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Research article

Assessing the economic and energy use efficiencies of hybrid and inbred rice varieties through omission-plot technique in Lamjung, Nepal

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ABSTRACT

Agricultural productivity relies upon energy input in the form of improved seeds, fertilizers, chemicals, irrigation and mechanization including management practices. This energy input is crucial for enhancing crop yields and meeting the demands of an ever-growing population. The increasing demand for rice production from an ever-increasing population and the dwindling nature of natural resources as a result of their continuous and excessive use underscore the urgency of studying energy use efficiency and sustainability in rice production. By conducting this experiment, the goal was to assess the yields, economics, and energy use efficiencies in rice. The experiment employed a Randomized Complete Block Design (RCBD) with three replications, comprising ten treatment combinations viz. US-312 + 60:30:20 kg NPK ha^{-1}, US-312 + 0:30:20 kg NPK ha^{-1}, US-312 + 60:0:20 kg NPK ha^{-1}, US-312 + 60:30:0 kg NPK ha^{-1}, US-312 + 0:0:0 kg NPK ha^{-1}, Sukhadhan-2+60:30:20 kg NPK ha^{-1}, Sukhadhan-2+0:30:20 kg NPK ha^{-1}, Sukhadhan-2+60:0:20 kg NPK ha^{-1}, Sukhadhan-2+60:30:0 kg NPK ha^{-1}, Sukhadhan-2+ 0:0:0 kg NPK ha^{-1}. Results revealed that the highest grain yield and yield attributes were obtained from US-312 + 60:30:20 kg NPK ha^{-1} (4.98 t ha^{-1}) followed by US-312 + 60:30:0 kg NPK ha^{-1} (4.76 t ha^{-1}), and US-312 + 60:0:20 kg NPK ha^{-1} (4.54 t ha^{-1}). The highest energy use efficiency of 3.95 was observed under US-312 + 60:30:0 kg NPK ha^{-1} which was supported by the highest output energy obtained from grain and biomass yield (153 GJ ha^{-1}) and the highest net energy (117 GJ ha^{-1}). The benefit-cost ratio was found highest in US-312 + 60:30:20 kg NPK ha^{-1} (1.98), signifying its economic viability and potential profitability. In the context of the western mid-hills of Nepal, the rice variety US-312, coupled with a nutrient composition of 60:30:20 kg NPK ha^{-1} proved to be an optimal selection. This combination demonstrated higher grain yields and noteworthy economic efficiency.

1. Introduction

Rice (*Oryza sativa* L., 2n = 24) is considered one of the staple food crops of over half of the world's population [1–3]. Globally, rice

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cultivation covers 165.25 million ha, yielding 787.29 million tons at an average productivity of 4.8 t ha^{-1} in 2021 [4]. Meanwhile, in Nepal, it is annually grown on about 1.47 million ha producing 5.62 million tons with a productivity of 3.82 t ha^{-1} in 2020/21 [5]. Rice is cultivated across diverse agroecological zones, adapting to various climatic conditions, altitudes, and topographical features, ranging from as low as 60 m in the terai to as high as 3050 m above sea level in regions like Chumchure, Jumla [6].

Agricultural productivity is proportional to energy input in the form of improved seeds, fertilizers, chemicals, irrigation, and mechanization including management practices [7]. Rice production requires much higher energy input, mainly due to its high water and fertilizers requirements coupled with other agronomic practices like transplanting, harvesting and threshing. The rising usage and expenses associated with energy in agriculture necessitate to make agricultural practices more energy efficient. A plan to conserve energy for future generations without threatening the food supply requires a comprehensive analysis of energy inputs and outputs [8]. The overuse of energy input in agriculture may cause serious problems to human health and the environment [9]. Since rice is one of the highest-produced cereal crops, there is a need for effective planning to use inputs in the rice production process, aiming to achieve energy-use efficiency without harming the Earth. Energy use efficiency entails the use of the appropriate amount of energy input in production in the right form and at the right time which helps achieve sustainable rice production. If energy consumed can be reduced, while production is maintained or increased, energy use efficiency is improved. To assure food security in rice-consuming countries, rice production would have to be increased by 50% in the developing countries of Asia by 2025 and this additional production will have to be done on less land with less usage of water, labor and chemicals [10]. Excess use of fertilizers implies an increase in cost and decrease in returns and risk of environmental pollution. On the other hand, the underuse of nutrients depresses the scope for increasing the present level of nutrients to the economically optimum level to exploit production potential to a larger extent [11].

