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Effect of nutrient management on energetics of rice bean-safflower cropping system

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Abstract
The rice bean–safflower cropping system demonstrates strong potential for improving energy efficiency and sustainability in rainfed and semi-arid agricultural regions. Field experiments conducted during 2017–18 and 2018–19 revealed that nutrient treatments, particularly sulphur at 30 kg/ha and phosphorus at 80 kg/ha, significantly influenced energy input, gross and net energy output, energy productivity, energy use efficiency, and energy intensity. Higher nutrient levels enhanced biomass yield and nutrient uptake, resulting in greater energy gains while reducing energy intensity in both physical and economic terms. Sulphur and phosphorus showed positive residual effects on the succeeding safflower crop, contributing to improved performance. Control treatments consistently recorded lower energy metrics. These findings confirm that balanced nutrient management plays a vital role in optimizing crop energetics and improving system resilience. Future research should prioritize region-specific nutrient strategies, multi-year evaluations, precision farming, and life cycle assessments to promote low-input, energy-efficient cropping systems suitable for climate-challenged environments.

Keywords: Energetics, rice bean, safflower, sulphur, phosphorus, residual nutrient management

1. Introduction

The rice bean–safflower cropping system holds significant promise for enhancing soil health, increasing farm profitability, and promoting sustainable agriculture, especially in semi-arid regions. Central to this system's success is effective nutrient management, which influences crop productivity and the energy efficiency of farming practices [14]. Rice bean, a nitrogen-fixing legume, improves soil fertility and provides a valuable protein source, while safflower thrives on residual moisture and yields nutritious oilseeds. By carefully managing nutrient inputs using methods such as integrated nutrient management (INM) and site-specific applications based on soil testing farmers can optimize energy input and output ratios, leading to improved resource utilization and sustainable yields. Research [19] indicates that systems guided by tailored nutrient strategies, particularly those utilizing recommended NPK levels through soil test crop response techniques, consistently outperform less-managed plots in terms of growth, yield, and energetic efficiency. The rice bean–safflower cropping system offers a sustainable farming strategy, especially suited to rainfed and semi-arid environments. Rice bean (*Vigna umbellata*), a leguminous crop, enriches the soil by fixing atmospheric nitrogen and contributes a nutritious food or fodder source. Safflower (*Carthamus tinctorius*), with its resilience to dry conditions, yields oil-rich seeds and makes use of residual soil moisture, making it a fitting counterpart in crop rotation [19].Optimal crop performance in this system hinges on the thoughtful use of key nutrients particularly phosphorus (P) and sulphur (S). Phosphorus is crucial for energy transfer within plants and drives root development and photosynthesis. Sulphur supports protein formation and activates enzymes, making it indispensable for plant health and seed quality. Inadequate supply of either nutrient may lead to poor growth and lower efficiency [11].

From an energy standpoint, farming involves various inputs such as fertilizers, labour, and machinery, and outputs like grain and biomass yield [9]. Nutrient management directly affects how efficiently these inputs are converted into productive outputs. Practices such as integrated nutrient management (INM), which blend organic and inorganic sources, or applying nutrients based on soil testing, help increase energy use efficiency—ensuring higher returns for lower energy investment. Research [20] highlights that balanced nutrient application, especially involving phosphorus and sulphur, enhances productivity while minimizing environmental impact. The adoption of efficient genotypes and smart fertilization methods promotes better energy gain and resource optimization. With rising costs, climate unpredictability, and soil exhaustion becoming major agricultural concerns, systems that prioritize nutrient and energy efficiency are essential. By focusing on strategic phosphorus and sulphur management within the rice bean–safflower rotation, farmers can cultivate a system that supports sustainable productivity and conserves ecological integrity [21].

The rice bean–safflower cropping system has considerable promise in semi-arid and rainfed farming regions, yet it remains underutilized due to limited research [2]. Focused studies [21] are essential to understand how phosphorus and sulphur—two nutrients often lacking in Indian soils—affect the growth and productivity of these crops. Since rice bean and safflower have unique nutrient requirements, it's crucial to refine fertilizer recommendations to suit specific soil and climate conditions [10]. Energy input and output dynamics also need close examination, as efficient nutrient use can significantly boost energy use efficiency and reduce farming costs [16]. Site-specific nutrient management based on soil test crop response offers a pathway to balance productivity with resource conservation. Additionally, evaluating the economic returns from precise phosphorus and sulphur applications helps farmers make cost-effective decisions [7]. With growing challenges like soil degradation, climate variability, and the need for low-input farming, research in this area can provide the tools and knowledge for a more resilient, energy-efficient, and sustainable agricultural model.

