

Research Article

Optimizing sulphur fertilization for enhanced energy-carbon efficiency and biological yield of rice-groundnut cropping system

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Abstract

Rice-groundnut is one of the most important cropping systems in Eastern India. Optimization of sulphur fertilization positively affects the energy and carbon balance, contributing to long-term sustainability of the system. An experiment was conducted with the aim of finding energy - carbon efficient and productive sulphur management practices for the system. Five sulphur fertilization strategies for rice (no sulphur, 20 kg S/ha as bentonite, 20 kg S/ha as gypsum, 40 kg S/ha as bentonite, and 40 kg S/ha as gypsum) assigned to main plots, and three sulphur levels (kg/ha) for groundnut (0, 30 and 60) assigned to the subplots were laid out in a split-plot design with four replications during 2021–22 and 2022–23 at Bhubaneswar, Odisha, India. Sulphur @ 40 kg/ha as gypsum/bentonite in rice recorded higher system energy use efficiency (12.83/12.72), energy productivity (6.06/6.01) and energy profitability (11.83/11.72) than other fertilization methods. Application of 40 kg S/ha as gypsum in rice was the most carbon-efficient (system carbon efficiency, 3.59) and had the minimum carbon footprint (0.123 kg C equivalent/kg biomass), keeping 40 kg/ha bentonite S at par. Among the S levels in groundnut, 60 kg/ha was the most energy-efficient, with system energy use efficiency (12.31%), energy productivity (5.86 kg/MJ), and energy profitability (11.31). Carbon efficiency decreased with increasing S levels in groundnut. The combined application of 40 kg S/ha as gypsum/bentonite in rice and 60 kg S/ha in groundnut was the most productive (biological yield: 18.22/18.17 t/ha, respectively) and energy-efficient. Future research should explore low-carbon or carbon-neutral sulphur sources to enhance the system's carbon efficiency.

Key words: Carbon equivalent, Carbon footprint, Energy equivalent, Energy output, Sustainability

INTRODUCTION

Rice, the most widely cultivated staple crop, covers 165 M ha globally with an annual production of 523 million tons (Mt) and a productivity of 4.32 t/ha, while India, the second-largest producer, contributes 196 Mt from 46.4 M ha with a productivity of 4.22 t/ha (FAOSTAT, 2022). Groundnut, a major protein-rich oilseed, is grown on 30.5 M ha worldwide, yielding 54.2 Mt annually with productivity of 1.77 t/ha (FAOSTAT, 2022). The rice-groundnut cropping system is predominant in eastern

and southern India, including Odisha.

Sulphur is a vital nutrient in the rice (*Oryza sativa*)–groundnut (*Arachis hypogaea*) cropping system, essential for protein and oil synthesis, chlorophyll formation, and nitrogen fixation in legumes (Giri *et al.*, 2025). Research in eastern India, especially Odisha, reveals widespread sulphur deficiency, affecting about 36–44% of soils. Field trials show that applying 40 kg S/ha via gypsum to rice and 60 kg S/ha to groundnut significantly enhances growth, yield, quality, and farm profitability, doubling net returns and increasing profitability by

106% compared to no-sulphur controls (Giri *et al.*, 2025). The leading causes of sulphur deficiency include limited application of sulphur-containing fertilizers, intensive cropping systems, and reduced use of sulphur-based fungicides (Narayan *et al.*, 2023). Deficiency impairs physiological processes, reducing growth and rice productivity (Samant *et al.*, 2023), while adequate sulphur in groundnut improves pod yield (Dileep *et al.*, 2021).

Energy auditing and carbon budgeting are vital for sustainable rice-groundnut production. These energy-intensive systems require optimized input management to ensure economic and environmental sustainability. Improving energy use efficiency reduces dependence on non-renewable resources and environmental harm, while carbon budgeting helps mitigate greenhouse gas emissions and enhances soil carbon sequestration (Lal, 2004). In Odisha, climate variability and resource constraints demand strategies that maximize energy and carbon efficiency to support resilient agriculture (Das *et al.*, 2019). Using renewable energy sources and improving input management reduces energy consumption, costs, and environmental impact (Nabavi-Pelesaraei *et al.*, 2023).

Despite progress in agricultural research, the energy dynamics of sulphur-dependent rice-groundnut systems in Odisha remain unexplored. Energy accounting, balancing inputs (labour, machinery, fertilizers, irrigation) and outputs (crop yields), is essential for evaluating sustainability. Fertilizer inputs alone may account for up to 58% of total energy costs (Ansari *et al.*, 2021), highlighting the need to assess the energy impact of sulphur supplementation in this system. Carbon budgeting involves examining fertilizer use, fossil fuels, crop residues, root biomass, and emissions. Sulphur management significantly affects soil carbon dynamics and the environment (Mohanty *et al.*, 2024).

The present study was undertaken with the hypothesis that judicious sulphur management in the rice-groundnut cropping system would maximize biological yield (economic yield + residue) of the component crops and minimize the system's energy and carbon footprints.

MATERIALS AND METHODS

A field experiment was conducted during the *kharif* and *rabi* seasons of 2021–22 and 2022–23 at the Agricultural Research Station, Chhatabar, Siksha 'O' Anusandhan University, Bhubaneswar, Odisha (20°26' N; 85°68' E; 50.9 m above mean sea level), situated in the East and South-Eastern Coastal plain agro-climatic zone. The climate of Bhubaneswar is characterized by a hot, moist sub-humid climate, with hot summers and mild winters. The mean maximum temperature is 32.0 °C and the minimum is 21.3 °C, while the average

annual rainfall is 1359.3 mm, based on data from the last 10 years. The mean maximum temperature in the hottest month (June) is 36.6°C and the mean minimum temperature in the coldest month (January) is 12.8°C. The soil of the experimental site was clay loam in texture, acidic in nature (pH 5.82), low in electrical conductivity (0.45 dS/m), low in organic carbon (0.4%), medium in available nitrogen (288.6 kg/ha), medium in available phosphorus (18.54 kg/ha), medium in potassium (210 kg/ha) and low in sulphur (8.7 ppm). The soil was analyzed to determine texture, pH, electrical conductivity, organic carbon, available nitrogen, available phosphorus, available potassium and available sulphur with the methodology proposed by Bouyoucos (1962), Jackson (1973), Jackson (1973), Walkley and Black (1934), Subbiah and Asija (1956), Bray and Kurtz (1945), Jackson (1973) and Chesnin and Yien (1950), respectively. The split-plot design with four replications comprised five sulphur fertilization treatments in rice (20 and 40 kg S/ha applied as bentonite sulphur and gypsum, compared with no sulphur) in the main plots, and three sulphur levels in groundnut (S₁:0, S₂:30, and S₃:60 kg S/ha as bentonite sulphur) in the subplots. Agricultural grade gypsum (16% S) and bentonite sulphur (90% S) were used as S sources. The experiment was conducted using rice variety 'Naveen' and groundnut variety 'Devi' as test crops, both with a 120-day duration. The transplanted rice was grown in the *kharif* season with a spacing of 20 cm × 10 cm, whereas groundnut was grown in the *rabi* season, followed by rice, with a spacing of 25 cm × 10 cm. Rice was grown with the application of farmyard manure (5 t/ha) and a basal fertilizer dose of 80-40-40 kg N-P₂O₅-K₂O /ha, along with sulphur applied according to the treatment schedule. Weed control in rice was achieved through pretilachlor (0.75 kg/ha, pre-emergence) followed by a manual weeding 21 days after transplanting (DAT). Details on agro-inputs, machinery, human labour, electricity, diesel, etc. are given in Table 1. The rice crop was raised as rainfed, whereas the groundnut crop was grown under irrigated conditions. Grain yield was recorded plot-wise at 12% moisture and expressed in t/ha. Groundnut was sown using 175 kg pod/ha with a basal application of 20-40-40 kg N-P₂O₅-K₂O/ ha, while sulphur was applied through bentonite as per treatment. Pod yield was recorded plot-wise at 10% moisture and expressed in t/ha.