Inadequate and unbalanced fertilizer application not only leads to diminished crop yield but also degrades soil health [12–14]. Hence, effective nutrient management significantly contributes to increased production [15]. To quantitatively assess soil nutrient supply, the omission plot technique proves valuable [16–18]. However, limited research on economic aspects and input-output relations in rice production has resulted in escalated energy requirements and production costs. Additionally, there exists a research gap concerning the performance of hybrid and drought-tolerant inbred varieties in Lamjung, Nepal. This study aims to identify the best performing rice variety between the hybrid US-312 and the inbred Sukhadhan-2, and the optimal combination of Nitrogen, Phosphorus, and Potash (NPK) fertilizers, thereby enhance energy and economic efficiency to maximize profitability and sustainability within the rice production system.

2. Materials and methods

The research was conducted in the farmer's field located in Sundarbazar Municipality-7, Lamjung, Nepal, under conditions of low rainfed agriculture. The study area falls within the subtropical agroecological belt, situated between latitude 28°12′ N and longitude 84°41′ E at an altitude of 700 m above sea level. The region experiences a maximum temperature ranging from 30 °C to 32.3 °C during April–June, while the minimum temperature remains at 8 °C–9 °C in December–January. The average annual rainfall received is approximately 2000 mm [19]. The pH of the experimental site was 5.5 with loamy soil containing a total nitrogen content of 0.10, available phosphorous (P_2O_5) content of 20.60 kg ha^{-1}, available potassium (K_2O) content of 294.80 kg ha^{-1}, and soil organic carbon level of 1.36%. The research was carried out in two factorial Randomized Complete Block Design (RCBD) with 3 replications and ten treatment combinations (Table 1). Seeding was done with a seed rate of 60 kg ha^{-1} for Sukhadhan-2 and 20 kg ha^{-1} for US-312 on 23rd June. Healthy seedlings of 32 days old were transplanted, maintaining a plant spacing of 20 cm × 20 cm. Altogether 30 plots of size 3 m × 2 m (6 m^2) were made and each plot was separated by bunds of around 25 cm in width and height. The 50 cm space was left between the two plots in such a way that no water and dissolved fertilizers could flow between the adjacent plots. Different combinations of chemical fertilizers along with dry Farm Yard Manure (FYM) (6 t ha^{-1}) were applied in different plots. A full dose of Farm Yard Manure (FYM) (N-0.5%, P_2O_5-0.2%, K_2O-0.5%), Diammonium Phosphate (DAP) (N-18%, P_2O_5-46%) or Single Super Phosphate (SSP) (P_2O_5-16%), and Muriate of Potash (MOP) (K_2O-60%) was applied as a basal dose whereas urea was applied in 3 split doses. FYM was incorporated in all plots, while SSP replaced DAP in plots with a zero-nitrogen recommendation. Urea was split, with 50% applied during transplanting and the remaining 50% top-dressed after the 1st and 2nd weeding, occurring at 25 and 45 days after transplanting, respectively.

Data for grain and straw yield were recorded from the net plot area of 4.4 m^2 (2.2 m × 2 m). Grains were weighed at 14% moisture

Table 1
Treatment combinations for the experiment.

SN	Treatment	Details
1.	T_1	US-312 + 60:30:20 kg NPK ha^{-1}
2.	T_2	US-312 + 0:30:20 kg NPK ha^{-1}
3.	T_3	US-312 + 60:0:20 kg NPK ha^{-1}
4.	T_4	US-312 + 60:30:0 kg NPK ha^{-1}
5.	T_5	US-312 + 0:0:0 kg NPK ha^{-1}
6.	T_6	Sukhadhan-2+60:30:20 kg NPK ha^{-1}
7.	T_7	Sukhadhan-2+0:30:20 kg NPK ha^{-1}
8.	T_8	Sukhadhan-2+60:0:20 kg NPK ha^{-1}
9.	T_9	Sukhadhan-2+60:30:0 kg NPK ha^{-1}
10.	T_{10}	Sukhadhan-2+0:0:0 kg NPK ha^{-1}

content using a digital weighing balance and yield per hectare was calculated for each plot. The wet straw yield in t ha^{-1} was calculated by weighing the straw from each plot immediately after threshing. To calculate the dry straw yield, 500 g of straw was initially weighed from each plot and sun-dried for 15 days until its moisture content reached 14%. After the drying process, the straw samples were re-weighed using a balance to assess the resulting weight. To analyze energy inputs and outputs, inputs for rice production, including labor, seeds, fuel, chemical fertilizers, etc., were quantified. Similarly, outputs in the form of grain and straw were also calculated. Total energy input and output were estimated using energy equivalents (Table 2) as suggested by Refs. [20–22].