2. Materials and Methods

The present investigation was carried out at agricultural research farm, Palli Siksha Bhavana, Visva-Bharati, Sriniketan, Birbhum, West Bengal during *kharif* and *rabi* seasons 2017-18 and 2018-19. The site is characterized by sub-humid semi-arid climate with the average maximum temperature was 32.39°C, 32.97°C and the average minimum temperature was 24.67°C, 23.78°C during the cropping period of rice bean in the year 2017 and 2018 respectively. During cropping period of safflower, average maximum temperature was 29.99°C, 29.87°C and the average minimum temperature 14.85°C, 14.86°C in the year 2017-18 and 2018-19 respectively, In both the year, the temperature range, during the cropping season, was recorded normal and evenly distributed. Total rainfall received during the rice bean growing period (*kharif* season) was 974.20 mm. and 533.80 mm in the year 2017 and 2018 respectively. In both the year, monsoon breaks in the middle of June and it continues up to October and rainfall was evenly distributed. During cropping period (*rabi* season) of safflower total rainfall received were 73 mm and 155.80 mm in the year 2017-18 and 2018-19 respectively. Occurrence of rainfall were very rare in both the year. The chemical composition indicated that soil was medium in organic carbon (0.74%), low in available nitrogen (263 $kgha^{-1}$), medium in available phosphorus (25 kg ha^{-1}), low in available potassium (130 kg ha^{-1}) and low in available sulphur (27 mg kg^{-1}). The soil was slightly acidic (pH 6.2) in reaction with an electrical conductivity of 0.48 dsm^{-1}. The texture of the soil at experimental site was sandy loam. The bulk density of soil was 1.24 Mg m^{-3}.

The experiment was laid out in Randomized Block Design (3×3+1 factorial) during the *kharif* season the treatments comprised three levels of phosphorus (P_2O_5) @ 40, 60 and 80 $kgha^{-1}$, three levels of sulphur (S) @ 10, 20 and 30 $kgha^{-1}$ and absolute control, respectively comprising of nine treatment combinations with absolute control each replicated thrice and during *rabi* season after harvest of rice bean, safflower was sown without disturbing the previous layout. The rest recommended package of practices adopted for safflower except phosphorus and sulphur nutrient doses to see the residual effect of previous experiment on succeeding safflower crop. While, blanket application of N @ 30, 60 kg ha^{-1} and K_2O @ 40, 30 kg ha^{-1} applied in rice bean and safflower crop both the years, respectively. The nutrient sources were urea, diammonium phosphate (DAP), murate of potash (MoP) and elemental sulphur to fulfil. The recommended dose was applied according to the treatment details through DAP and elemental sulphur. The treatment combinations presented in following table

Table 1: Details treatment combination:

Treatments	Treatment Combinations
T1	P_2O_5 @ 40 $kgha^{-1}$ + Sulphur @ 10 $kgha^{-1}$
T2	P_2O_5 @ 60 $kgha^{-1}$ + Sulphur @ 10 $kgha^{-1}$
T3	P_2O_5 @ 80 $kgha^{-1}$ + Sulphur @ 10 $kgha^{-1}$
T4	P_2O_5 @ 40 $kgha^{-1}$ + Sulphur @ 20 $kgha^{-1}$
T5	P_2O_5 @ 60 $kgha^{-1}$ + Sulphur @ 20 $kgha^{-1}$
T6	P_2O_5 @ 80 $kgha^{-1}$ + Sulphur @ 20 $kgha^{-1}$
T7	P_2O_5 @ 40 $kgha^{-1}$ + Sulphur @ 30 $kgha^{-1}$
T8	P_2O_5 @ 60 $kgha^{-1}$ + Sulphur @ 30 $kgha^{-1}$
T9	P_2O_5 @ 80 $kgha^{-1}$ + Sulphur @ 30 $kgha^{-1}$
T10	Control

** Blanket application of N @ 30, 60 kg ha^{-1} for rice bean and safflower respectively and K_2O @ 40, 30 kg ha^{-1} for rice bean and safflower respectively.

Energetics

Table 2: Energy input and output of individual crop was calculated using an energy equivalent conversion factors for each treatments

Sr. No.	Items	Units	Energy equivalent (MJ $unit^{-1}$)	References
1	Diesel	1	56.1	[13]
2	N	kg	60.6	[13]
3	P	kg	11.1	[13]
4	K	kg	6.7	[12]
5	S	kg	1.12	[4]
6	Herbicides	kg	254.45	[3]
7	Insecticides	kg	184.63	[8]
8	Rice bean / Green Gram	kg	14.03	[5]
9	Safflower	kg	14	[1]
10	Farm machines	hour	62.7	[13]
11	Labour (Adult man)	man hour	1.96	[13]
12	Safflower oil	kg	39.5	[1]
13	Stover (Rice bean, safflower)	kg	18	[18]

Energy use efficiency

The energy input referred to both renewable and non-renewable energy, Renewable energy constituted manual, animal (bullock), seed, manure etc., whereas, non-renewable energy encompassed chemical fertilizer, tractor, diesel, electricity, lubricants, machinery, and agrochemicals etc., Total physical output referred to both grain/seed and by-product yield. For estimation of energy inputs and outputs (expressed in MJ ha^{-1}) for each item of inputs and agronomic practices, energy equivalents were utilized (Table No. 2). Based on the energy equivalents of the inputs and output, energy use efficiency, energy productivity [17], energy intensity in physical terms and energy intensity in economic terms [6] were calculated.