The energy use efficiency, energy productivity, specific energy, and net energy are calculated using the formula given below. Energy equivalent coefficients of various energy sources used for calculating input energy have been given in Table 2.

Gross Energy output (MJ/ha) = (Grain yield × Energy equivalent of grain) + (straw yield × Energy equivalent of straw) (Eq.1)

Net Energy = Gross Energy output (MJ/ha) - Energy input (MJ/ha) (Eq.2)

$$\text{Energy use efficiency} = \frac{\text{Output energy (MJ/ha)}}{\text{Input energy (MJ/ha)}} \dots (\text{Eq. 3})$$

$$\text{Energy productivity} = \frac{\text{Production (kg/ha)}}{\text{Input energy (MJ/ha)}} \dots (\text{Eq. 4})$$

$$\text{Specific energy} = \frac{\text{Input energy (MJ/ha)}}{\text{Production (kg/ha)}} \dots (\text{Eq.5})$$

$$\text{Energy Profitability} = \frac{\text{Net energy output (MJ/ha)}}{\text{Energy Input (MJ/ha)}} \dots (\text{Eq.6})$$

$$\text{Energy Intensiveness} = \frac{\text{Energy input (MJ/ha)}}{\text{Cost of Production (Rs/ha)}} \dots (\text{Eq.7})$$

The estimation of carbon inputs, carbon output, carbon sustainability index, and carbon efficiency was carried out using the methodology outlined by Behera *et al.* (2024). Emission factors (kg CO₂ e/unit) of various sources used for calculating total carbon input have been given in Table 3.

$$\text{Carbon output} = \text{Total biomass} \times 0.44 \dots (\text{Eq. 8})$$

$$\text{Carbon Efficiency} = \frac{\text{Carbon output}}{\text{Carbon input}} \dots (\text{Eq. 9})$$

$$\text{Carbon Sustainable Index} = \frac{\text{Carbon output} - \text{Carbon input}}{\text{Carbon input}} \dots (\text{Eq 10})$$

$$\text{Carbon footprint} = \frac{\text{Carbon input (kg C equivalent/ha)}}{\text{Biomass produced (kg)}} \dots (\text{Eq. 11})$$

The data collected in the field were statistically analyzed (Gomez and Gomez, 1984). The pooled analysis was conducted when the error variances for both years (2021–22 and 2022–23) were homogeneous, as indicated by Bartlett's Test. The ANOVA, followed by a post-hoc test such as LSD, was used in the study to compare means.

RESULTS AND DISCUSSION

Biological yield

Rice

Among the different treatment combinations, the application of 40 kg S/ha through gypsum (F₅) or bentonite sulphur (F₄) in rice, when coupled with 60 kg S/ha in groundnut (L₃), resulted in the highest biological yield of rice (12.0 t/ha) (Fig. 1). These combinations (F₅L₃ and F₄L₃) were statistically comparable with F₅L₂ (11.7 t/ha) and F₄L₂ (11.5 t/ha), where 40 kg S/ha was applied in rice along with 30 kg S/ha in groundnut. However, all these treatments produced yields significantly higher than those of the remaining combinations. Irrespective of the source, increasing levels of sulphur application resulted in a progressive enhancement of the biological yield of rice (Fig. 1). The improvement can be attributed to both the direct effect

of sulphur applied to rice and the residual contribution of sulphur applied to the succeeding groundnut crop, which together maximized rice biological yield. This response was associated with improved growth parameters, translating into higher grain and straw yields. Similar positive effects of sulphur fertilization on growth and yield attributes of rice and legumes have been reported previously (Dileep *et al.*, 2021; Narayan *et al.*, 2023).

Groundnut

The highest biological yield (6.26 t/ha) was recorded under the treatment combination F₄L₃ (Fig. 2). The treatment combinations F₅L₃ (6.14 t/ha) and F₄L₂ (6.06 t/ha) produced biological yields that were statistically similar. This indicates that higher sulphur application in groundnuts, when supplemented with adequate sulphur in rice, substantially enhances biomass accumulation and overall productivity. The biological yield (pod + haulm) presented in Fig. 2 clearly indicates that groundnut productivity improved with increasing levels of sulphur application, along with the residual effect of higher sulphur doses applied to rice, irrespective of the source. This enhancement can be attributed to improved growth and yield-contributing traits which collectively resulted in higher biological yield of groundnut. Similar findings have been reported by Samant *et al.* (2023).

System

The treatment combination 40 kg S/ha in rice+ 60 kg S/ha in groundnut (F₄L₃) gave the maximum biological yield rice (grain 4.9 t/ha, straw 7.1 t/ha, biomass 12.0 t/ha), groundnut (pod 2.22 t/ha, haulm 4.04 t/ha, biomass 6.26 t/ha) and the system (economic yield 7.07 t/ha, residue 11.15 t/ha, biomass 18.22 t/ha), placing 40 kg S/ha as gypsum to rice and 60 kg sulphur to groundnut (biomass 18.15 t/ha) at par and being superior to other combinations (Fig 1, 2 and 3) revealing positive impact of S fertilization in groundnut on groundnut and rice yield.

