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Optimizing sulphur management for growth, productivity and profitability in rice-groundnut cropping system

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Abstract

The rice *(Oryza sativa* L.)- groundnut (*Arachis hypogaea* L.) is one of the most important cropping systems of Eastern India for human and animal diets. Both rice and groundnut benefit from sulphur application, but a major challenge in maintaining their growth, productivity and profitability is the widespread sulphur deficiency, affecting about 44% of Indian soils and 36% of soils in Odisha. A field experiment comprising five sulphur fertilisation strategies for rice *viz.,* no sulphur, S @ 20 kg ha^{-1} through bentonite, S @ 20 kg ha^{-1} through gypsum, S @ 40 kg ha^{-1} through bentonite and S @ 40 kg ha^{-1} through gypsum allocated to main plots and three sulphur levels for groundnut *viz.,* no sulphur, S@ 30 kg ha^{-1} and S @ 60 kg ha^{-1} allocated to the subplots was conducted in a split-plot design with four replications during the *kharif and rabi* seasons of 2021-22 and 2022-23 at Bhubaneswar, India to assess the effect of treatments on growth, productivity, quality and profitability of the component crops and the system. The application of S @ 40 kg ha^{-1} through gypsum to rice recorded the maximum values of growth parameters, biological yield, quality parameters and economics indices of rice, whereas the application of S @ 60 kg ha^{-1} in groundnut recorded the maximum values of growth parameters, biological yield and quality parameters of groundnut. Application of S @ 40 kg ha^{-1} through bentonite to rice combined with S @ 60 kg ha^{-1} in groundnut was the most remunerative with the maximum system net return (Rs. 113640 ha^{-1}) and return per rupee investment (1.89) which is 106.96 % and 30.34 % higher respectively than no sulphur application to both the crops.

Keywords

biological yield; oil yield; protein content; return per rupee investment; SPAD

Introduction

Rice, the broadly cultivated staple food crop of the world, is cultivated in an area of 165 M ha with an annual production of 523 million tonnes and productivity of 3.16 t ha^{-1} (1). India, the second-largest producer, cultivates rice on an area of 46.4 M ha, contributing approximately 196 million tonnes to the global rice pool with a productivity of 4.22 t ha^{-1} (1). Groundnut, being an important protein-rich oilseed crop, is grown worldwide on about 30.5 million hectares, with an annual world-wide production of 54.2 million tonnes with productivity of 1.77 t ha^{-1} (1). The rice-groundnut cropping system is widely practised in eastern and southern states of India including Odisha. In the agroecological situation of Eastern India, where there is plenty of rainfall in the *kharif* season, rice is the only feasible crop under the situation of standing water and groundnut is cultivated after harvest of rice with residual soil moisture, off-season rainfall and supply of limited irrigation water available in the region. This double cropping system allows for better utilization of available water resources, restores soil fertility and optimizes land productivity (2).

Besides the primary nutrients like Nitrogen, Phosphorus and Potassium, the productivity and quality of component crops of the system depend on sulphur status of the soil (3). Sulphur (S) is a critical secondary nutrient for plant growth, playing an essential role in synthesising amino acids, proteins, enzymes and chlorophyll (4). However, sulphur deficiency is becoming increasingly common in intensively farmed regions due to factors such as overuse of nitrogenous fertilizers with low or no sulphur content, leaching in flooded rice fields, higher sulphur removal from soil by crops and reduced sulphur deposition from the atmosphere (5). In rice, sulphur helps in the formation of chlorophyll, thereby enhancing photosynthesis and improving the plant's ability to produce energy for growth and grain development (6). In groundnut, sulphur is crucial for the development of healthy pods and the formation of oil in the seeds (7). In the rice-groundnut cropping system, sulphur fertilisation is especially important due to the responsiveness of both crops towards sulphur. Rice is typically grown in flooded fields, which can lead to leaching loss of sulphur from the soil. On the other hand, groundnut is usually grown in drier conditions, where sulphur may be limited, particularly in sandy soils with low organic matter content. Sulphur deficiency can result in stunted growth, reduced pod formation and lower seed quality in groundnut, while rice may exhibit poor grain development and reduced protein content (7). Sulphur fertilization has been shown to improve crop yields and quality in both rice and groundnut (8). In rice, sulphur application enhances grain quality, increases protein content and improves overall growth. In groundnut, sulphur increases oil content, improves pod development and enhances the nutritional value of the seeds (9).

Sulphur requirement of the system can be met through various sources which differ in rate of mineralisation and availability to the plant. Sulphur bentonite is a form of sulphur that is typically bound to a clay-like material (bentonite). The sulphur in bentonite is in the elemental form, which is not immediately available to plants. Over time, soil microorganisms oxidize the elemental sulphur to sulphate, which is the form plants can absorb. This slow-release mechanism makes it ideal for rice crops, which can benefit from a sustained supply of sulphur during their growing season (10). Unlike sulphur bentonite, gypsum is a source of sulphate sulphur (SO_4^{2-}), which is immediately available to plants. This is beneficial when the crop requires the element quickly after application, particularly during critical stages of growth such as tillering or flowering in rice (11). Sulphate-S is readily available to crops but is vulnerable to leaching loss, the extent of which is predominantly decided by soil type and rainfall. In high rainfall environments, leaching is a major loss (12). Hence, there is a need to assess the efficacy of both sources of sulphur in improving the performance of the crop.

Both rice and groundnut are sensitive to sulphur deficiency. Though research findings are available on sulphur management on rice or ground as sole crop, literature on sulphur management in rice-groundnut cropping system in eastern India is very meagre. A part of sulphur applied to rice is left in the post-harvest soil for utilisation by succeeding groundnut, depending on the source and level. This residual sulphur can meet the need of groundnut crop partially. Hence, additional sulphur is applied to groundnut to fulfil the crop demand. There is a need to develop sulphur management strategy for the system to promote microbial activity in the soil, aid in nutrient mineralization, improve soil health, maximise productivity and profitability with good quality produce and prevent sulphur toxicity (8,13).

Under above background, it is hypothesised that sulphur fertilisation comprising right rate and source in rice and right level of sulphur to groundnut would favour growth of component crops, enhance system productivity and profitability. This same may improve produce quality under sulphur deficiency situation in Eastern India.