$$\text{Energy use efficiency (\%)} = \frac{\text{Total energy output (MJ ha}^{-1})}{\text{Total energy output (MJ ha}^{-1}}$$

Net energy (MJ ha^{-1}) = Energy output (MJ ha^{-1}) – Energy input (MJ ha^{-1})

$$\text{Energy productivity (kg MJha}^{-1}) = \frac{[\text{Total output (grain + stover) (MJ ha}^{-1}]}{\text{Total energy input (MJha}^{-1})}$$

$$\text{Energy intensity in economic terms (MJ ₹}^{-1}) = = \frac{\text{Total energy output (MJ ha}^{-1})}{\text{Cost of cultivation (₹ ha}^{-1})}$$

$$\text{Energy intensity in physical terms (MJ kg}^{-1}) = = \frac{\text{Total energy input (MJ ha}^{-1})}{\text{Total output (grain + stover)(Kg ha}^{-1})}$$

Statistical analysis

The data recorded during the course of investigation were subjected to statistical analysis as per method of analysis of variance (Skeleton). The significance and non-significance of the treatment effect were judged with the help of ‘F’ variance ratio test. Calculated ‘F’ value (variance ratio) was compared with the table value of ‘F’ at 5% level of significance. If calculated value exceeded the table value, the effect was considered to be significant. The significant difference between the means was tested against the critical difference at 5% level of significance as described by [15].

3. Results

3.1 Energetics of rice bean

3.1.1. Energy input/output and Net energy of rice bean

The energy metrics of rice bean under varying phosphorus and sulphur levels were assessed over two consecutive years. Findings showed statistically significant differences across treatments.

Energy Input Energy input varied according to nutrient doses. The highest input was recorded under sulphur application at 30 kg/ha (4.75–4.77 GJ/ha) and phosphorus at 80 kg/ha (4.96–4.98 GJ/ha), while the lowest input was observed under sulphur 10 kg/ha (4.73–4.74 GJ/ha) and phosphorus 40 kg/ha (4.52–4.53 GJ/ha). Notably, control plots had the least input (4.05–4.07 GJ/ha), whereas the control vs rest comparison treatments registered moderately higher values (4.74–4.75 GJ/ha).

Energy Output Energy output was significantly influenced by nutrient levels. Sulphur at 30 kg/ha yielded the highest output (48.42–54.21 GJ/ha), outperforming lower doses especially in 2018. Similarly, phosphorus at 80 kg/ha delivered maximum output (48.95–54.15 GJ/ha), showing superiority over lower phosphorus rates. Control vs rest treatments also showed enhanced outputs (47.09–52.53 GJ/ha), while control plots lagged (40.56–41.63 GJ/ha).

Net Energy The net energy, reflecting the gap between energy output and input, also favored higher nutrient doses. Sulphur at 30 kg/ha yielded peak net energy gains (43.67–49.44 GJ/ha), with significant improvement over lower sulphur levels. Phosphorus at 80 kg/ha resulted in highest net energy values (43.98–49.17 GJ/ha), while phosphorus 40 kg/ha and control plots showed the lowest figures (40.73–45.85 GJ/ha and 36.51–37.56 GJ/ha respectively).

3.1.2 Energy use efficiency of rice bean

Energy input in rice bean varied significantly based on nutrient treatments. Sulphur at 30 kg/ha recorded the highest input (approx. 4.75 GJ/ha), while the lowest was under 10 kg/ha application. Similarly, phosphorus at 80 kg/ha led to maximum input (nearly 4.98 GJ/ha), with 40 kg/ha showing the least. Control plots had the lowest overall input, whereas comparative control treatments showed slightly elevated values. Energy output followed a similar trend. Highest gains were seen with sulphur at 30 kg/ha and phosphorus at 80 kg/ha (around 54 GJ/ha), significantly surpassing lower doses. Control vs rest treatments also yielded more energy than pure control setups, which remained at the bottom of the range. Net energy—reflecting actual return—was maximized under the highest nutrient levels. Both sulphur and phosphorus at their top doses delivered the strongest gains (approx. 49 GJ/ha), while minimum values were recorded in control plots and under the lowest nutrient applications.

3.1.3. Energy productivity of rice bean

Energy productivity of rice bean was notably affected by sulphur and phosphorus treatments across two growing seasons. Sulphur at 30 kg/ha yielded the highest productivity (0.61 and 0.68 kg/MJ in 2017 and 2018), closely followed by 20 kg/ha, both outperforming the 10 kg/ha rate. Phosphorus treatments were non-significant in 2017, but in 2018, 60 kg/ha recorded the highest energy productivity, comparable to 40 kg/ha and surpassing the 80 kg/ha level. Regarding control versus other treatments, no difference was observed in 2017, while in 2018, all non-control treatments showed improved energy productivity. Overall, optimal nutrient levels enhanced energy efficiency and crop performance significantly in both years.