Energetics

Rice

There was a gradual increase in input energy with increasing sulphur levels (Table 4). The application of 40 kg S/ha as gypsum to rice produced the highest gross energy output (158.5 × 10³ MJ/ha), net energy output (149.1 × 10³ MJ/ha), energy use efficiency (16.89%), energy productivity (0.513 kg/MJ), and energy profitability (15.89). In contrast, the highest specific energy (2.42 MJ/kg) was recorded under no sulphur application. For the residual effect of sulphur on groundnut, applying 60 kg S/ha resulted in maximum energy output (148.4 × 10³ MJ/ha), net energy output (139.0 × 10³ MJ/ha), energy use

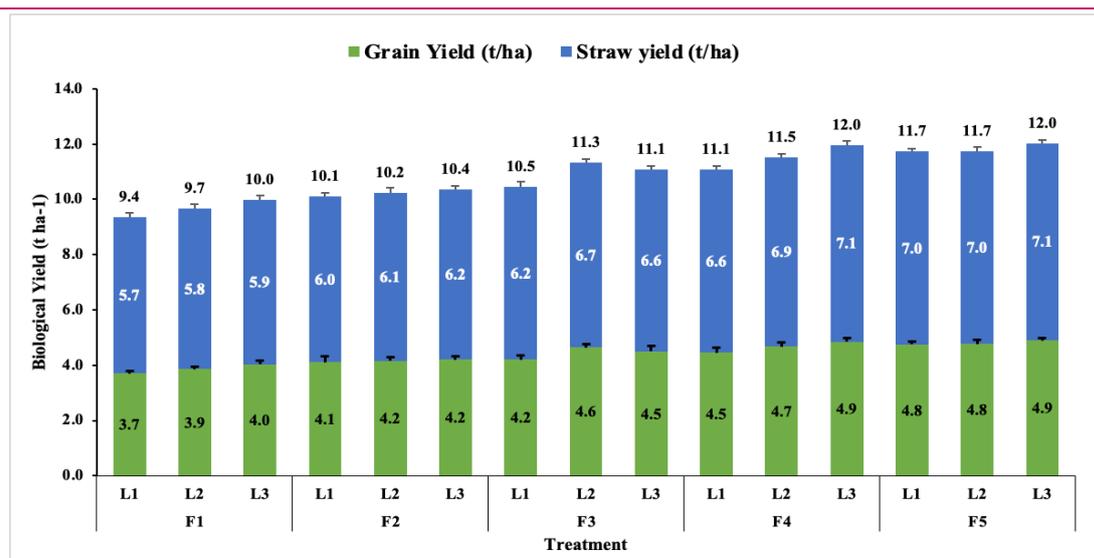


Fig. 1. Impact of sulphur management on biological yield of rice (F₁: No sulphur, F₂: 20 kg S/ha as bentonite; F₃: 20 kg S/ha as gypsum; F₄: 40 kg S/ha as bentonite; F₅: 40 kg S/ha as gypsum; L₁: 0 kg S/ha; L₂: 30 kg S/ha and L₃: 60 kg S/ha. In this fig., the sum of grain yield (green bar) and straw yield (blue bar) indicates the biological yield of rice)

efficiency (15.84%), energy productivity (0.480 kg/MJ), and energy profitability (14.84). The highest specific energy (2.23 MJ/kg) occurred without sulphur application. The highest specific energy indicates the least energy-efficient nature of the treatment.

Groundnut

There was a gradual increase in input energy when higher sulphur levels were applied to groundnuts (Table 5). The application of 60 kg S/ha to groundnut resulted

in the highest gross energy output (98.20×10^3 MJ/ha), net energy output (87.54×10^3 MJ/ha), energy use efficiency (9.21%), energy productivity (0.192 kg/MJ), and energy profitability (8.214). In contrast, the highest specific energy (6.13 MJ/kg) was observed under no sulphur application, indicating a reversal of the trend. As a residual effect of sulphur applied to rice, 40 kg S/ha as bentonite yielded the highest energy output (100.19×10^3 MJ/ha), net energy output (89.56×10^3 MJ/ha), energy use efficiency (9.43%), energy productivity (0.195

Table 1. Input requirements of rice and groundnut

Components	Rice					Groundnut		
	F ₁ : No S	F ₂ : 20 kg S/ha as bentonite	F ₃ : 20 kg S/ha as gypsum	F ₄ : 40 kg S/ha as bentonite	F ₅ : 40 kg S/ha as gypsum	L ₁ : 0 kg S/ha	L ₂ : 30 kg S/ha	L ₃ : 60 kg S/ha
Tractor / machinery (hour)	8	8	8	8	8	8	8	8
Diesel (L)	32	32	32	32	32	32	32	32
Human labourer (hour)	111	111	111	111	111	92	92	92
Rice seed (kg)	60	60	60	60	60			
Groundnut seed (kg)						175	175	175
Nitrogen (kg)	80	80	80	80	80	20	20	20
Phosphorus (kg)	40	40	40	40	40	40	40	40
Potassium (kg)	40	40	40	40	40	40	40	40
Sulphur (kg)		20	20	40	40		30	60
Boron (kg)						0.5	0.5	0.5
Weedicide (kg)	1.5	1.5	1.5	1.5	1.5			
Fungicide (kg)	0.2	0.2	0.2	0.2	0.2			
Insecticide (kg)	1.5	1.5	1.5	1.5	1.5	0.75	0.75	0.75
Manure (kg)	5000	5000	5000	5000	5000	5000	5000	5000
Irrigation (hour)						30	30	30
Electricity (kWH)						30	30	30

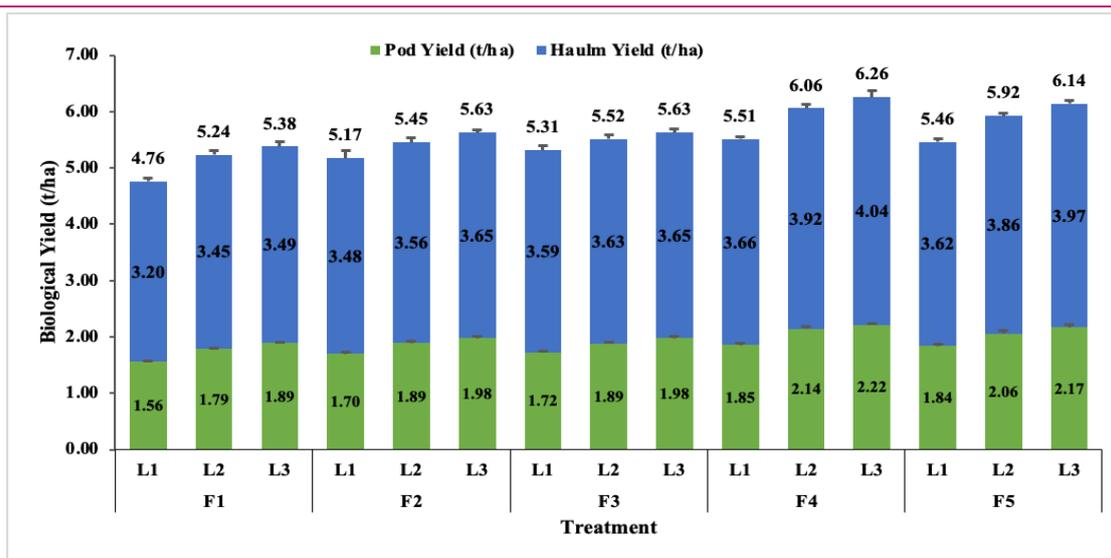


Fig. 2. Impact of sulphur management on biological yield of groundnut (F₁: No sulphur, F₂: 20 kg S/ha as bentonite; F₃: 20 kg S/ha as gypsum; F₄: 40 kg S/ha as bentonite; F₅: 40 kg S/ha as gypsum; L₁: 0 kg S/ha; L₂: 30 kg S/ha and L₃: 60 kg S/ha. In this fig., the sum of pod yield (green bar) and haulm yield (blue bar) indicates the biological yield of groundnut)