Materials and Methods

Experimental site

The field experiment was conducted during the *Kharif* and *rabi* seasons of 2021-22 and 2022-23 at the Agricultural Research Station (20^0 25' N; 85^0 67'E and 50.9 m above mean sea level), Chhatabar, Siksha 'O' Anusandhan (Deemed to be) University, Bhubaneswar, Odisha, India. The soil of the experimental site was clay loam, slightly acidic in reaction (pH 5.82), low in electrical conductivity (0.45 dS m^{-1}), low in organic carbon (0.40 %), medium in available nitrogen (288.6 kg ha^{-1}); available phosphorus (18.54 kg ha^{-1}); available potassium (210 kg ha^{-1}) and low in available sulphur (8.7 ppm). The soil properties mineral content, including texture (14), pH (15), electrical conductivity (15), organic carbon (16), available nitrogen (17), phosphorus (15), potassium (15) and sulphur (18) were measured by standard procedure i.e. Bouyoucos hydrometer method, Glass electrode pH meter method, Solubridge conductivity meter method, wet digestion method, alkaline permanganate method, Bray's analysis method, neutral normal ammonium acetate method and turbidimetry method respectively.

Treatment details

The experiment comprising five sulphur fertilization methods in rice viz., F_1- no sulphur; F_2- S @ 20 kg ha^{-1} through bentonite; F_3- S @ 20 kg ha^{-1} through gypsum; F_4- S @ 40 kg ha^{-1} through bentonite and F_5- S @ 40 kg ha^{-1} through gypsum allocated to the main plots and three levels of sulphur through bentonite in groundnut viz., L_1- no sulphur, L_2- S @ 30 kg ha^{-1} and L_3- S @ 60 kg ha^{-1} allocated to the subplots was conducted in split plot design with four replications. The sulphur sources used in the experiment were agricultural-grade gypsum (16% S) and bentonite sulphur (90% S). Sulphur levels for rice were selected considering sulphur uptake of 1kg t^{1} grain yield (19), yield potentiality of the crop, rate of mineralization of applied sulphur, losses of sulphur through various channels in soil and crop response to sulphur levels in different rice growing ecologies (19,20,21). The sulphur sources were selected considering the differential release pattern of each. Gypsum is readily available while bentonite is slowly mineralizable. (22) The split-plot design was selected for the study due to the existence of greater variability among sulphur fertilization methods compared to sulphur levels in groundnut. Hence, there is a need to assess the sulphur level of groundnut with greater precision than the sulphur fertilisation method in rice.

Nitrogen was supplied through di-ammonium phosphate (DAP, 18-46-0) and urea (46-0-0) while phosphorus was provided exclusively via DAP (46% P_2O_5). Potassium was applied as muriate of potash (60% K_2O). Rice cv. '*Naveen*' and groundnut cv. '*Devi*' were used as test crops in the experiment. Rice nursery raising was done on 25th June 2021 and 24th June 2022 and transplanting was done on 18th July 2021 and 17th July 2022 with spacing 20 cm × 10 cm with 2-3 seedlings hill^{-1}. The rice crop was supplied with 5 tonnes Farm Yard Manure ha^{-1} along with 80-40-40 kg N-P_2O_5-K_2O ha^{-1}. The sulphur was applied basal as per treatment specifications. Weed was managed by applying pretilachlor @ 0.75 kg ha^{-1} followed by one hand weeding 22 days after transplanting (DAT). For the control of bacterial leaf blight disease, a mixture of streptocyclin @ 2.0g and Copper oxychloride @ 0.5 g L^{-1} water was applied. The rice crop was raised totally as a rainfed crop and was harvested on 24th October 2021 and 22nd October 2022 in the respective years. The grains were dried up to 12% moisture content, net plot-wise weight was recorded and converted to t ha^{-1}. Groundnut crop was sown on 18th November 2021 and 20th November 2022 by using a seed rate of 175 kg pod/ha (125 kg kernel ha^{-1}), spacing of 25 cm ´10 cm and fertilizer dose of 20-40-40 kg N-P_2O_5-K_2O ha^{-1} was applied as basal. The sulphur was also applied at the basal as per the treatments through bentonite. Weeds were managed by application of pendimethalin @ 1 kg ha^{-1} and two-hand weedings were done at 22 and 58 days after sowing (DAS). To control leaf defoliators (insects) Dichlorvos @750 ml ha^{-1} was applied. Groundnut crop was harvested on 1st March 2022 and 2nd March 2023, when the plants turned yellow, leaves started drying and pods developed blackish streaks inside the pods. Pods were dried up to 10% moisture content and net plot-wise weight was recorded and converted to t ha^{-1}.

Recording of biometric observations

Biometric data were recorded at 20-day intervals for rice and 25-day intervals for groundnut throughout the growing season. Leaf-area was measured using a leaf-area meter (LI-COR, Li-3100C). Leaf-area index (LAI) was computed by standard procedure (23). The leaf chlorophyll content, which is expressed as Soil Plant Analysis Development (SPAD) was monitored with a chlorophyll meter (SPAD-502 plus) at the midpoint of the second fully expanded leaf of 10 marked plants (24).

Estimating quality parameters

The protein contents in the grain of rice and kernel of groundnut were estimated by multiplying nitrogen (N) content with the conversion factor of 6.25 (25). The oil content of groundnut seed was determined by the Automatic Soxhlet apparatus. The oil content present in seeds was expressed as a percentage. The following formulae were used to compute protein yield (kg ha^{-1}) along with oil yield (kg ha^{-1}).

$$\text{Protein yield (kg ha}^{-1}\text{)} = \frac{\text{Protein content in grain or kernal (\%)} \times \text{grain or learned yield (kg ha}^{-1}\text{)}}{\times 100}$$

$$\text{Oil yield (kg ha}^{-1}\text{) in groundnut} = \frac{\text{Oil content in kernel (\%)} \times \text{kernel yield (kg ha}^{-1}\text{)}}{\times 100}$$

Economic analysis

The economics indices viz., cost of cultivation, net return, gross return and return per rupee invested were computed by using the following formulae.

Gross return of rice (kg ha^{-1}) = {Minimum Support Price (Rs t^{-1}) × grain yield (t)} + {Rs. 2000 t^{-1}´ straw yield (t)}

Gross Return of groundnut (kg ha^{-1}) = {Minimum Support Price (Rs t^{-1}) × pod yield (t)} + {Rs.1000 t^{-1} × haulm yield (t)}

Net Return = Gross returns - Cost of cultivation

$$\text{Return Rs.}^{-1}\text{ invest} = \frac{\text{Gross return}}{\text{Cost of cultivation}}$$

Statistical analysis

The data collected from the field was subjected to statistical analysis by following standard procedure (26). The data were subjected to pooled analysis when the error variances of both the years (2021-22 and 2022-23) were homogeneous (Bartlett's Test). The data were analysed by using the SPSS software.