3.1.4. Energy Intensity of Rice Bean (Physical & Economic Terms, 2017–18 & 2018–19)

Energy intensity in rice bean, both physical and economic, was influenced by sulphur and phosphorus levels as well as control treatments. Physically, the highest energy intensity was observed under sulphur 10 kg/ha (1.74 MJ/kg in 2017, 1.56 MJ/kg in 2018), whereas the lowest was under 30 kg/ha. For phosphorus, 80 kg/ha showed the highest intensity, particularly in 2018 (1.53 MJ/kg), while 40 and 60 kg/ha recorded the lowest values. Control treatments showed minimal variation in 2017 but differed in 2018.Economically, nutrient levels had no significant effect, though sulphur 20 kg/ha and phosphorus 40–60 kg/ha showed marginally higher intensity. Control treatments were notably less efficient, with the highest economic energy intensity under control in 2017 (2.10 MJ/₹) and control vs rest in 2018 (1.95 MJ/₹).

Table 3: Response of phosphorus and sulphur levels on energy use in rice bean

Treatments	Energy input (GJ ha^{-1})		Energy output (GJ ha^{-1})		Net energy (GJ ha^{-1})	
	2017	2018	2017	2018	2017	2018
Sulphur levels (kg ha^{-1})						
10	4.73	4.74	45.41	50.54	40.68	45.80
20	4.74	4.75	47.44	52.83	42.70	48.08
30	4.75	4.77	48.42	54.21	43.67	49.44
S.Em±	-	-	0.41	0.20	0.41	0.20
CD (*p*=0.05)	-	-	1.23	0.59	1.23	0.59
Phosphorus levels (kg ha^{-1})						
40	4.52	4.53	45.25	50.38	40.73	45.85
60	4.74	4.75	47.08	53.05	42.34	48.30
80	4.96	4.98	48.95	54.15	43.98	49.17
S.Em±	-	-	0.41	0.20	0.41	0.20
CD (*p*=0.05)	-	-	1.23	0.59	1.23	0.59
Control vs Rest						
Control	4.05	4.07	40.56	41.63	36.51	37.56
Rest	4.74	4.75	47.09	52.53	42.35	47.77
SEd±	-	-	0.76	0.36	0.76	0.36
CD (*p*=0.05)	-	-	1.59	0.76	1.59	0.76

Table 4: Response of phosphorus and sulphur levels on energy efficiencies in rice bean

Treatments	Energy use efficiency (%)		Energy productivity (kg MJ^{-1})		Energy intensity in physical terms (MJ kg^{-1})		Energy intensity in economic terms (MJ ₹$^{-1}$)	
	2017	2018	2017	2018	2017	2018	2017	2018
Sulphur levels (kg ha^{-1})								
10	9.6	10.7	0.58	0.64	1.74	1.56	1.95	1.95
20	10.0	11.1	0.60	0.67	1.67	1.50	1.96	1.96
30	10.2	11.4	0.61	0.68	1.64	1.46	1.92	1.94
S.Em±	0.1	0.0	0.00	0.00	0.01	0.01	0.02	0.01
CD (p=0.05)	0.26	0.13	0.01	0.01	0.05	0.02	NS	NS
Phosphorus levels (kg ha^{-1})								
40	10.0	11.11	0.60	0.67	1.67	1.50	1.95	1.94
60	9.9	11.16	0.60	0.67	1.68	1.49	1.94	1.97
80	9.9	10.9	0.59	0.65	1.69	1.53	1.94	1.94
S.Em±	0.1	0.0	0.00	0.00	0.01	0.01	0.02	0.01
CD (p=0.05)	NS	0.13	NS	0.01	NS	0.02	NS	NS
Control vs Rest								
Control	10.0	10.2	0.60	0.61	1.68	1.63	2.10	1.90
Rest	9.9	11.1	0.60	0.66	1.68	1.51	1.94	1.95
SEd±	0.2	0.1	0.01	0.00	0.03	0.01	0.03	0.01
CD (p=0.05)	NS	0.2	NS	0.01	NS	0.02	0.07	0.03

3.2 Energetics of safflower

3.2.1 Energy input/output and net energy of safflower

Energy input for safflower was uniformly assumed across all treatments (5.76 GJ/ha) due to its residual dependency on prior rice bean applications. During both years of study, safflower crop treatments were assumed to have equal energy input (5.76 GJ/ha) across all sulphur and phosphorus levels. This uniformity was based on the premise that any nutrient effects would be residual, carried over from the preceding rice bean crop, and thus not statistically differentiated in safflower. However, energy output differed significantly. Sulphur at 30 kg/ha produced the highest output (64.82–67.13 GJ/ha), closely matched by 20 kg/ha, while 10 kg/ha yielded the lowest (61.34–62.98 GJ/ha). Phosphorus treatments showed a similar trend—80 kg/ha led to peak output (64.82–67.36 GJ/ha), comparable with 60 kg/ha and notably higher than 40 kg/ha (61.07–63.37 GJ/ha). Control vs rest comparisons revealed greater energy output under treated plots (63.32–65.34 GJ/ha) than untreated controls (54.18–54.37 GJ/ha).