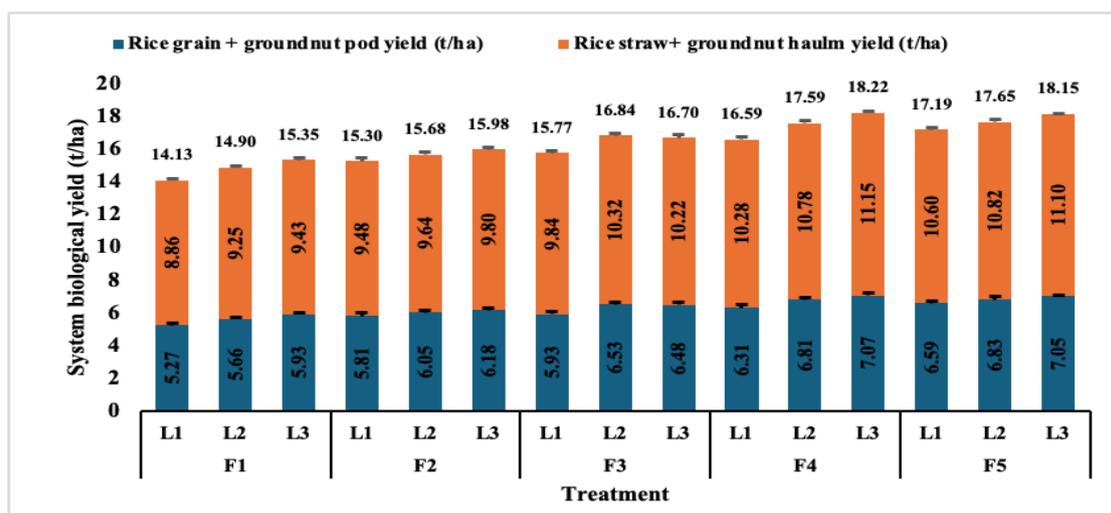


Fig. 3. Impact of sulphur management on biological yield of rice-groundnut system (S/ha as gypsum; L₁: 0 kg S/ha; L₂: 30 kg S/ha and L₃: 60 kg S/ha. In this fig., the sum of rice grain groundnut pod yield (blue bar) and rice straw + groundnut haulm yield (orange bar) indicates the biological yield of the system)

kg/MJ), and energy profitability (8.428). The highest specific energy (6.12 MJ/kg) was observed in the no-sulphur treatment.

System

There was a gradual increase in input energy with higher sulphur levels (Table 6). Application of 40 kg S/ha as gypsum to rice recorded higher gross energy output (256.76 × 10³ MJ/ha), net energy output (236.75 × 10³ MJ/ha), energy use efficiency (12.83%), energy productivity (6.06 kg/MJ), and energy profitability (11.83) than other sulphur fertilization methods. A specific energy of 2.42 MJ/kg was significantly the highest with 20 kg S/ha bentonite. Regarding sulphur applied to groundnut, 60 kg S/ha produced the highest energy output (246.57

× 10³ MJ/ha), net energy output (226.55 × 10³ MJ/ha), energy use efficiency (12.31%), energy productivity (5.86 kg/MJ), energy profitability (11.31), and specific energy (3.34 MJ/kg). Among the various components of energy input, fertilizer (N, P, K, and B) and sulphur have a major share. Fertilizer contributed 59.5, 59.6, 59.6, 59.8 and 59.8 % to input energy in F₁, F₂, F₃, F₄ and F₅, respectively (Fig. 4). Sulphur @ 40 kg/ha as gypsum/bentonite + Sulphur @ 60 kg/ha in groundnut treatment combination was the most energy efficient for rice – groundnut cropping system with the maximum EUE (13.3/13.2), EP (6.33/6.30 kg/MJ) and EPf (12.28/12.22) (Fig. 5).

In the rice-groundnut cropping system, energy requirements are primarily influenced by management

Table 2. Energy equivalent coefficients of various energy sources used in rice-groundnut cropping system

Components	Unit	Energy equivalent (MJ/ Unit)	Source
Tractor	hour	62.7	Mittal <i>et al.</i> (1985)
Human labourer	Hour	1.96	Mohammadi <i>et al.</i> (2008)
Rice seed	kg	14.7	Mittal <i>et al.</i> (1985)
Rice straw	kg	12.5	Mittal <i>et al.</i> (1985)
Groundnut seed	Kg	25	Nia <i>et al.</i> (2024)
Groundnut haulm	kg	12.5	Nia <i>et al.</i> (2024)
Nitrogen	kg	60.6	Yadav <i>et al.</i> (2017)
Phosphorus	kg	11.1	Yadav <i>et al.</i> (2017)
Potassium	kg	6.7	Yadav <i>et al.</i> (2017)
Sulphur	kg	1.12	Rana <i>et al.</i> (2021)
Boron	kg	120	Canakci and Akinci, 2006
Weedicide	kg	120	Canakci and Akinci, 2006
Fungicide	kg	196	Nia <i>et al.</i> , 2024
Insecticide	kg	199	Nia <i>et al.</i> , 2024
Manure	kg	0.3	Nia <i>et al.</i> , 2024
Irrigation	Hour	62.7	Rana <i>et al.</i> (2021)

Table 3. Emission factor (kg CO₂ e/unit) of various sources used in rice-groundnut cropping system

Components	Unit	Emission Factor (kg CO ₂ e / Unit)	Source
Machinery	hour	3.32	Choudhury <i>et al.</i> (2017)
Diesel	L	3.32	Rana <i>et al.</i> (2021)
Human labourer	kg	0.86	Rana <i>et al.</i> (2021)
Electricity	kWH	7.25	Rana <i>et al.</i> (2021)
Manure	T	0.007	Choudhury <i>et al.</i> (2017)
Seed	kg	1.22	Choudhury <i>et al.</i> (2017)
Nitrogen	kg	4.96	Lal (2004)
Phosphorus	kg	1.35	Lal (2004)
Potassium	kg	0.58	Lal (2004)
Sulphur	kg	7.3	Rana <i>et al.</i> (2021)
Boron	kg	9.1	Rana <i>et al.</i> (2021)
Weedicide	L	6.3	Choudhury <i>et al.</i> (2017)
Fungicide	kg	3.9	Choudhury <i>et al.</i> (2017)
Insecticide	L	5.1	Lal (2004)
Irrigation	Hour	1.02	Rana <i>et al.</i> (2021)

practices and external input levels (Pan *et al.*, 2024). Sulphur application rate and source significantly affected energy inputs (Kumar *et al.*, 2019), while energy output was determined by total biomass, including grain and straw (Fatima *et al.*, 2023). The 40 kg S/ha gypsum application was the most energy-efficient, delivering higher gross energy output with lower energy inputs (Pan *et al.*, 2022). This enhanced energy productivity was due to higher biomass yield per

unit of energy (Behera *et al.*, 2024). No-sulphur treatments exhibited the highest specific energy due to reduced biomass, resulting in lower energy output (Yadav *et al.*, 2020).