2.1. Energy analysis

2.1.1. Energy Output (EO)

$$\text{Energy Output} = \text{Emp} + \text{Ebp}$$

where,

$$\text{Emp} = \text{Energy from the main product}$$

$$\text{Ebp} = \text{Energy from by-product}$$

2.1.2. Net Energy (NE)

$$\text{Net Energy} = \text{Energy Output}\left(\text{GJ ha}^{-1}\right) - \text{Energy Input}\left(\text{GJ ha}^{-1}\right).$$

2.1.3. Energy Use Efficiency (EUE)

$$\text{EUE} = \text{Energy Output}\left(\text{GJ ha}^{-1}\right) \Big/ \text{Energy Input}\left(\text{GJ ha}^{-1}\right).$$

2.1.4. Partial Factor Productivity (PFP)

It was calculated by dividing economic yield with NPK fertilizers applied to the different conditions.

2.2. Economic analysis

Economic analysis was done to determine the profitability of different treatments and identify the best and most efficient one. The following economic parameters were calculated based on input cost and values of output in the local market:

2.2.1. Cost of cultivation

The cost of cultivation was calculated based on local charges for different agro-inputs, i.e. labor, fuel, fertilizers, seeds, and other necessary materials.

2.2.2. Gross return

The economic yield (grain + straw) of rice was converted into the gross return (Rs. ha^{-1}) based on the local market price.

2.2.3. Net return

Net return = (Product price + by-product price) – Input cost

2.2.4. Benefit-to-cost ratio (B:C ratio)

B:C ratio = Gross return/Cost of production

Table 2
Energy equivalents for different inputs and outputs in rice production.

Items	Unit	Energy equivalent (MJ/unit)
Inputs		
Seed	Kg	4.7
Fertilizers		
N	Kg	60.6
P	Kg	11.1
K	Kg	6.7
Fuel	L	56.3
Labor	Hr	1.96
Outputs		
Main product	Kg	14.7
By-product	Kg	12.5

Kg = Kilogram, L = Liter, Hr = Hour.

Data were entered into Microsoft Excel-2010 and analysis was done by using GenStat 15th edition. The treatment mean was compared by Least Significant Difference (LSD) at a 0.05% level of significance.

3. Results and discussion

3.1. Effect of treatments on grain and straw yield

The grain and straw yield varied significantly due to varieties and fertilizer combinations whereas it was non-significant for interaction. Higher grain yield (4.29 t ha^{-1}) and straw yield (6 t ha^{-1}) were obtained from the US-312 variety compared to Sukhadhan-2. Similarly, by averaging the yield of two varieties, it was found that the treatment containing 60:30:20 kg NPK ha^{-1} gave a maximum grain yield of 4.60 t ha^{-1} followed by the 60:30:0 kg NPK treatment (4.30 t ha^{-1}). The straw yield of 60:30:20 kg NPK ha^{-1}, 60:30:0 kg NPK ha^{-1} and 60:0:20 kg NPK ha^{-1} plots were statistically similar (Table 3). The higher yield in US-312 was due to its genetic makeup. This result was consistent with the discoveries of [23–25], who proposed that the differences in genetic composition might account for the observed variations. The higher yield of hybrid rice was associated with higher sink size (i.e., product of spikelet number and grain weight), total dry weight, and longer total crop growth duration compared with inbred rice [26,27]. According to Refs. [28,29] the application of nitrogen fertilizer can increase the plant height, panicles number and spikelet number which largely determine the yield capacity of rice. Higher levels of nitrogen promote enhanced nutrient absorption, leading to the rapid expansion of foliage. This, in turn, facilitates better accumulation of photosynthates and ultimately results in improved structural growth [30–32]. Consequently, this could contribute to the development of larger grains with increased weight, ultimately amplifying overall yield. The number of filled grains per panicle significantly increased through increasing nitrogen [33] and potassium doses by up to 50% [34]. Additionally, increased levels of phosphorus and potassium were found to decrease sterility [34,35].