Net energy, calculated as output minus input, was also influenced by treatment. Sulphur at 30 kg/ha showed the highest net gain (59.06–61.37 GJ/ha), with 20 kg/ha statistically similar, both outperforming 10 kg/ha (55.58–57.22 GJ/ha). Phosphorus at 80 kg/ha provided maximum net energy (59.06–61.60 GJ/ha), slightly higher than 60 kg/ha and significantly above 40 kg/ha (55.31–57.61 GJ/ha). Control vs rest treatments followed the same pattern, with treated plots registering stronger net returns (57.56–59.58 GJ/ha) than control plots (48.42–48.61 GJ/ha). Overall, while energy input remained constant across treatments, output and net energy were clearly enhanced by higher nutrient applications and integrated management, validating the importance of balanced phosphorus and sulphur supply in optimizing safflower energy efficiency and productivity.

3.2.2 Energy use efficiency of safflower

Energy use efficiency (EUE) of safflower was significantly impacted by nutrient treatments across both years. Sulphur applied at 30 kg/ha resulted in the highest EUE (11.26% and 11.66% in 2017–18 and 2018–19), performing similarly to 20 kg/ha and markedly better than 10 kg/ha, which recorded the lowest efficiency. For phosphorus treatments, 80 kg/ha produced the highest EUE (11.26% and 11.70%), comparable to 60 kg/ha and significantly higher than 40 kg/ha, which showed minimum values (10.61% and 11.01%). In control versus rest comparisons, treated plots consistently exhibited greater efficiency (11% and 11.35%), while control plots registered the lowest EUE (9.41% and 9.44%) across both seasons. Overall, higher phosphorus and sulphur applications enhanced energy utilization, demonstrating the importance of balanced nutrient supply for sustainable safflower production.

3.3.3 Energy productivity of safflower

Energy productivity in safflower was notably influenced by nutrient treatments over 2017–18 and 2018–19. Statistically, sulphur at 30 kg/ha delivered the highest productivity (0.66 and 0.68 kg/MJ), performing on par with 20 kg/ha and significantly better than 10 kg/ha, which yielded the lowest values (0.62 and 0.64 kg/MJ). Similarly, phosphorus at 80 kg/ha resulted in maximum productivity (0.66 and 0.69 kg/MJ), matching 60 kg/ha but surpassing 40 kg/ha, the weakest performer (0.62 and 0.65 kg/MJ). In control vs rest treatments, plots receiving nutrient applications recorded higher energy productivity (0.64 and 0.67 kg/MJ), while untreated controls showed the least efficiency (0.55 kg/MJ in both years). Overall, balanced sulphur and phosphorus levels significantly enhanced safflower's energy conversion efficiency.

Energy Intensity of Safflower (2017–18 & 2018–19)

Physical Terms: Energy intensity (MJ/kg) was significantly affected by sulphur, phosphorus, and control treatments. Maximum physical energy intensity occurred under 10 kg/ha sulphur (1.61 and 1.56 MJ/kg), while 30 kg/ha sulphur showed the lowest values (1.52 and 1.47 MJ/kg). For phosphorus, 40 kg/ha recorded the highest intensity (1.62 and 1.55 MJ/kg), outperforming 60 kg and 80 kg in 2017, and remaining statistically higher than 80 kg in 2018. The lowest physical intensity was seen under 80 kg phosphorus (1.52 and 1.46 MJ/kg). Control plots exhibited the highest intensity (1.82 and 1.81 MJ/kg), whereas control vs rest showed lower values (1.56 and 1.50 MJ/kg), indicating better efficiency under treated conditions.

Economic Terms: Energy intensity (MJ/₹) rose with increasing nutrient application. Sulphur at 30 kg/ha yielded the highest values (5.04 and 4.98 MJ/₹), comparable to 20 kg/ha and significantly better than 10 kg/ha (4.77 and 4.67 MJ/₹). Phosphorus at 80 kg/ha recorded the peak intensity (5.04 and 4.99 MJ/₹), matching 60 kg but surpassing 40 kg/ha (4.75 and 4.70 MJ/₹). Control treatments showed the least efficiency (4.21 and 4.03 MJ/₹), while control vs rest treatments performed better (4.92 and 4.84 MJ/₹).