Carbon budgeting

Rice

Total carbon input increased with rising sulphur levels, regardless of the sulphur source applied to rice (Table

Table 4. Effect of sulphur management in rice-groundnut cropping system on the energetics of rice

Treatments	Total input energy (x 10 ³ MJ/ ha)	Gross energy output (x 10 ³ MJ/ ha)	Net energy Output (x10 ³ MJ/ha)	Energy use efficiency (%)	Energy productivity (kg/ MJ)	Specific energy (MJ/kg)	Energy intensiveness (MJ/Rs.)	Energy profitability
Sulphur fertilization in rice								
F ₁ : No sulphur	9.34	129.4	120.0	13.86	0.415	2.42	0.17	12.86
F ₂ : 20 kg S/ha as bentonite	9.36	137.0	127.7	14.64	0.444	2.26	0.16	13.64
F ₃ : 20 kg S/ha as gypsum	9.36	146.7	137.3	15.68	0.476	2.11	0.16	14.68
F ₄ : 40 kg S/ha as bentonite	9.38	154.3	144.9	16.45	0.497	2.02	0.16	15.45
F ₅ : 40 kg S/ha as gypsum	9.38	158.5	149.1	16.89	0.513	1.95	0.16	15.89
CD (P=0.05)	-	2.86	2.86	0.31	0.014	0.07	-	0.31
Sulphur levels (kg S /ha) in groundnut								
L ₁ : 0	9.36	141.2	131.8	15.08	0.454	2.23	0.16	14.08
L ₂ : 30	9.36	145.9	136.6	15.59	0.472	2.13	0.16	14.59
L ₃ : 60	9.36	148.4	139.0	15.84	0.480	2.10	0.16	14.84
CD (P=0.05)	-	1.7	1.74	0.19	0.007	0.03	-	0.19

Table 5. Effect of sulphur management in rice-groundnut cropping system on energetics of groundnut

Treatments	Total input energy (x 10 ³ MJ/ ha)	Total energy output (x 10 ³ MJ/ ha)	Net energy output (x10 ³ MJ/ha)	Energy use efficiency (%)	Energy productivity (kg/ MJ)	Specific energy (MJ/kg)	Energy intensiveness (MJ/Rs.)	Energy profitability
Sulphur fertilization in rice								
F ₁ : No sulphur	10.62	85.91	75.28	8.08	0.164	6.12	0.167	7.084
F ₂ : 20 kg S/ha as bentonite	10.62	90.93	80.31	8.56	0.175	5.75	0.167	7.558
F ₃ : 20 kg S/ha as gypsum	10.62	91.89	81.27	8.65	0.175	5.72	0.167	7.648
F ₄ : 40 kg S/ha as bentonite	10.62	100.19	89.56	9.43	0.195	5.16	0.167	8.428
F ₅ : 40 kg S/ha as gypsum	10.62	98.31	87.68	9.25	0.190	5.28	0.167	8.251
CD (P=0.05)	-	1.43	1.44	0.14	0.003	0.10	-	0.135
Sulphur levels (kg S /ha) in groundnut								
L ₁ : 0	10.59	87.25	76.66	8.24	0.164	6.13	0.171	7.238
L ₂ : 30	10.62	94.88	84.26	8.93	0.184	5.47	0.167	7.930
L ₃ : 60	10.66	98.20	87.54	9.21	0.192	5.22	0.163	8.214
CD (P=0.05)	-	0.51	0.52	0.05	0.001	0.04	-	0.049

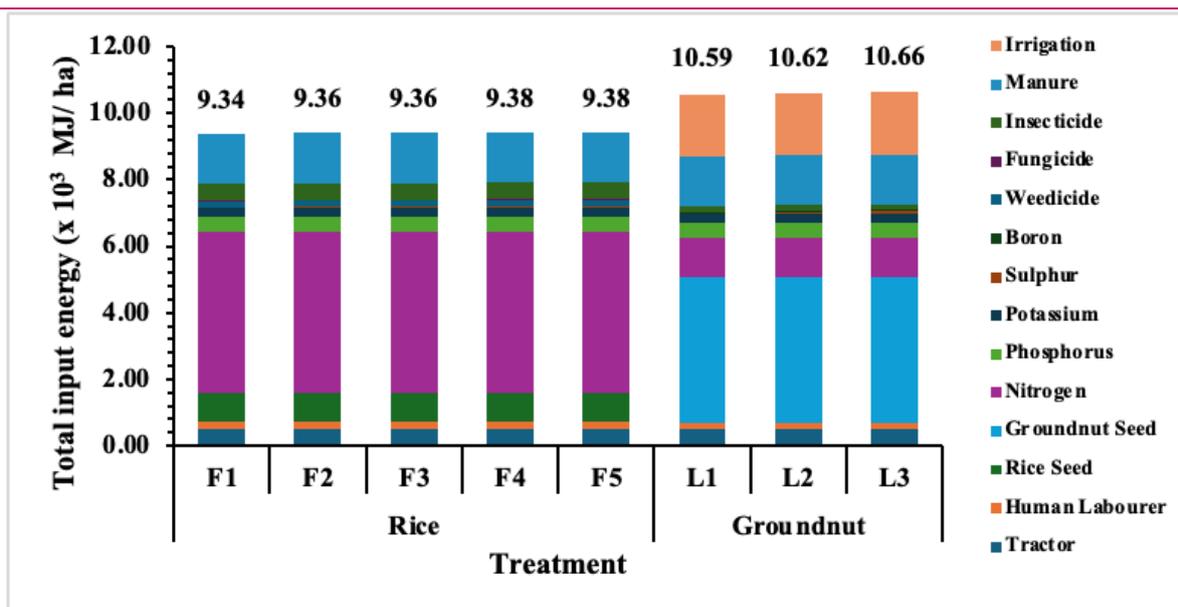


Fig. 4. Treatment wise input energy of rice-groundnut system under sulphur management (F₁: No sulphur, F₂: 20 kg S/ha as bentonite; F₃: 20 kg S/ha as gypsum; F₄: 40 kg S/ha as bentonite; F₅: 40 kg S/ha as gypsum; L₁: 0 kg S/ha; L₂: 30 kg S/ha and L₃: 60 kg S/ha)