3.2. Effect of treatments on energy

The quantities of inputs used in different treatments were similar, with the sole distinction being the seed quantity for hybrid and inbred rice, as well as the amount of fertilizer used. Thus, not much difference in input energy was observed. Though the difference was not significant, the maximum input energy of 40.25 GJ ha^{-1} was found in Sukhadhan-2+60:30:20 kg NPK ha^{-1} due to the higher seed rate of inbred rice and the application of a recommended dose of NPK. Conversely, a minimum input energy of 32.03 GJ ha^{-1} was incurred for US-312 in the control plot. Labor input accounted for the maximum input energy in this experiment. Comparing the two rice varieties, output energy was found to be higher in the US-312 hybrid (138.1 GJ ha^{-1}) than in the inbred Sukhadhan-2 (111.2 GJ ha^{-1}). Similarly, the fertilizers combination of 60:30:20 kg NPK ha^{-1} had the maximum energy output (141.2 GJ ha^{-1}) which was statistically similar to 60:0:20 kg NPK ha^{-1} and 60:30:0 kg NPK ha^{-1} whereas the interaction of variety and fertilizers combination was observed non-significant (Table 4). In hybrid rice resource use efficiency of various resources and the ratio of marginal value product and marginal input cost is much better than inbred rice [36]. Similarly, the net energy of the hybrid rice US-312 was 15% more than that of the inbreed Sukhadhan-2. The net energy of treatment containing a recommended dose of NPK was nearly 27% more than the control. Net energy was higher in those having higher output energy. Hybrid rice yielded higher output energy and hence higher net energy than the inbred. Low net energy in Sukhadhan-2 and the control was accompanied by poor crop establishment and a lower yield. With the same amount of inputs, the energy use efficiency of hybrid rice (3.69) was found to be more than the inbred (3.0). The EUE of 60:30:20 kg NPK ha^{-1}, 60:30:0 kg NPK ha^{-1}, 60:0:20 kg NPK ha^{-1}, and 0:30:20 kg NPK ha^{-1} was significantly higher than the control. The energy use efficiency of rice was increased by an increase in NPK levels by 25 %. This showed the importance of

Table 3
Effect of Variety and fertilizer combination on grain yield and straw yield of rice.

Variety (A)	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})
US-312	4.29^{a}	6.0^{a}
Sukhadhan-2	3.54^{b}	4.73^{b}
F test (5%)	**	**
LSD $_{(0.05)}$	0.26	0.40
CV (%)	4.5	10.1
Fertilizer combinations (B)		
60:30:20 kg NPK ha^{-1}	4.60^{a}	5.95^{a}
0:30:20 kg NPK ha^{-1}	3.82^{c}	5.21^{b}
60:0:20 kg NPK ha^{-1}	4.16^{bc}	5.82^{ab}
60: 30: 0 NPK ha^{-1}	4.30 ^{ab}	5.87 ^{ab}
0: 0:0 NPK ha(control)	2.70^{d}	3.96^{c}
F test (5%)	**	**
LSD value	0.418	0.63
CV (%)	4.5	10.1
A x B	NS	NS

Means separation in a column followed by the same letters are not significantly different at p = 0.05, ** = Significant at 1% level of significance, N=Nitrogen, P=Phosphorus, K=Potash, LSD = Least Significant Difference, CV= Coefficient of Variation, NS= Non-significant.

Table 4
Effect of variety and fertilizer combination on output energy, net energy, and energy use efficiency.

Variety (A)	Output energy (GJ ha^{-1})	Net energy (GJ ha^{-1})	Energy use efficiency
US-312	138.1	100.9	3.691
Sukhadhan-2	111.2	74.2	2.997
F test	**	**	**
LSD $_{(0.05)}$	0.076	0.076	0.206
Fertilizer combination (B)			
60:30:20 kg NPK ha^{-1}	141.2^{a}	100.9^{a}	3.511^{a}
0:30:20 kg NPK ha^{-1}	121.3^{b}	87.6^{b}	3.594^{a}
60:0:20 kg NPK ha^{-1}	133.9^{a}	94.4^{ab}	3.392^{a}
60:30:0 kg NPK ha^{-1}	137.5^{a}	97.6^{ab}	3.44^{a}
0:0:0 kg NPK ha^{-1} (control)	89.2^{b}	57.1^{c}	2.782^{b}
F test	**	**	**
LSD	0.121	0.121	0.327
A*B	NS	NS	NS

Means separation in a column followed by the same letters are not significantly different at p = 0.05, ** = Significant at 1% level of significance, N=Nitrogen, P=Phosphorus, K=Potash, LSD = Least Significant Difference, NS= Non-significant.

incremental doses of K and P along with N to attain the maximum energy benefit [37].

