crop residues) are reported to increase SOC content in agricultural soils [76]. Application of bulky manure and crop residues enhances SOM, microbial activities and physico-chemical properties, which also increase SOC content and stocks [77]. Concomitant high root biomass and addition of OM to the soil through the decay of a large volume of dead roots and detritus enhance the SOC stock in soil [78].

In the present study, the relatively high carbon content in ONS/straw and the prevailing moderate temperature might have contributed to a higher build-up of SOC. A slight increase in SOC under the control might be due to input through crop stubble, roots and weed biomass recycling which helped to build SOM [79]. Organic inputs in the present study included 80 kg N ha^{-1} through 8.6 Mg ha^{-1} (PM) to 11 Mg ha^{-1} (FYM) biomass per year. Assuming a concentration of 40% in crop biomass [80], 20% in FYM, 21% in PM and 15% in VC, the annual C input was about 2.2, 1.81, 4.24 and 1.33 Mg C ha^{-1} (i.e. 8.1 to 25.4 Mg ha^{-1} C input in 6 years) for FYM, PM, PS and VC, respectively. In addition, about 3–4 Mg ha^{-1} rice biomass (stubble and roots of rice and its ratoon crops) was recycled annually, which corresponds to 1.2–1.6 Mg C ha^{-1} (i.e. 8.4 ± 0.12 Mg C ha^{-1} in 6 years). Thus, about 15.3–35 Mg ha^{-1} C input was added to the soil through ONS and rice residue recycling in 6 years. In the present study, the increase in C stock (0–30 cm depth) in 6 years relative to the antecedent level ranged from 2.72 Mg ha^{-1} under VC to 3.94 Mg ha^{-1} under PM, which is about 16.6% and 20.45.24% of the cumulative C inputs under the respective treatments in 6 years. The increase in SOC stock under the control treatment was perhaps due to the addition of about 8 Mg C ha^{-1} through rice stubble and roots. SOC levels have been reported to typically increase at a rate of 10–25% of the amount of C added, and greater C retention rates are expected with an increase in precipitation and a decrease in cropping intensity [81]. The SOC stock increase in the present study confirms this expectation for the eastern Himalayan region of India.

The difference in SOC content (Table 6) under different varieties could be due to differential root growth, volume, aboveground biomass production and decaying leaves, and their subsequent decomposition to add SOM. In addition, diverse ONSs with different chemical (i.e. C:N ratio) and structural (i.e. cellulose and lignin contents) composition might have affected humification and mineralization processes of organic compounds via soil microbial activity [29,82]. OM in crop residues (i.e. PS) are reported to be more easily degradable than those in organic manure like FYM, PM and others and may, therefore, have less of an effect on SOC content [83].

Rice varieties with higher grain yield also produced higher carbohydrate equivalent. Similarly, varieties with higher straw yield produced higher carbon output (Figure 5). This trend can be attributed to the cumulative effect of carbohydrate and carbon concentration in grains and straw. Since quality parameters are mostly impacted by genotypes and the environment, management practices have little influence on them. Higher carbohydrate equivalent and carbon output under FYM, VC and PM than under other ONSs might be due to greater biomass production with the respective ONS treatments than with no manure application [84].

Relatively higher economic benefits (Table 6) under PM and FYM as ONS than with other sources were attributed to higher yields under these treatments than those from other sources. Shahsarang-1 has been reported to perform satisfactorily under low-input management practices, and the variety is tolerant to most of the diseases prevalent in the studied ecosystems. The suitability of Shahsarang-1 for OF with higher productivity and income compared with other varieties was indicated by earlier researchers in the hill ecosystem of the Eastern Himalayas, India [23]. The higher energy use efficiency obtained with the varieties Lampnah and Shahsarang (Table 7) was mainly due to the higher yields of these two varieties relative to others. The higher EI with PS was attributed to the maximum energy put into it. Variations in energy inputs and outputs are responsible for differences in EUE, EI and productivity [85,86].

Conclusions

This 6-year study indicated that the rice varieties Shahsarang-1 and IR 4 are suitable for double cropping through ratooning to achieve high total productivity (main + ratoon crop) and net returns in the northeastern hill ecosystems of India. The study also found that PM and FYM are the most efficient organic nutrient sources for maximizing rice productivity and net reruns and improving soil health. The study further demonstrated that Lampnah and Shahsarang-1 are more energy use efficient than the other tested varieties. SOC stock and energy output were highest under PM treatment, followed by FYM, after 6 years of rice cultivation. The efficient use of PM can be a viable nutrient management practice for sustainable crop production in northeastern Himalayan regions where pig is the main livestock and is in high demand among the ethnic population.

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Disclosure statement

The authors declare that they have no potential conflicts of interest.

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