Table 6. Effect of sulphur management in rice-groundnut cropping system on energetics of the system

Treatments	Total input energy (x 10 ³ MJ/ ha)	Energy output (x 10 ³ MJ/ ha)	Net energy (x10 ³ MJ/ ha)	Energy use efficiency (%)	Energy productivity (kg/ MJ)	Specific energy (MJ/kg)	Energy intensiveness (MJ/Rs.)	Energy profitability
Sulphur fertilization in rice								
F ₁ : No sulphur	19.96	215.28	195.32	10.78	5.04	2.73	5.25	9.78
F ₂ : 20 kg S/ha as bentonite	19.98	227.97	207.99	11.41	5.38	3.26	6.21	10.41
F ₃ : 20 kg S/ha as gypsum	19.98	238.60	218.61	11.94	5.61	3.21	6.25	10.94
F ₄ : 40 kg S/ha as bentonite	20.01	254.48	234.47	12.72	6.01	3.17	5.83	11.72
F ₅ : 40 kg S/ha as gypsum	20.01	256.76	236.75	12.83	6.06	2.96	5.54	11.83
CD (P=0.05)		3.34	3.34	0.17	0.10	1.18	1.65	0.17
Sulphur levels (kg S /ha) in groundnut								
L ₁ : 0	19.95	228.45	208.50	11.45	5.30	2.82	5.35	10.45
L ₂ : 30	19.99	240.83	220.84	12.05	5.70	3.04	5.68	11.05
L ₃ : 60	20.02	246.57	226.55	12.31	5.86	3.34	6.43	11.31
CD (P=0.05)		1.78	1.78	0.09	0.05	0.48	0.70	0.09

7). The highest total carbon output (5205.2 kg C eq./ha) was achieved with 40 kg S/ha gypsum application in rice, representing an 18.2% increase over no sulphur treatment. However, the maximum carbon use efficiency (CUE: 5.26) and carbon sustainability index (CSI: 4.26) were observed under no sulphur

application, while the highest carbon footprint (CFP: 0.096 kg C eq./kg biomass) occurred with 40 kg S/ha bentonite. The residual sulphur effect on groundnut significantly influenced carbon parameters. Total energy output increased progressively with higher sulphur levels in groundnut. The best results for carbon

Table 7. Effect of sulphur management in rice-groundnut cropping system on carbon budgeting of rice

Treatments	Total carbon input (kg C equivalent/ ha)	Total carbon output (kg C equivalent/ ha)	Carbon efficiency	Carbon sustainability Index	Carbon foot print (kg C equivalent/ kg biomass)
Sulphur fertilization in rice					
F ₁ : No sulphur	809.4	4254.2	5.26	4.26	0.084
F ₂ : 20 kg S/ha as bentonite	955.4	4502.1	4.71	3.71	0.094
F ₃ : 20 kg S/ha as gypsum	955.4	4819.3	5.04	4.04	0.087
F ₄ : 40 kg S/ha as bentonite	1101.4	5070.1	4.60	3.60	0.096
F ₅ : 40 kg S/ha as gypsum	1101.4	5205.2	4.73	3.73	0.093
CD (P=0.05)		91.6	0.09	0.09	0.002
Sulphur levels (kg S /ha) in groundnut					
L ₁ : 0	984.595	4641.6	4.74	3.74	0.093
L ₂ : 30	984.595	4794.8	4.90	3.90	0.090
L ₃ : 60	984.595	4874.1	4.97	3.97	0.089
CD (P=0.05)		56.7	0.06	0.06	0.001

Table 8. Effect of sulphur management in rice-groundnut cropping system on carbon budgeting of groundnut

Treatments	Total Carbon input (kg C equivalent/ ha)	Total carbon output (kg C equivalent/ ha)	Carbon efficiency	Carbon sustainability Index	Carbon foot print (kg C equivalent/ kg biomass)
Sulphur fertilization in rice					
F ₁ : No sulphur	1072.78	2255.2	2.14	1.14	0.208
F ₂ : 20 kg S/ha as bentonite	1072.78	2384.3	2.27	1.27	0.197
F ₃ : 20 kg S/ha as gypsum	1072.78	2414.4	2.31	1.31	0.195
F ₄ : 40 kg S/ha as bentonite	1072.78	2615.4	2.49	1.49	0.179
F ₅ : 40 kg S/ha as gypsum	1072.78	2570.0	2.44	1.44	0.183
CD (P=0.05)		42.8	0.04	0.04	0.003
Sulphur levels (kg S /ha) in groundnut					
L ₁ : 0	853.78	2307.7	2.70	1.70	0.163
L ₂ : 30	1072.78	2480.5	2.31	1.31	0.191
L ₃ : 60	1291.78	2555.4	1.98	0.98	0.223
CD (P=0.05)		14.5	0.01	0.01	0.001

output (4874.1 kg C eq./ha), CUE (4.97), and CSI (3.97) were recorded with 60 kg S/ha sulphur. In contrast, the highest CFP (0.135 kg C eq./kg biomass) was also recorded at this level, indicating a trade-off between productivity and environmental impact.

Groundnut

Total carbon input in groundnut increased with higher sulphur application levels (Table 8). The highest total

carbon output (2555.4 kg C eq./ha) was recorded with 60 kg S/ha sulphur application. However, the maximum carbon use efficiency (CUE: 2.70) and carbon sustainability index (CSI: 1.70) were observed in the control (no sulphur). The highest carbon footprint (CFP) of 0.223 kg C eq./kg biomass was associated with 60 kg S/ha sulphur application. The residual effect of sulphur applied to rice significantly influenced carbon-related parameters. Total energy output increased