3.3. *Effect of treatments on economics*

All treatments had consistent inputs (labor, fuel, water, pesticides), varying only in seed quantity (inbred vs. hybrid) and fertilizer type. However, due to the higher cost of hybrid seeds and fertilizers, the maximum cost was incurred in the treatment with US-312 and the recommended dose of NPK fertilizers. The average cost of production incurred was NRS.100.02 thousand ha^{-1}.

Gross return was obtained higher in US-312 (1.862*10ˆ5 NPR ha^{-1}) than in Sukhadhan-2 (1.417*10ˆ5 NPR ha^{-1}). This might be due to the higher yield of hybrid rice which resulted in increased gross return. Similarly, the gross and net return of 60:30:20 kg NPK ha^{-1}, 60:0:20 kg NPK ha^{-1}, and 60:30:0 kg NPK ha^{-1} treatments were found higher than the 0:30:20 kg NPK ha^{-1} and the control. This signifies that N plays an important role in increasing yield and thereby gross output. The results of [17,19] showed that the production of hybrid has been relatively more profitable. The net return from US-312 was 29% more than the Sukhadhan-2 due to its higher yield. Likewise, the 60:30:20 kg NPK ha^{-1}, 60:30:0 kg NPK ha^{-1}, and 60:0:20 kg NPK ha^{-1} treatments had significantly higher net returns than the 0:30:20 kg NPK ha^{-1} and the control. The highest gross returns, net returns and per rupee invested were higher with the application of NPK @ 210-60-40 kg ha^{-1} [37]. The variety US-312 gave a higher B:C ratio (1.783) than the Sukhadhan-2 (1.463). The lowest B:C ratio was seen in the control treatment whereas the 60:30:20 kg NPK ha^{-1} treatment had the highest B:C ratio of 1.836 which was significantly at par with the 60:30:0 kg NPK ha^{-1} and 60:0:20 kg NPK ha^{-1} treatment (Table 5). The B:C ratio increases with the use of optimum fertilizer recommendations due to the better utilization of nutrients to produce higher yields [38]. Moreover, high-yielding varieties can sustain yield levels with reduced input, ultimately resulting in a heightened benefit-to-cost ratio [39,40].

US-312 had a higher partial factor productivity (PFP) for N (23.37), PFP for P (34.39) and PFP for K (82.6) than Sukhadhan-2 (Table 6). PFP for N and P were found significantly higher for the interaction US-312 + 60:30:20 kg NPK ha^{-1} followed by the interaction US-312 + 60:30:0 kg NPK ha^{-1} (Table 7). Similarly, PFP for K was higher for the interaction US-312 + 60:30:20 kg NPK ha^{-1}. This indicates that the same combination of fertilizers can give a higher yield for US-312 than for Sukhadhan 2.

Table 5
Effect of varieties and fertilizer combinations on economics.

Variety (A)	Gross return (*10ˆ5NPR/ha)	Net return (*10ˆ5NPR/ha)	B:C ratio
US-312	1.862	0.822	1.783
Sukhadhan-2	1.417	0.452	1.463
F test	**	**	**
LSD	0.102	0.102	0.101
Fertilizer combinations (B)			
60:30:20 kg NPK ha^{-1}	1.901^{a}	0.869^{a}	1.836^{a}
0:30:20 kg NPK ha^{-1}	1.598^{b}	0.574^{b}	1.55^{b}
60:0:20 kg NPK ha^{-1}	1.749^{ab}	0.751^{a}	1.746^{a}
60:30:0 kg NPK ha^{-1}	1.804^{a}	0.787^{a}	1.766^{a}
0:0:0 kg NPK ha^{-1} (Control)	1.147^{c}	0.205^{c}	1.213^{c}
F test	**	**	**
LSD	0.161	0.161	0.160
A x B	NS	NS	NS

Means separation in a column followed by the same letters are not significantly different at p = 0.05, ** = Significant at 1% level of significance, N=Nitrogen, P=Phosphorus, K=Potash, LSD = Least Significant Difference, NS= Non-significant.

Table 6
Effect of varieties and fertilizer combination on Partial Factor Productivity (PFP).