Table 5: Residual response of phosphorus and sulphur levels on energy use in safflower

Treatments	Energy input (GJ ha^{-1})		Energy output (GJ ha^{-1})		Net energy (GJ ha^{-1})	
	2017-18	2018-19	2017	2018	2017	2018
Sulphur levels (kg ha^{-1})						
10	5.76	5.76	61.34	62.98	55.58	57.22
20	5.76	5.76	63.79	65.91	58.03	60.15
30	5.76	5.76	64.82	67.13	59.06	61.37
S.Em±	-	-	0.53	0.80	0.53	0.80
CD (*p*=0.05)	-	-	1.58	2.36	1.58	2.36
Phosphorus levels (kg ha^{-1})						
40	5.76	5.76	61.07	63.37	55.31	57.61
60	5.76	5.76	64.06	65.29	58.30	59.53
80	5.76	5.76	64.82	67.36	59.06	61.60
S.Em±	-	-	0.53	0.80	0.53	0.80
CD (*p*=0.05)	-	-	1.58	2.36	1.58	2.36
Control vs Rest						
Control	5.76	5.76	54.18	54.37	48.42	48.61
Rest	5.76	5.76	63.32	65.34	57.56	59.58
SEd±	-	-	0.97	1.45	0.97	1.45
CD (*p*=0.05)	-	-	2.04	3.05	2.04	3.05

Table 6: Residual response of phosphorus and sulphur levels on energy efficiencies in safflower

Treatments	Energy use efficiency (%)		Energy productivity (kg MJ^{-1})		Energy intensity in physical terms (MJ kg^{-1})		Energy intensity in economic terms (MJ ₹$^{-1}$)	
	2017	2018	2017	2018	2017	2018	2017	2018
Sulphur levels (kg ha^{-1})								
10	10.65	10.94	0.62	0.64	1.61	1.56	4.77	4.67
20	11.08	11.45	0.65	0.67	1.54	1.49	4.96	4.88
30	11.26	11.66	0.66	0.68	1.52	1.47	5.04	4.98
S.Em±	0.09	0.14	0.01	0.01	0.01	0.02	0.04	0.06
CD (*p*=0.05)	0.28	0.41	0.02	0.02	0.04	0.05	0.12	0.18
Phosphorus levels (kg ha^{-1})								
40	10.61	11.01	0.62	0.65	1.62	1.55	4.75	4.70
60	11.12	11.34	0.65	0.67	1.54	1.51	4.98	4.84
80	11.26	11.70	0.66	0.69	1.52	1.46	5.04	4.99
S.Em±	0.09	0.14	0.01	0.01	0.01	0.02	0.04	0.06
CD (*p*=0.05)	0.28	0.41	0.02	0.02	0.04	0.05	0.12	0.18
Control vs Rest								
Control	9.41	9.44	0.55	0.55	1.82	1.81	4.21	4.03
Rest	11.00	11.35	0.64	0.67	1.56	1.50	4.92	4.84
SEd±	0.17	0.25	0.01	0.01	0.02	0.03	0.08	0.11
CD (*p*=0.05)	0.36	0.53	0.02	0.03	0.05	0.06	0.16	0.23

3.3 Energetics of rice bean- safflower cropping system

3.3.1 Energy Input, Output & Net Energy in Rice Bean–Safflower Cropping System (2017–18 & 2018–19)

Energy Input: Energy input varied significantly with treatment levels. The highest input was recorded with sulphur at 30 kg/ha (10.51–10.52 GJ/ha) and phosphorus at 80 kg/ha (10.72–10.73 GJ/ha), both exceeding lower application rates. Control vs rest treatments also showed increased input (10.50–10.51 GJ/ha), while pure control plots had the lowest values (9.81–9.82 GJ/ha).

Energy Output: Sulphur at 30 kg/ha and phosphorus at 80 kg/ha led to maximum output (up to 121.51 GJ/ha), outperforming lower nutrient levels. Treatments with 20 kg sulphur and 60 kg phosphorus showed intermediate results. Control vs rest treatments offered better yields (110.41–117.87 GJ/ha) compared to control (94.74–96 GJ/ha).

Net Energy: Net energy, calculated as output minus input, was highest with 30 kg sulphur (102.73–110.81 GJ/ha) and 80 kg phosphorus (103.04–110.77 GJ/ha). These treatments significantly exceeded those with lower nutrient applications. Control vs rest treatments also showed greater net returns (99.91–107.35 GJ/ha), while control plots remained least efficient (84.92–86.17 GJ/ha).

3.3.2 Energy use efficiency of rice bean-safflower system

The energy use efficiency (EUE) of the rice bean–safflower cropping system was notably affected by sulphur, phosphorus, and control treatments across both study years. Sulphur applied at 30 kg/ha yielded the highest EUE (21.45% in 2017–18 and 23.04% in 2018–19), performing on par with 20 kg/ha initially, and significantly better than 10 kg/ha throughout. Phosphorus at 80 kg/ha also achieved maximum EUE (21.12% and 22.58%), surpassing lower doses in the first year, though differences were not statistically significant in the second. Control vs rest comparisons revealed stronger efficiency in treated plots (20.93% and 22.40%), while untreated controls showed the least effectiveness (19.42% and 19.68%). Overall, increased nutrient applications clearly enhanced the system's energy efficiency.

3.3.3. Energy intensity

Energy intensity in economic terms for the rice bean–safflower cropping system showed notable differences across treatments.