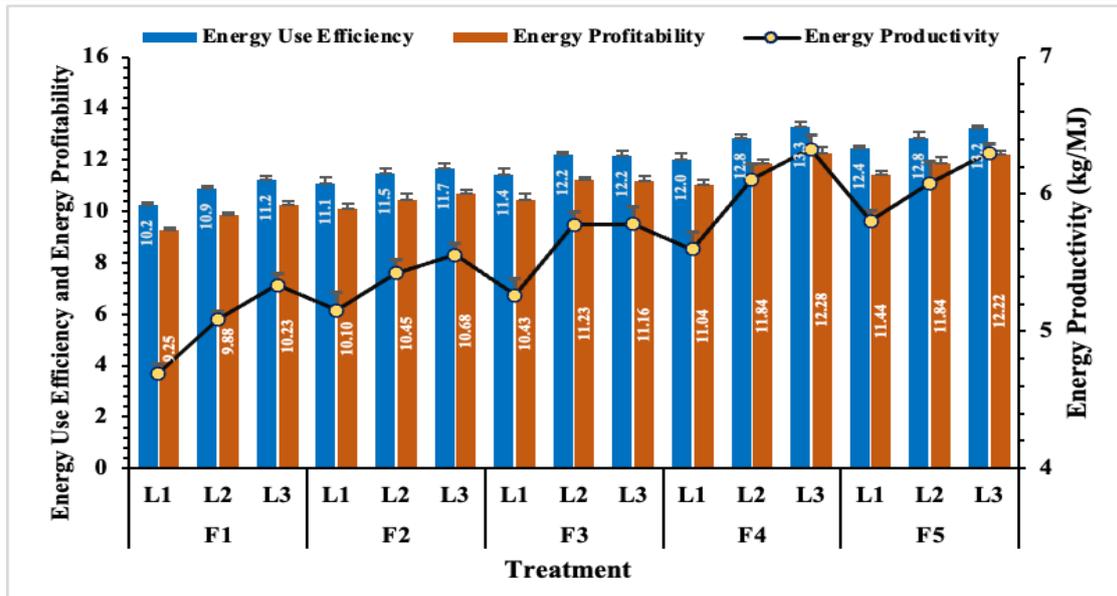


Fig. 5. Impact of sulphur management on energetics of rice-groundnut system (F₁: No sulphur, F₂: 20 kg S/ha as bentonite; F₃: 20 kg S/ha as gypsum; F₄: 40 kg S/ha as bentonite; F₅: 40 kg S/ha as gypsum; L₁: 0 kg S/ha; L₂: 30 kg S/ha and L₃: 60 kg S/ha)

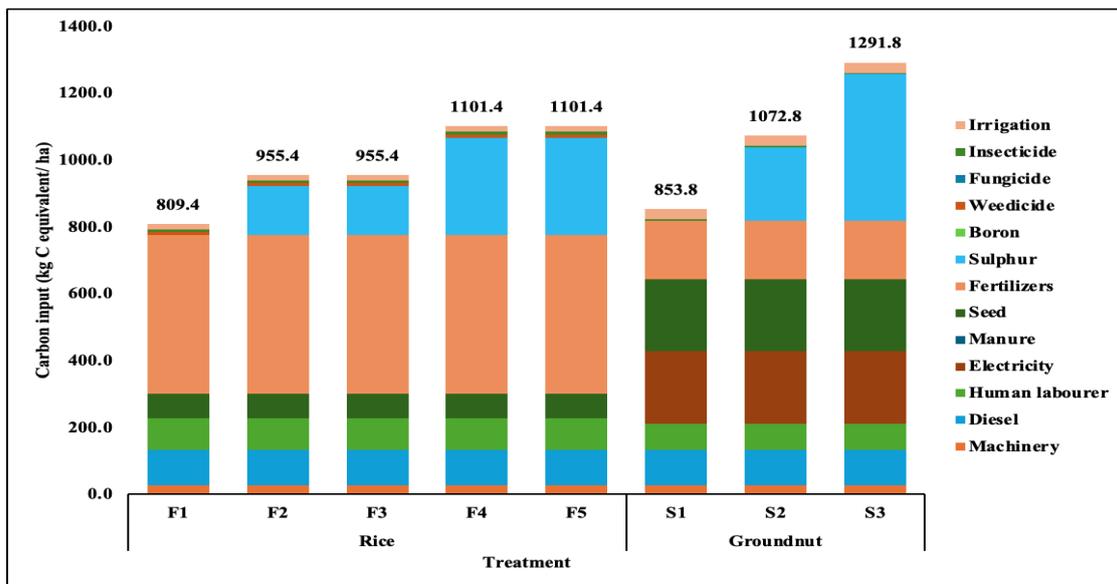


Fig. 6. Treatment wise carbon input of rice-groundnut system under sulphur management (F₁: No sulphur, F₂: 20 kg S/ha as bentonite; F₃: 20 kg S/ha as gypsum; F₄: 40 kg S/ha as bentonite; F₅: 40 kg S/ha as gypsum; L₁: 0 kg S/ha; L₂: 30 kg S/ha and L₃: 60 kg S/ha)

progressively with rising sulphur levels in groundnut. The highest carbon output (2615.4 kg C eq./ha), CUE (2.49), and CSI (1.49) were achieved with 40 kg S/ha bentonite, while the highest CFP (0.208 kg C eq./kg biomass) occurred in the control, indicating an inverse relationship between CUE, CSI, and CFP.

System

In the rice-groundnut cropping system, total carbon input increased with higher sulphur application rates, regardless of the sulphur source in rice. Applying 40 kg S/ha as gypsum in rice produced the highest total carbon output (5205.2 kg C eq./ha). However, the best

carbon use efficiency (CUE) and carbon sustainability index (CSI) were achieved with 20 kg S/ha gypsum. The highest carbon footprint (CFP) occurred with 40 kg S/ha of bentonite applied, indicating a greater environmental cost per biomass unit. The residual sulphur effect on groundnut significantly impacted carbon parameters. Total energy output rose consistently with higher sulphur levels. Application of 60 kg S/ha in groundnut yielded the maximum carbon output (4874.1 kg C eq./ha), CUE (4.97), and CSI (3.97), but also the highest CFP (0.93 kg C eq./kg biomass), reflecting a trade-off between productivity and carbon intensity. Among treatment combinations,

the treatments comprising the higher levels of S fertilization in rice and no sulphur in groundnut i.e. F₅L₁ (CE3.87, CSI 2.87) and F₄L₁ (CE 3.73, CSI 2.73) recorded higher CE and CSI than other combinations indicating need for use of low carbon or carbon-neutral sulphur sources (Fig.7).

Among the various components of carbon input, fertilizer (N, P, K, and B) and sulphur have a major share. Fertilizer contributed 58.6, 49.6, 49.6, 43 and 43% to carbon input in F₁, F₂, F₃, F₄ and F₅, respectively. The

respective contributions by sulphur were 0, 15.3, 15.3, 26.5, and 26.5%. The contributions to carbon input in L₁, L₂ and L₃ were 20.7, 16.4 and 13.7 % by fertilizer, and 0, 20.4, 33.9% by sulphur, respectively (Fig. 6).