Variety	PFP for N	PFP for P	PFP for K
US-312	23.37	34.39	82.6
Sukhadhan-2	19.4	28.37	68.3
F test	**	**	**
LSD	1.867	3.372	6.87
Fertilizer combinations			
60:30:20 kg NPK ha^{-1}	38.79[a]	70.6[a]	138.1[a]
0:30:20 kg NPK ha^{-1}	0[c]	20.35[c]	114.5[b]
60:0:20 kg NPK ha^{-1}	31.9[b]	0[d]	124.8[b]
60:30:0 kg NPK ha^{-1}	36.22[a]	65.93[b]	0[c]
0:0:0 kg NPK ha^{-1} (control)	0[c]	0[d]	0[c]
F test	**	**	**
LSD	2.952	3.75	10.87

Means separation in a column followed by the same letters are not significantly different at p = 0.05, ** = Significant at 1% level of significance, N=Nitrogen, P=Phosphorus, K=Potash, LSD = Least Significant Difference, NS= Non-significant NS= Non-significant.

Table 7
Effect of interaction of variety and fertilizer combination on Partial Factor Productivity (PFP).

Varieties x Fertilizer combinations	PFP for N	PFP for P	PFP for K
US-312 + 60:30:20 kg NPK ha^{-1}	41.91[a]	76.29[a]	149.26[a]
US-312 + 0:30:20 kg NPK ha^{-1}	0[d]	22.69[d]	127.63[bc]
US-312 + 60:0:20 kg NPK ha^{-1}	34.84[b]	0[e]	136.33[ab]
US-312 + 60:30:0 kg NPK ha^{-1}	40.08[a]	72.96[a]	0[e]
US-312 + 0:0:0 kg NPK ha^{-1}	0[d]	0[e]	0[e]
SD2+60:30:20 kg NPK ha^{-1}	35.66[b]	64.92[b]	127.01[bc]
SD2+0:30:20 kg NPK ha^{-1}	0[d]	18.02[d]	101.37[d]
SD2+60:0:20 kg NPK ha^{-1}	28.95[c]	0[e]	113.31[cd]
SD2+60:30:0 kg NPKha^{-1}	32.36[bc]	58.90[c]	0[e]
SD2+0:0:0 kg NPK ha^{-1}	0[d]	0[e]	0[e]
F test	*	*	*
LSD	4.174	5.303	15.37
CV (%)	2.7	1.3	6.5

Means separation in a column followed by the same letters are not significantly different at p = 0.05, * = significant at 5% level of significance, N=Nitrogen, P=Phosphorus, K=Potash, SD2 = Sukhadhan-2, LSD = Least Significant Difference, CV= Coefficient of Variation, NS= Non-significant.

4. Conclusion

Hybrid rice US-312 performed better in terms of yield (4.29 t ha^{-1}), gross return ($1.86*10^5$ NRS ha^{-1}), and energy use efficiency (3.69) than Sukhadhan-2 under the application of similar inputs in our study area. Despite the higher cost associated with cultivating US-312 due to higher seed prices, the variety demonstrated a higher benefit-cost ratio (1.78) compared to Sukhadhan-2. The increase in grain and straw yield caused an increase in output energy which resulted in an increase in energy use efficiency. Notably, the nutrient dose of 60:30:20 kg NPK ha^{-1} emerged as the optimal choice, delivering maximal yield while exhibiting favorable economics and energy efficiency, highlighting its viability for adoption. This outcome emphasizes that the hybrid variety US-312 achieves high yields without necessitating excessive agronomic interventions or labor inputs, making it a judicious choice. In conclusion, the hybrid variety US-312 with optimal fertilizer application proved to be a promising approach for achieving enhanced rice production, energy efficiency, and economic returns than the inbred Sukhadhan-2. These results underscore the importance of embracing hybrid varieties and targeted nutrient management approaches to ensure sustainable and productive rice cultivation. However, as this was a short-term study in a small area under a farmer's field, it may not capture the long-term effects of cultivating hybrid rice varieties on a large scale. Long-term studies on a large scale can provide a more comprehensive understanding of sustainability and yield stability.

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CRediT authorship contribution statement

Alina Pokhrel: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sambriddhi Subedi:** Writing – review & editing, Methodology. **Dharma Raj Katuwal:** Writing – review & editing, Methodology. **B.B. Adhikari:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Abishek Shrestha:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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