Results

Growth parameters

Rice : Among sulphur fertilisation methods, S @ 40 kg ha^{-1} through gypsum in rice produced the tallest plant (116.5 cm), maximum number of tillers m^{-2} at harvest (335.2), highest LAI at 75 DAT (5.86), maximum SPAD reading at both 50 (42.1) and 75 DAT (28.2) and proved to be significantly better than all other treatments (Table 1). Sulphur levels applied to groundnuts exerted a significant influence on the

Table 1. Effect of sulphur fertilization in rice and sulphur levels in groundnut on growth parameters of rice

Treatments	Plant height at harvest (cm)	Tillers m^{-2} at harvest	Leaf Area Index at 75 DAT	SPAD value at 50 DAT	SPAD value at 75 DAT
Sulphur fertilization in rice					
F_1: No sulphur	94.3	303.0	5.09	36.0	22.6
F_2: S @ 20 kg ha^{-1} through bentonite	98.3	313.7	5.29	37.7	24.0
F_3: S @ 20 kg ha^{-1} through gypsum	104.5	321.4	5.38	39.2	25.3
F_4: S @ 40 kg ha^{-1} through bentonite	110.2	330.5	5.61	40.8	26.3
F_5: S @ 40 kg ha^{-1} through gypsum	116.5	335.2	5.86	42.1	28.2
SEm±	0.57	1.08	0.07	0.29	0.42
CD (P=0.05)	1.67	3.14	0.19	0.83	1.22
Sulphur levels in groundnut					
L_1: S @ 0 kg ha^{-1}	103.6	318.4	5.38	38.7	25.0
L_2: S @ 30 kg ha^{-1}	104.6	320.8	5.47	39.2	25.3
L_3: S @ 60 kg ha^{-1}	106.0	323.9	5.49	39.6	25.5
SEm±	0.3	0.56	0.03	0.20	0.20
CD (P=0.05)	0.9	1.57	0.09	0.57	0.57

F- Sulphur fertilization in rice; L- Sulphur levels in groundnut; SPAD- Soil Plant Analysis Development; S – Sulphur; SEm ± Standard Error of mean; CD (P=0.05)- Critical Difference at 5% level of significance, DAT- Days After Transplanting.

growth parameters of rice. The residual effect of S @ 60 kg ha^{-1} applied in groundnut produced the tallest plant (106 cm), maximum tillers m^{-2} (323.9), maximum LAI (5.49), highest SPAD values (39.6 and 25.5 at 50 and 75 DAT, respectively) and proved significantly superior to other levels of sulphur, except LAI and SPAD readings for which S @ 60 kg ha^{-1} and S @ 30 kg ha^{-1} were at par.

Groundnut : The carry-over effect of sulphur applied in rice exerted a significant effect on the growth of succeeding groundnut (Table 2). Application of S @ 40 kg ha^{-1} through bentonite in rice recorded the maximum plant height (39.1cm), maximum branches plant^{-1} (7.5), highest LAI (2.96) at 90 DAS, maximum SPAD readings (34.6 and 35.4 for 60 DAS and 90 DAS, respectively) and highest nodules plant^{-1} at 30 DAS (46.7), keeping S @ 40 kg ha^{-1} through gypsum at par. Residual effects of both bentonite and gypsum as S @ 40 kg ha^{-1} exerted a similar influence on the growth of groundnut.

Application of S @ 60 kg ha^{-1} to groundnut produced tallest plant (36.9 cm), maximum branches plant^{-1} (7.0), highest LAI (2.39) at 90 DAS, maximum SPAD readings (33.3 and 34.5 for 60 DAS and 90 DAS, respectively) and highest nodules plant^{-1} 30 DAS (45.6) and proved superior to other levels of sulphur.

Biological yield

Rice: The interaction effects of sulphur fertilization methods in rice and sulphur levels in groundnut were found to be significant on the biological yield *i.e.* sum of grain and straw yield of rice (Fig.1). Application of S @ 40 kg ha^{-1} through gypsum or bentonite in rice combined with the application of S @ 60 kg ha^{-1} in groundnut (F_5L_3 and F_4L_3) produced the maximum biological yield of rice (12 t ha^{-1}), being at par with F_5L_2 (11.7 t ha^{-1}) and F_4L_2 (11.5 t ha^{-1}) and significantly better than other treatment combinations.

Groundnut : The interaction effect of sulphur fertilisation methods in rice and sulphur levels in groundnut were found to be significant on the biological yield *i.e.* sum of pod and haulm yield of groundnut (Fig. 2). Application of S @ 40 kg ha^{-1} through gypsum in rice and S @ 60 kg ha^{-1} in groundnut (F_4L_3) produced the maximum groundnut biological yield of 6.26 t ha^{-1}, being at par with F_5L_3 (6.14 t ha^{-1}) and F_4L_2 (6.06 t ha^{-1}).

Quality of rice grains

Protein content and protein yield : Both application of S @ 40 kg ha^{-1} (6.90 %) through bentonite and S @ 40 kg ha^{-1} through gypsum (6.84 %) in rice were at par for protein content, being significantly superior to other sulphur fertilization methods (Table 3). Residual effects S @ 60 kg

Table 2. Effect of sulphur fertilization in rice and sulphur levels in groundnut on growth parameters of groundnut

Treatments	Plant height (cm)	Primary branches plant^{-1}	Leaf Area Index at 90 DAS	SPAD Value at 60 DAS	SPAD Value at 90 DAS	Nodules plant^{-1} at 30 DAS
Sulphur fertilization in rice						
F_1: No sulphur	31.3	5.7	1.65	29	32.7	40.3
F_2: S @ 20 kg ha^{-1} through bentonite	34.3	6.4	2.01	32.6	32.7	44.2
F_3: S @ 20 kg ha^{-1} through gypsum	33.5	6.6	1.85	32	33.4	45.2
F_4: S @ 40 kg ha^{-1} through bentonite	39.1	7.5	2.96	34.6	35.4	46.7
F_5: S @ 40 kg ha^{-1} through gypsum	38.8	7	2.93	34.4	35.1	46
SEm±	0.3	0.3	0.02	0.3	0.3	0.51
CD (P=0.05)	0.8	0.9	0.05	0.8	0.8	1.48
Sulphur levels in groundnut						
L_1: S @ 0 kg ha^{-1}	34.0	6.3	2.18	31.7	33.2	43.4
L_2: S @ 30 kg ha^{-1}	35.3	6.6	2.28	32.5	33.9	44.4
L_3: S @ 60 kg ha^{-1}	36.9	7.0	2.39	33.3	34.5	45.6
SEm±	0.1	0.2	0.01	0.19	0.2	0.38
CD (P=0.05)	0.3	0.5	0.03	0.53	0.6	1.08