The variation in carbon input across treatments was primarily attributed to differences in agronomic inputs. Among various practices, land preparation and fertilizer application accounted for the largest share of carbon input, as noted by Jat *et al.* (2019). Elevated carbon output was associated with higher biomass accumula-

Table 9. Effect of sulphur management in rice-groundnut cropping system on carbon budgeting of rice-groundnut cropping system

Treatments	Total carbon input (kg C equivalent/ ha)	Total carbon output (kg C equivalent/ ha)	Carbon efficiency	Carbon sustainability index	Carbon foot print (kg C equivalent/ kg biomass)
Sulphur fertilization in rice					
F ₁ : No sulphur	1882.2	6509.4	3.48	2.48	0.127
F ₂ : 20 kg S/ha as bentonite	2028.2	6886.4	3.42	2.42	0.130
F ₃ : 20 kg S/ha as gypsum	2028.2	7233.6	3.59	2.59	0.123
F ₄ : 40 kg S/ha as bentonite	2174.2	7685.6	3.55	2.55	0.124
F ₅ : 40 kg S/ha as gypsum	2174.2	7775.2	3.59	2.59	0.123
CD (P=0.05)		106.3	0.05	0.05	0.002
Sulphur levels (kg S /ha) in groundnut					
L ₁ : 0	1838.4	6949.3	3.78	2.78	0.117
L ₂ : 30	2057.4	7275.3	3.53	2.53	0.125
L ₃ : 60	2276.4	7429.5	3.26	2.26	0.135
CD (P=0.05)		57.1	0.03	0.03	0.001

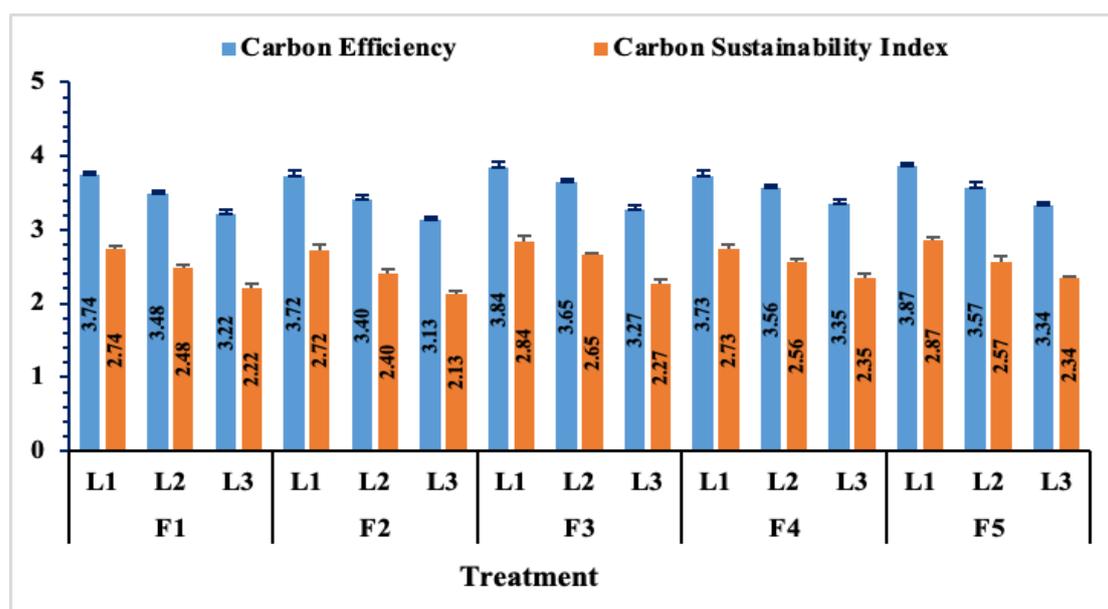


Fig. 7. Impact of sulphur management on carbon indices of rice-groundnut system (F₁: No sulphur, F₂: 20 kg S/ha as bentonite; F₃: 20 kg S/ha as gypsum; F₄: 40 kg S/ha as bentonite; F₅: 40 kg S/ha as gypsum; L₁: 0 kg S/ha; L₂: 30 kg S/ha and L₃: 60 kg S/ha)

tion under sulphur-enriched treatments (Behera *et al.*, 2024). Interestingly, non-sulphur treatments exhibited relatively higher CUE and CSI than sulphur-applied treatments, likely due to proportionately higher biomass production, resulting in reduced carbon input requirements, in line with the observations of Singh *et al.* (2024) and Babu *et al.* (2020).

Higher levels of S fertilization in rice failed to enhance CE and CSI of rice (Table 7), whereas higher S levels in groundnut failed to enhance CE and CSI of groundnut (Table 8) and rice – groundnut system (Table 9), although S fertilization excelled over no sulphur treatment for yield of rice, groundnut and the system. Energy consuming processes across the lifecycle of a material leads to carbon footprint. Gypsum sulphur, from mining/industrial production through processing (crushing, grinding, drying), transportation to markets, and field application, has a carbon footprint. Similarly, bentonite sulphur, involving processes such as mining of bentonite clay, producing and processing sulphur, mixing/coating sulphur with clay, and packaging and distribution, has a carbon footprint. In case of rice (Table 7), higher levels of S fertilization involving gypsum and bentonite, though they gave higher rice yields, proved to be carbon inefficient. Higher levels of S in groundnut resulted in higher biological yields of rice, groundnut, and the system, but failed to record higher CE and CSI for groundnut and the rice-groundnut system. Higher levels of S in groundnut proved to be productive but carbon-inefficient, indicating the need to use carbon-neutral or carbon-efficient sulphur sources (organic manures, compost, elemental sulphur, single super phosphate, sulphur-oxidizing microorganisms).

Adoption potential/Limitations

The response of the rice-groundnut system to sulphur fertilization depends on agro-climatic zones, land type (rainfed/irrigated), soil type, and cultivar. The results are valid for sulphur-deficient soils in the East and South-Eastern Coastal plain agro-climatic zone of Odisha and similar agroecologies worldwide. Before recommendations and large-scale adoption, multilocational trials involving different cultivars and land types must be conducted. The availability of sulphur sources and their affordability for farmers must be taken into consideration. Large-scale adoption also depends on government policy and support for S fertilizers.

Conclusion

The study concluded that applying 40 kg S/ha as gypsum or bentonite to rice and 60 kg S/ha to groundnut could be the best sulphur management practice in the rice-groundnut cropping system for higher system

yield, energy, and carbon efficiency. The present study uncovers many researchable issues for scientists to explore in the future. The pattern of sulphur buildup / mining and scheduling of sulphur with continued application of sulphur in rice groundnut system has to be studied. Since the application of sulphur fertilizer is energy-intensive and has a carbon footprint, optimizing S use across different climates, soil types, and cultivars is a major issue in fertilizer management. It is suggested that the future research program should focus on assessing the efficacy of S fertilization in combination with organic manures, quantifying sulphur mineralization in flooded rice soils to well-aerated groundnut soils, sulphur budgeting for component crops of the system, studying interaction between sulphur and other important elements for the system, exploiting alternate sources of sulphur (elemental S, SSP, and sulphur-coated fertilizers), possibility of using sulphur-oxidizing microbes in enhancing soil S availability and degree of improvement in produce quality by sulphur fertilization for developing an economic, remunerative, eco-friendly and climate smart sulphur management schedule for the system.

Conflict of interest

The authors declare that they have no conflict of interest.

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