Sulphur application at 30 kg/ha resulted in the highest values (6.95 MJ/₹ in 2017–18 and 6.92 MJ/₹ in 2018–19), matching the performance of 20 kg/ha and significantly outperforming 10 kg/ha, which had the lowest readings (6.72 and 6.62 MJ/₹). Similarly, phosphorus applied at 80 kg/ha led to the greatest economic energy intensity (6.98 and 6.93 MJ/₹), equalling the results from 60 kg/ha and exceeding those from 40 kg/ha, which recorded the minimum (6.69 and 6.64 MJ/₹). Control vs rest treatments also demonstrated improved efficiency (6.86 and 6.79 MJ/₹), while control plots showed the lowest figures (6.31 and 5.93 MJ/₹) in both years. These trends highlight that optimal nutrient application substantially boosts energy intensity per economic return, enhancing system performance.

Table 7: Response of phosphorus and sulphur levels on energy use in ricebean-safflower cropping system

Treatments	Energy input ($GJ\ ha^{-1}$)		Energy output ($GJ\ ha^{-1}$)		Net energy ($GJ\ ha^{-1}$)		Energy use efficiency (%)		Energy intensity in economic terms ($MJ\ ₹^{-1}$)	
	2017-18	2018-19	2017-18	2018-19	2017-18	2018-19	2017-18	2018-19	2017-18	2018-19
Sulphur levels ($kg\ ha^{-1}$)										
10	10.49	10.50	106.75	113.52	96.26	103.02	20.25	21.60	6.72	6.62
20	10.50	10.51	111.23	118.74	100.73	108.23	21.09	22.56	6.91	6.85
30	10.51	10.52	113.24	121.34	102.73	110.81	21.45	23.04	6.95	6.92
S.Em±	-	-	0.72	0.81	0.72	0.81	0.13	0.14	0.05	0.06
CD (p=0.05)	-	-	2.13	2.41	2.13	2.41	0.40	0.42	0.14	0.18
Phosphorus levels ($kg\ ha^{-1}$)										
40	10.28	10.29	106.32	113.75	96.05	103.46	20.62	22.12	6.69	6.64
60	10.50	10.51	111.14	118.34	100.64	107.83	21.06	22.50	6.92	6.81
80	10.72	10.73	113.77	121.51	103.04	110.77	21.12	22.58	6.98	6.93
S.Em±	-	-	0.72	0.81	0.72	0.81	0.13	0.14	0.05	0.06
CD (p=0.05)	-	-	2.13	2.41	2.13	2.41	0.40	NS	0.14	0.18
Control vs Rest										
Control	9.81	9.82	94.74	96.00	84.92	86.17	19.42	19.68	6.31	5.93
Rest	10.50	10.51	110.41	117.87	99.91	107.35	20.93	22.40	6.86	6.79
SEd±	-	-	1.31	1.48	1.31	1.48	0.24	0.26	0.09	0.11
CD (p=0.05)	-	-	2.75	3.12	2.75	3.12	0.51	0.55	0.18	0.23

4. Discussion

Recent research [15] has underscored the value of rice bean–safflower cropping systems, especially in improving nutrient use, energy efficiency, and sustainable farming in rice-fallow zones. A [16] spotlighted how combining pulses and oilseeds like rice bean and safflower in eastern India's post-rice fields can optimize land use. These short-duration, water-efficient crops enhance productivity, improve soil through nitrogen fixation, and contribute to resilience under limited moisture. A [13] assessed safflower under rice-based systems using STCR-based nutrient strategies. Applying 75% of recommended NPK based on soil testing resulted in superior yield and profits compared to no-fertilizer plots. Precision nutrient management boosted energy output and economic efficiency.

Research by [12] examined nitrogen management in hybrid rice–safflower systems. Organic inputs such as cow dung urine and FYM improved energy conversion efficiency and output-input ratios over chemical-only treatments, proving their sustainability benefits. A [17] study emphasized the importance of crop diversification, showing that integrating safflower and pulses into rice systems improves soil health, microbial activity, and nutrient cycling. These diversified models also delivered better economic and ecological outcomes than traditional rice–wheat monocultures.

Recent trials in [19, 20] validated SSNM approaches for safflower, showing that tailoring fertilizer doses based on soil test values significantly improves yield, energy efficiency, and nutrient uptake. These studies support the idea that precision nutrient management is key to optimizing both crop performance and resource use. [14] highlighted that rice-based systems are energy-intensive but can be made more efficient through crop rotation, organic amendments, and reduced tillage. It emphasized the importance of calculating energy input–output ratios to guide sustainable intensification Together, these studies advocate for the rice bean–safflower rotation as a robust pathway to low-input, resource-efficient, and climate-resilient agriculture.