F- Sulphur fertilization in rice; L- Sulphur levels in groundnut; SPAD- Soil Plant Analysis Development; S- Sulphur; SEm ± Standard Error of mean; CD (P=0.05)- Critical Difference at 5% level of significance, DAS- Days after sowing.

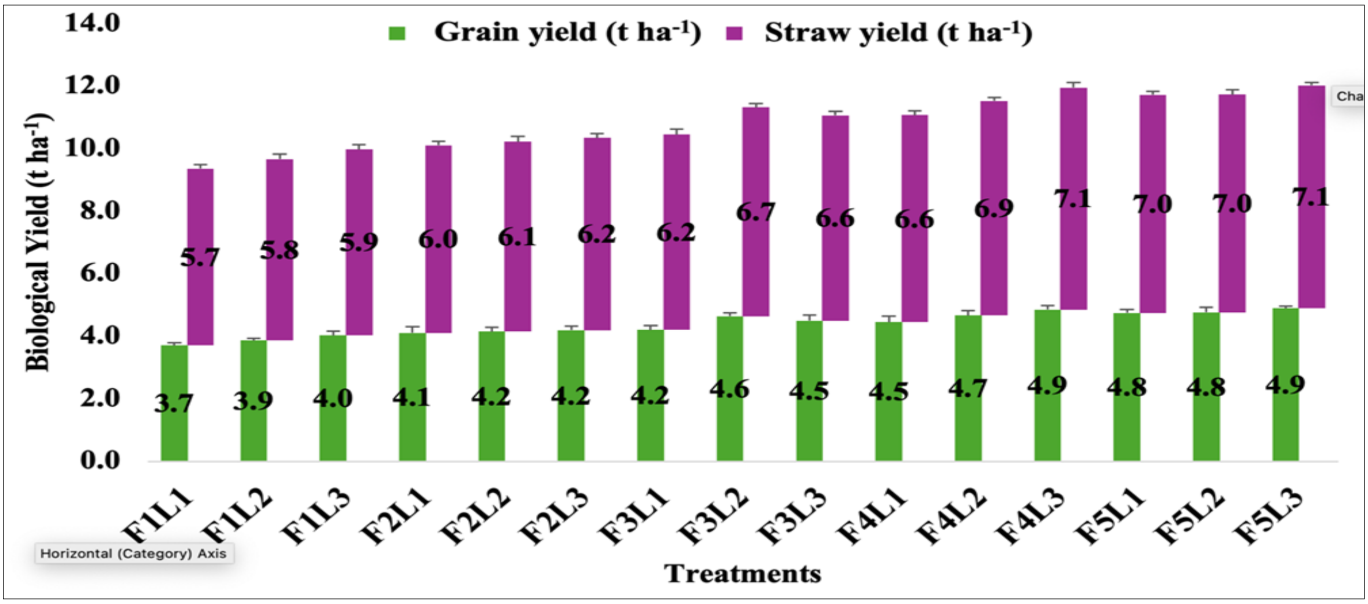

Fig. 1. Effect of sulphur fertilization in rice and sulphur levels in groundnut on biological yield of rice.

F_1: No Sulphur, F_2: S @ 20 kg ha^{-1} through bentonite; F_3: S @ 20 kg ha^{-1} through gypsum; F_4: S @ 40 kg ha^{-1} through bentonite; F_5: S @ 40 kg ha^{-1} through gypsum; L_1: S @ 0 kg ha^{-1}; L_2: S @ 30 kg ha^{-1} and L_3: S @ 60 kg ha^{-1}. In this figure, the sum of grain yield (green bar) and straw yield (purple bar) indicates the biological yield of rice.

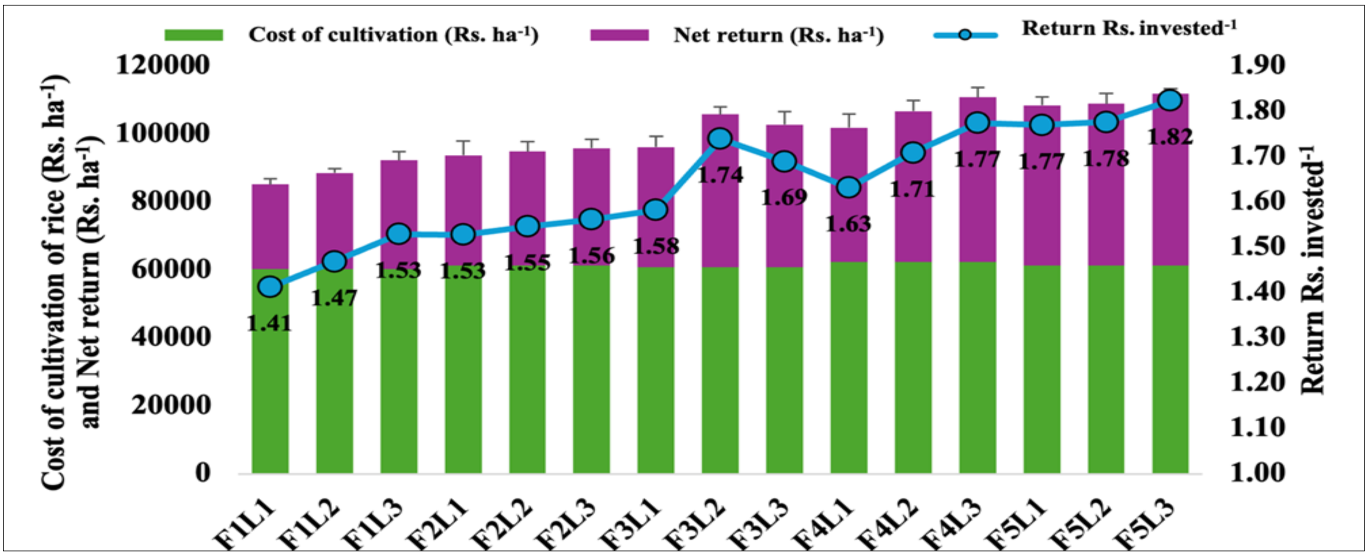

Fig. 2. Effect of sulphur fertilization in rice and sulphur levels in groundnut on biological yield of groundnut.

F_1: No Sulphur, F_2: S @ 20 kg ha^{-1} through bentonite; F_3: S @ 20 kg ha^{-1} through gypsum; F_4: S @ 40 kg ha^{-1} through bentonite; F_5: S @ 40 kg ha^{-1} through gypsum; L_1: S @ 0 kg ha^{-1}; L_2: S @ 30 kg ha^{-1} and L_3: S @ 60 kg ha^{-1}. In this figure, the sum of pod yield (green bar) and haulm yield (purple bar) indicates the biological yield of groundnut.

Table 3. Effect of sulphur fertilization in rice and sulphur levels in groundnut on quality traits of rice and groundnut

Treatments	Rice		Groundnut			
	Protein content (%)	**Protein yield (kg ha^{-1})**	**Oil content (%)**	**Oil yield (kg ha^{-1})**	**Protein content(%)**	**Protein yield (kg ha^{-1})**
Sulphur fertilization in rice						
F_1: No sulphur	6.14	237.9	45.4	793.1	17.11	299.6
F_2: S @ 20 kg ha^{-1} through bentonite	6.49	269.8	47.1	875.4	18.44	343.2
F_3: S @ 20 kg ha^{-1} through gypsum	6.39	284.4	46.2	861.3	18.35	342.6
F_4: S @ 40 kg ha^{-1} through bentonite	6.9	321.8	49.7	1029.3	21.2	439.7
F_5: S @ 40 kg ha^{-1} through gypsum	6.84	328.9	49.5	999.1	20.83	420.7
SEm±	0.03	3.3	0.4	9.1	0.19	4.5
CD (P=0.05)	0.08	9.7	1.1	26.4	0.57	13
Sulphur levels in groundnut						
L_1: S @ 0 kg ha^{-1}	6.45	275.0	47.1	820.1	18.59	324.5
L_2: S @ 30 kg ha^{-1}	6.56	290.9	47.5	930.8	19.22	377.3
L_3: S @ 60 kg ha^{-1}	6.64	299.8	48.0	984.1	19.75	405.7
SEm±	0.02	1.94	0.1	3.44	0.11	2.3
CD (P=0.05)	0.06	5.48	0.4	9.73	0.33	6.5

F- Sulphur fertilization in rice; L- Sulphur levels in groundnut; S – Sulphur; SEm ± Standard Error of mean; CD (P=0.05)- Critical Difference at 5% level of significance.

ha^{-1} (6.64) applied to groundnut excelled over other levels in enhancing the protein content of rice. Although the protein content was higher with S @ 40 kg ha^{-1} through bentonite, the highest protein yield was recorded with S @ 40 kg ha^{-1} through gypsum (328.9 kg ha^{-1}) due to higher grain yield of rice crop.

Quality of groundnut kernels

Oil content and oil yield : The carry over effect of both S @ 40 kg ha^{-1} through bentonite (49.7 %) and S @ 40 kg ha^{-1} through gypsum (49.5 %) applied to rice were at par for oil content in groundnut kernels and proved to be superior to other treatment combinations (Table 3). Among sulphur levels applied in groundnut, S @ 60 kg ha^{-1} (48.0 %) produced significantly higher oil content than two lower levels. The highest oil yield was realised with S @ 40 kg ha^{-1} through bentonite applied to rice (1029.3 kg ha^{-1}). Among sulphur levels applied in groundnut, S @ 60 kg ha^{-1} (984.1 kg ha^{-1}) produced significantly more oil than lower sulphur levels.

Protein content and protein yield : The carry over effect of both S @ 40 kg ha^{-1} through bentonite (21.20 %) and S @ 40 kg ha^{-1} through gypsum (20.83 %) applied to rice recorded statistically similar protein content in groundnut and proved better than other treatments (Table 3). Application of S @ 60 kg ha^{-1} (19.75 %) in groundnut recorded significantly higher protein content than lower levels. The highest protein yield was also recorded with S @ 40 kg ha^{-1} through bentonite (439.7 kg ha^{-1}) applied in rice and S @ 60 kg ha^{-1} (405.7 kg ha^{-1}) in groundnut produced significantly more protein than other treatments.

Economics

Rice: The interaction effects of sulphur fertilisation methods in rice and sulphur levels in groundnut were found to be significant on net return and return Rs. investment^{-1} of rice (Fig.3). Application S @ 40 kg ha^{-1} through gypsum applied in rice and S @ 60 kg ha^{-1} applied in groundnut (F_5L_3) was the most remunerative with maximum net return and return Rs. investment^{-1} (Rs. 50533 ha^{-1}, 1.82) being at par with F_4L_2 (Rs. 48389 ha^{-1}, 1.77) and F_5L_3 (Rs. 47618 ha^{-1}, 1.78), The higher values of two economical indices was predominantly a function of yield (34).

Groundnut : The interaction effect of sulphur fertilization methods in rice and sulphur levels in groundnut were found to be significant on net return and return rupee investment^{-1} of groundnut (Fig.4). Application S @ 40 kg ha^{-1} through bentonite in rice and S @ 60 kg ha^{-1} in groundnut (F_4L_3) produced maximum net return and return Rs. investment^{-1} (Rs. 65251 ha^{-1}, 2.0) being at par with F_4L_2 (Rs. 62312 ha^{-1}, 1.98) and F_5L_3 (Rs. 61270 ha^{-1}, 1.94). The higher values of the two economic indices were predominantly a function of yield (35).