Sulphur Levels: Energy input in rice bean rose with increasing sulphur doses, largely due to sulphur's higher energy cost and varied labour needs. Treatments with 30 kg/ha sulphur delivered the highest output, net energy, energy productivity, and use efficiency—especially in the second year. Lower sulphur levels (10 kg/ha) resulted in reduced biomass and energy output, linked to nutrient deficiency and increased plant mortality. Energy intensity in physical terms was highest at 10 kg/ha sulphur, while it declined as sulphur levels increased, reaching its lowest at 30 kg/ha. Conversely, economic energy intensity peaked at 20 kg/ha, though differences across sulphur treatments were not statistically significant. The enhanced seed and stover yield from sulphur promoted energy gains and system efficiency.

Phosphorus Levels: Energy input also increased with higher phosphorus rates due to its inherent energy cost and labour dynamics. Application of 80 kg/ha phosphorus resulted in significantly higher energy output and efficiency across both years. Lower phosphorus levels led to weaker biomass, limiting output energy due to poor nutrient availability and disease pressure. In 2018, physical energy intensity peaked at 80 kg/ha phosphorus, but was statistically uniform across treatments in 2017. Economic energy intensity, however, reached its highest at 40 kg/ha phosphorus in 2017, likely due to favorable input-to-output cost ratios. In 2018, peak values shifted to 60 kg/ha, possibly influenced by market conditions and pricing. Phosphorus aided in photosynthate movement and sink development, boosting harvestable yield and overall energy gains.

Sulphur Response on Safflower Energetics: While energy input remained stable, sulphur applied in the preceding rice bean crop showed strong residual effects on safflower energetics. The 30 kg/ha sulphur level led to significantly higher energy output, net energy, energy use efficiency, and productivity compared to

10 kg/ha, and performed on par with 20 kg/ha. Compared to control plots, gross energy rose by up to 23.46%, and net energy by 26.24%.

The higher yield under 30 kg/ha was attributed to improved nutrient uptake and soil enrichment. Conversely, 10 kg/ha sulphur resulted in reduced efficiency and productivity due to insufficient nutrient supply. Physical energy intensity dropped with increasing sulphur, with maximum intensity under control treatments. The economic energy intensity was highest at 30 kg/ha, mainly due to lower cultivation costs and higher output from better biological yield.

Phosphorus Response on Safflower Energetics: Phosphorus applied to rice bean had notable residual effects on safflower energy parameters. The 80 kg/ha phosphorus rate recorded the highest gross and net energy, matching 60 kg/ha statistically and outperforming lower doses. Compared to control, gross energy output rose by up to 23.89%, and net energy by 26.72%.

Improved soil fertility boosted growth and yield, enhancing energy performance. The lowest productivity and efficiency were linked to minimum phosphorus levels, potentially due to imbalanced nutrient effects. Physical energy intensity reduced under higher phosphorus, especially 80 kg/ha, showing a 23.97% decrease compared to control. In contrast, 40 kg/ha phosphorus showed higher intensity due to weaker yields. Economically, energy intensity peaked under 80 kg/ha, attributed to optimized output and cost-effectiveness.

Energetics of rice bean-safflower system

Energy input in the rice bean–safflower cropping system was higher during 2018–19 compared to 2017–18, mainly due to increased labor usage. Among sulphur treatments, 30 kg/ha resulted in the highest input (10.51–10.52 GJ/ha), followed closely by 20 kg/ha. This is largely attributed to the energy contribution of chemical fertilizers, especially sulphur, phosphorus, nitrogen, and potassium.

Sulphur had a significant influence on gross and net energy outputs, with 30 kg/ha producing the highest results in both years and performing on par with 20 kg/ha in 2017–18. Its positive effect on rice bean growth and residual benefit to safflower contributed to the energy gains.

Phosphorus at 80 kg/ha led to the highest energy input (10.72–10.73 GJ/ha) and substantially increased system-wide energy output and net energy, driven by enhanced biological yields in both crops. Maximum gross (113.77–121.51 GJ/ha) and net energy (103.04–110.77 GJ/ha) were recorded at this rate.

Energy use efficiency and economic energy intensity improved with increasing sulphur and phosphorus levels. The highest values were seen with 30 kg/ha sulphur and 80 kg/ha phosphorus, comparable to 20 kg/ha sulphur and 60 kg/ha phosphorus, respectively. This was due to greater dry matter yield, resulting in more energy generation. Lower nutrient rates showed reduced efficiency, mainly due to higher chemical fertilizer energy input—especially from nitrogen and potassium and lower safflower yield.

5. Conclusion

The rice bean–safflower cropping system showed significant improvements in energy-related parameters when managed with optimal nutrient levels. Applying sulphur at 30 kg/ha and phosphorus at 80 kg/ha led to the highest energy input, gross and net energy output, energy productivity, and energy use efficiency, while simultaneously lowering energy intensity in physical and economic terms. These enhancements were attributed to increased biomass yield, better nutrient uptake, and strong residual effects on the succeeding safflower crop. Moving forward, research should focus on region-specific nutrient strategies, long-term performance across diverse climates, integration of organic and inorganic sources, and environmental impact assessments including carbon footprint. Incorporating precision agriculture and decision-support systems will further refine energy budgeting, helping to build sustainable, low-input, and resilient cropping models for rainfed and semi-arid farming.

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