Rice-groundnut system: Among sulphur fertilization methods applied in rice, S @ 40 kg ha^{-1} through gypsum generated the maximum system net return (Rs. 103629 ha^{-1}), keeping S @ 40 kg ha^{-1} through bentonite at par (Table 4). Among sulphur levels applied in groundnut, S @ 60 kg ha^{-1} generated the maximum system net return (Rs. 96571 ha^{-1}), which was significantly superior than other sulphur levels. The interaction effect of sulphur fertilization in rice and sulphur levels in groundnut was found to be significant on system net return. Combined application of S @ 40 kg ha^{-1} through bentonite in rice and S @ 60 kg ha^{-1} in groundnut generated the highest system net return (Rs. 113640 ha^{-1}), being at par with F_5L_3 (111803) and F_4L_2 (106594). Among sulphur fertilization methods applied in rice, S @ 40 kg ha^{-1} through gypsum (F_5) recorded the highest system return Rs^{-1} invested (1.83), keeping F_4 (1.81) at par (Table 4). Among sulphur levels applied to groundnut, S @ 60 kg ha^{-1} generated the highest system return Rs^{-1} invested (1.76), which was significantly higher than other sulphur levels. The interaction effects of sulphur fertilization in rice and sulphur levels in groundnut were found to be significant on system return Rs^{-1} invested. The combined application of S @ 40 kg ha^{-1} through bentonite in rice and S @ 60 kg ha^{-1} (F_4L_3) in groundnut produced the maximum system return of Rs^{-1} invested, which was at par with F_5L_3 and F_4L_2. The higher values of two economic indices under these treatments were predominantly a function of yield (34).

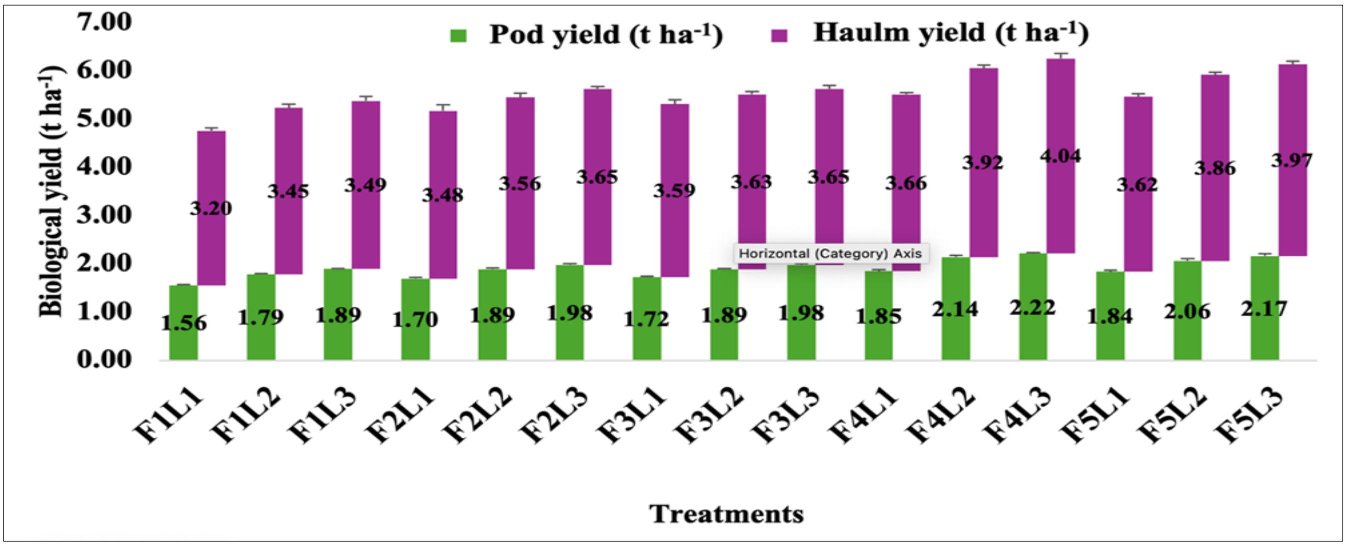

Fig. 3. Effect of sulphur fertilization in rice and sulphur levels in groundnut on economics of rice.

F_1: No Sulphur, F_2: S @ 20 kg ha^{-1} through bentonite; F_3: S @ 20 kg ha^{-1} through gypsum; F_4: S @ 40 kg ha^{-1} through bentonite; F_5: S @ 40 kg ha^{-1} through gypsum; L_1: S @ 0 kg ha^{-1}; L_2: S @ 30 kg ha^{-1} and L_3: S @ 60 kg ha^{-1}

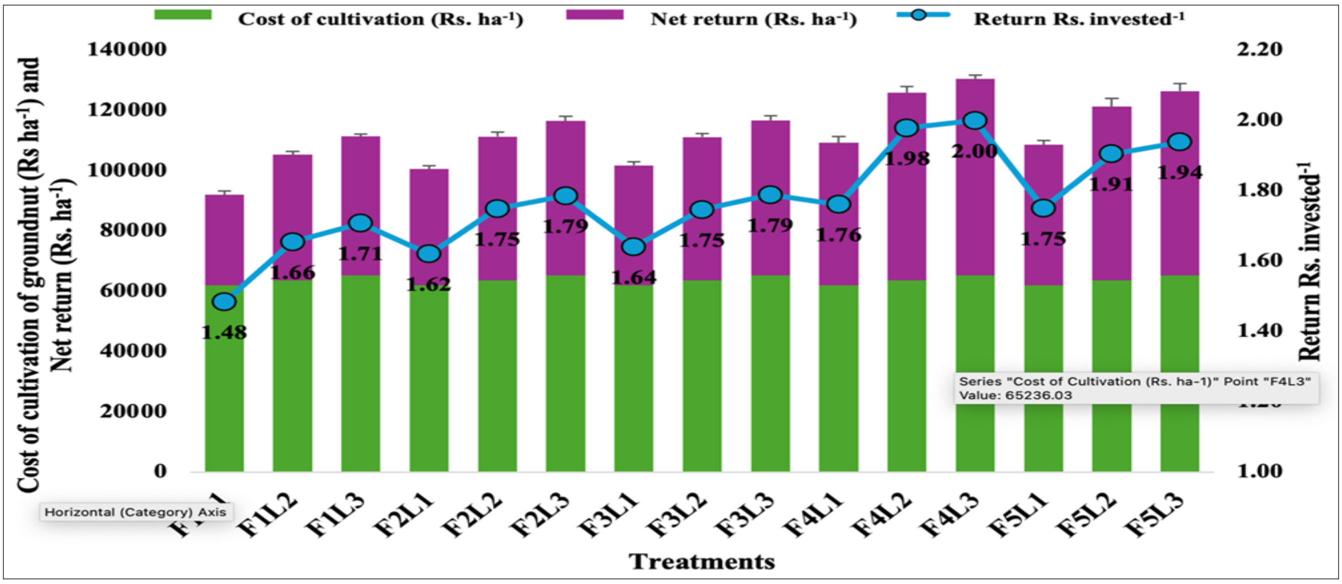

Fig. 4. Effect of sulphur fertilization in rice and sulphur levels in groundnut on economics of groundnut.

F_1: No Sulphur, F_2: S @ 20 kg ha^{-1} through bentonite; F_3: S @ 20 kg ha^{-1} through gypsum; F_4: S @ 40 kg ha^{-1} through bentonite; F_5: S @ 40 kg ha^{-1} through gypsum; L_1: S @ 0 kg ha^{-1}; L_2: S @ 30 kg ha^{-1} and L_3: S @ 60 kg ha^{-1}

Table 4. Effect of sulphur fertilization in rice and sulphur levels in groundnut on Net Return (Rs. ha^{-1}) and Return Rs.$^{-1}$ investment of rice-groundnut cropping system

	L_1: S @ 0 kg ha^{-1}	**L_2: S @30 kg S ha^{-1}**	**L_3: S @ 60 kg ha^{-1}**	**Mean**
	System net return (Rs. ha^{-1})			
F_1: No sulphur	54909	70029	78151	67696
F_2: S @ 20 kg ha^{-1} through bentonite	70951	81221	85784	79319
F_3: S @ 20 kg ha^{-1} through gypsum	75186	92513	93476	87058
F_4: S @ 40 kg ha^{-1} through bentonite	86697	106594	113640	102310
F_5: S @ 40 kg ha^{-1} through gypsum	93831	105254	111803	103629
Mean	76315	91122	96571	88003
SEm±	F= 1121	L= 584	FL= 2595	LF=2263
CD (P=0.05)	F= 3271	1653	7518	6401
	System return Rs.$^{-1}$ investment			
F_1: No sulphur	1.45	1.56	1.62	1.55
F_2: S @ 20 kg ha^{-1} through bentonite	1.57	1.65	1.68	1.63
F_3: S @ 20 kg ha^{-1} through gypsum	1.61	1.74	1.74	1.70
F_4: S @ 40 kg ha^{-1} through bentonite	1.70	1.85	1.89	1.81
F_5: S @ 40 kg ha^{-1} through gypsum	1.76	1.84	1.88	1.83
Mean	1.62	1.73	1.76	1.70
SEm±	F= 0.01	L= 0.01	FL= 0.02	LF= 0.02
CD (P=0.05)	F= 0.03	L= 0.02	FL= 0.06	LF= 0.05

F- Sulphur fertilization in rice; L- Sulphur levels in groundnut; FL= Sulphur fertilization in same or different levels of L; LF- Sulphur levels in same levels of F; SPAD- Soil Plant Analysis Development; S – Sulphur; SEm ± Standard Error of mean; CD (P=0.05)- Critical Difference at 5% level of significance.

Correlation Analysis: Grain yield of rice exhibited a significant positive correlation with growth parameters *viz,* plant height at harvest (0.95**), LAI at 75 DAT (0.93**), dry matter m^{-2} at harvest (0.93**) and SPAD at 75 DAT (0.93**), establishing these growth parameters as determinants of grain yield in case of rice. These growth parameters exhibited a positive correlation with each other (Fig 5).

Pod yield of groundnut exhibited significant positive correlation with growth parameters *viz,* plant height at harvest (0.86**), branches plant^{-1}(0.86**), LAI at 90 DAS (0.75*), SPAD at 60 DAT (0.82**), SPAD at 90 DAT (0.88**) and nodules plant^{-1} at harvest (0.81**) establishing these growth parameters as determinants of pod yield in case of groundnut. These growth parameters exhibited positive correlation with each other (Fig 6).

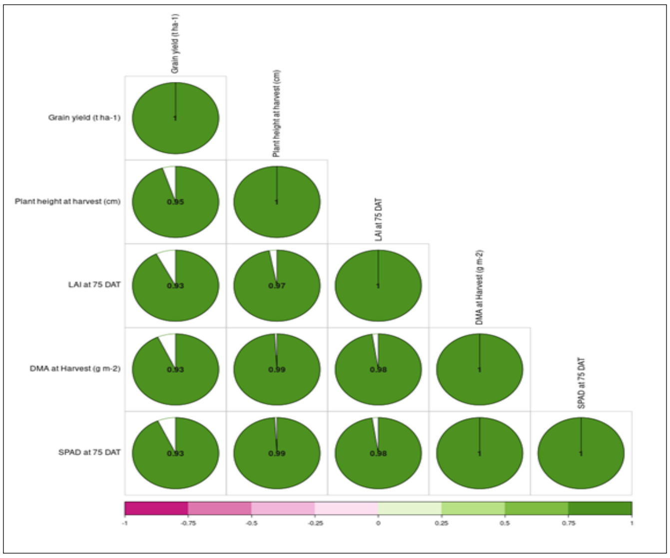

Fig. 5. Correlogram showing correlation between growth parameters and grain yield of rice.

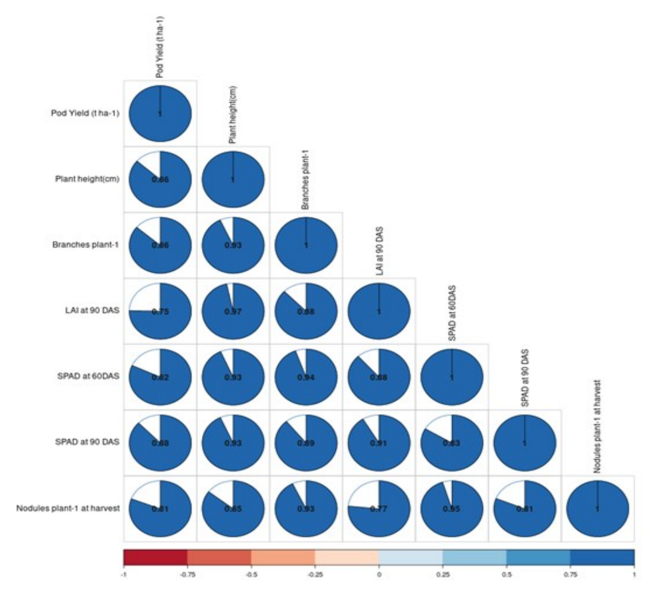

Fig. 6. Correlogram showing correlation between growth parameters and pod yield of groundnut.

Discussion

Growth parameters

Rice :The better growth of plants (Table 1) with higher levels of sulphur fertilisation was due to the vital role of the element in metabolic activities, *viz*., photosynthesis, biosynthesis of protein, chlorophyll and amino acids like methionine, cystine and cysteine (3). A higher number of tiller m^{-2} was due to the activation of axillary buds as a result of the optimal nutrient status of primary culm during early growth (27,28). The increase in LAI with an increase of sulphur levels was due to improved nutrient balance that enhanced carbohydrate utilisation for protoplasm formation, promotion of vigorous leaf growth, hike in leaf number and leaf blade expansion. The SPAD readings, indicative of leaf chlorophyll content, increased with an increase in sulphur fertilisation due to the involvement of the nutrient in the formation of succinyl-CoA, a precursor involved in the biosynthetic pathway of chlorophyll formation (29,30).

Better growth of rice due to the residual effects of the highest sulphur level can be attributed to a higher carry-over effect that supported metabolic processes, such as photosynthesis, protein biosynthesis, chlorophyll formation and amino acid synthesis in plants (Table 1). The experimental site, being clay loam in texture, restricted the leaching of sulphate from the soil. Hence, sufficient sulphur was left by groundnut for the utilization by succeeding rice (3,29 and 30).

Groundnut :The parity between bentonite and gypsum as S @ 40 kg ha^{-1} for growth of groundnut was due to similar contribution of both the sources towards the available sulphur status (Table 2) of soil during groundnut growth period (31). Better growth of groundnut with the carry over effect of higher sulphur levels, irrespective of the sources, has been reported by earlier workers (32). The sulphur requirement of groundnut was partly met by residual sulphur, which contributed to the synthesis of amino acids (methionine, cystine and cysteine), proteins, enzymes, nodulation and chlorophyll (4).

The application of S @ 60 kg ha^{-1} at sulphur in deficient soil could maintain nutrient balance in soil including sulphur that enhanced plant height, primary branches plant^{-1}, leaf area index, chlorophyll content and nodules plant^{-1} (33).

Biological yield

Rice : Irrespective of the sulphur source used, the biological yield of rice enhanced with enhancing levels of sulphur (Fig.1). The direct effect of sulphur in rice along with carry over effect of sulphur applied in groundnut could maximise the biological yield of rice, which was due to enhanced growth parameters in terms of plant height, tillers m^{-2} and LAI and yield of grain and straw (34,35).

Groundnut :The observed increase in biological yield (Fig. 2) was brought about by higher nodules plant^{-1} and chlorophyll content contributing to nitrogen fixation, protein synthesis, carbon assimilation and catalysing crop growth in the form of enhanced plant height, branches plant^{-1} and LAI) and yield of kernel and haulm (36).

Quality parameters

Rice (Protein content and protein yield) :The superiority of S @ 40 kg ha^{-1} through bentonite and gypsum over other S fertilization methods was due to the adequate supply of the nutrient to rice for the synthesis of amino acids (methionine, cysteine and cystine) that constitute protein (Table 3). Higher protein content with residual effect of the maximum sulphur level over other levels applied to groundnut was due to higher residual S left in the soil for use by rice (36). The maximum protein content with S @ 40 kg ha^{-1} through bentonite and the maximum protein yield with S @ 40 kg ha^{-1} through gypsum can be attributed to higher grain yield under the latter.

Groundnut (Oil content and oil Yield) :The enhance in oil content in kernels with enhance in sulphur levels in rice, irrespective of sources (Table 3) may be attributed to elevated glucoside levels leading to release of a greater quantity of oil upon hydrolysis, Higher oil content was found with rise in level of sulphur applied to groundnut has been reported earlier (37). The enhanced oil yield with direct and residual effects of higher levels of sulphur resulted from both an enhance in oil content of kernels and a significant improvement in pod yield.

Groundnut (Protein content and protein Yield) :The higher protein content of groundnut with carry over effects of S @ 40 kg ha^{-1}than other levels irrespective of sources applied to rice and direct effects of S @ 60 kg ha^{-1}than other levelsin groundnut was due to the involvement of sulphur in synthesizing sulphur-containing amino acids (methionine, cysteine and cystine), the fundamental building blocks of proteins (Table 3). Furthermore, sulphur contributes to the biochemical processes that convert these amino acids into high-quality functional proteins, thereby enhancing nutritional value. Incremental levels of sulphur produced higher protein content of groundnut because of synthesis of sulphur-containing amino acids (31).

System Economics :Higher system net return under F_4L_3, F_5L_3 and F_4L_2 may be attributed to direct effect of sulphur applied to component crops of the system, residual effect of sulphur in succeeding crop, adequate availability sulphur for crop use and higher yield of component crop in the system (Table 4). The higher system net returns under these treatments were predominantly due to higher yield of both the crops, as variation in cost of sulphur fertilisation was small (38). The higher values of two economical indices under these treatments was predominantly a function of yield (39).

Upscaling strategies : Our findings reveal that sulphur application enhances the biological yield, improves quality parameters and ultimately gives the maximum return and rupees per rupee investment of rice groundnut cropping system. Continuous use of Di-Ammonium Phosphate as a source of phosphorus in the system is depleting the sulphur status in the soil. Hence, there is a need to apply sulphur to sustain the productivity and profitability of the system. The promotional measures for sulphur application in the system comprise creating awareness among farmers on the benefits of sulphur application in the cropping system, incentives to the farmers for application of sulphur fertilizers and popularization of gypsum-urea fertilizer and sulphur bentonite as a source of sulphur. The higher levels of sulphur would give higher economic return till build-up of sulphur status in the soil above critical limit.

Conclusion

We planned this experiment to find out the appropriate sulphur management strategy for maximising productivity and profitability of rice-groundnut cropping system with good quality produce in S deficient soils of eastern India. It is concluded that the application of S @ 40 kg ha^{-1} through bentonite or gypsum in rice and S @ 60 kg ha^{-1} through bentonite in groundnut would boost crop growth, increase biological yield and improve quality parameters and ultimately give the maximum return and rupees per rupee investment of the component crops and the system.

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Authors' contributions

KSG carried out the field trial and manuscript preparation, BKS and BB reviewed the manuscript. AKB, GHS and MD provided guidance and helped throughout the process. All authors read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

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