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Effect of Sardar Amin Granules and Bentonite Sulfur on the Productivity of Rice-Based Cropping Systems

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ABSTRACT

The present study evaluated the impact of Sardar Amin Granules (SAG) and Bentonite Sulfur (BS) on the rice-wheat cropping system, focusing on crop productivity, soil health, and nutrient dynamics for three years (2018-2021). The experiment was conducted on rice based cropping systems viz: Rice-wheat (R-W), Rice-potato-spring maize (R-P-Sp), and Rice-raya-summer moong (R-R-Sm) at research farm, department of soil science, Punjab Agricultural University, Ludhiana. The results revealed that at the end of two-year field experiment, there was increase in the yield of wheat, potato, raya, spring maize, and summer moong crops under the treatment including additional fertilizer sources and recommended dose of fertilizers (RDF) combinations as compared to individual RDF doses (T_4). The recorded equivalent yield and system productivity also followed the same trend for three years. The maximum nitrogen (N) content was observed after the harvest of wheat under T_4 in R-W cropping system, while phosphorous (P) and potassium (K) were observed at the end of R-R-Sm under T_6 and R-P-Sp under T_8 respectively. These findings highlight the importance of integrating SAG and bentonite sulfur into conventional fertilization programs to enhance productivity and sustain soil fertility in rice-based cropping systems.

Keywords Rice, Cropping system, Fertilizer, Soil, Yield, Productivity.

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INTRODUCTION

Over the last three decades, the rice-wheat cropping system (RWCS) has been a cornerstone of food production in many regions, particularly South Asia and India. RWCS almost covers here 28.8 m. ha of total area out of which 13 m.ha in China, 12.3 m. ha in India, 2.2 m.ha in Pakistan, 0.8 m.ha in Bangladesh, and 0.5 m. ha in Nepal (Bhatt *et al*. 2016). This system supports 43% of the global population while utilizing just 20% of the world's arable land. The system alternates rice as the *kharif* (monsoon) crop with wheat as the *rabi* (winter) crop, which is critical for food security due to the high demand for both crops. In India alone, the RWCS spans 9.2 million hectares, significantly influencing the nation's food security (Jat *et al.* 2020). However, the intensification of this system over the years has also led to many challenges such as soil nutrient depletion, declining soil health, and reduced productivity, which ultimately affect crop yield and quality.

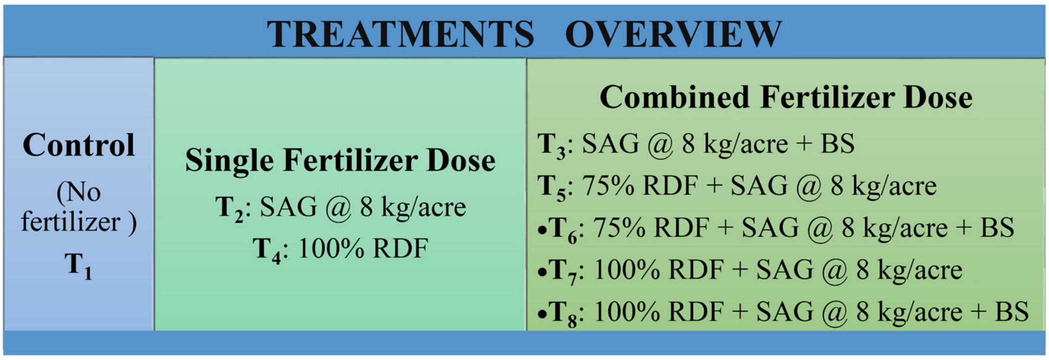
To address these challenges, there is growing interest in improving soil fertility and promoting sustainable farming practices to enhance crop productivity while maintaining or preserving soil health (Bhatt *et al.* 2016, Debangshi and Ghosh 2022, Saini *et al*. 2022). One of the critical aspects of improving soil health in the rice-wheat system is the efficient use of fertilizers and soil amendments. While traditional chemical fertilizers have been instrumental in boosting short-term yields, their excessive and imbalanced application often leads to nutrient depletion, soil degradation, and environmental pollution. Consequently, researchers and farmers are increasingly exploring alternative bio-based solutions that complement or partially substitute chemical fertilizers. These bio-based products not only supply essential nutrients but also enhance soil microbial activity, contributing to long-term soil health and sustainable productivity (Sarkar 2015, Panwar *et al.* 2019).

Sardar Amin Granules (SAG) and Bentonite Sulfur have gained attention for their potential benefits in improving crop productivity and soil quality in the rice-wheat cropping system. Sardar Amin Granules contain amino acids derived from plant proteins, along with essential micronutrients, which support seed germination, root and shoot development, and overall plant growth. Applied either as a basal fertilizer or top dressing, SAG has demonstrated its ability to improve nutrient uptake, increase plant resilience, and promote better crop establishment, particularly in nutrient-deficient soils. Furthermore, SAG can enhance the soil's microbial activity, contributing to long-term soil fertility and health (Muscolo *et al.* 2020, Sikka *et al.* 2024).

Bentonite Sulfur, a naturally occurring soil amendment, is widely recognized for its ability to improve soil pH, particularly in alkaline soils, and to increase the availability of essential nutrients like phosphorus and trace elements. Its granular form facilitates rapid oxidation and efficient acidifying properties, which help in improving nutrient availability and preventing nutrient lockout. Bentonite Sulfur has also shown potential in combating soil-borne diseases which are common in the rice-wheat cropping system, thus providing an added advantage for overall crop health and productivity (Muscolo *et al*. 2020, Sikka *et al.* 2024).

Furthermore, the study highlights that the application of advanced sulfur-based fertilizers has the potential to enhance crop yield and soil health. Granular fertilizers enriched with sulfur, humic acids, and halloysite were shown to improve fertilizer properties, including increasing the share of larger granules and bulk density. These fertilizers also stabilized soil pH and boosted sulfur content in the soil (Souri and Sayadi 2021, Nabati *et al.* 2025). Similarly, the application of Gromor Sulfur Bentonite Pastilles significantly enhanced grain and straw yield and improved the uptake of essential nutrients such as N, P, K, Ca, Mg, S, Fe, Mn, Zn, and Cu in a hybrid rice-potato-green gram cropping system compared to gypsum and single superphosphate (SSP). The residual benefits of Gromor Bentonite Sulfur Pastilles on succeeding green gram crops surpassed those of gypsum and SSP, making them a recommended sulfur fertilizer due to their high sulfur concentration, slow-release properties, and reduced leaching losses (Jena and Kabi 2012, Lisowska *et al.* 2022, Bahloul *et al.* 2024). Recent findings by Sikka *et al.* (2024) further emphasize the advantages of applying Sardar Amin Granules and Bentonite Sulfur in maize-based cropping systems. Their research demonstrated notable increases in system productivity and significant improvements in soil nitrogen (N) and phosphorus (P) content compared to treatments without these products or where they were applied individually or in combination.

Building on this foundation, a study conducted between 2018 and 2021 evaluated the impact of Sardar Amin Granules and Bentonite Sulfur on the rice-wheat cropping system, focusing on crop productivity, soil health, and nutrient dynamics. The results provide critical insights into sustainable agricultural practices that enhance both yield and soil quality in the rice-wheat system. This research underscores



SAG: Sardar Amin Granules
BS: Bentonite Sulfur
RDF: Recommended Dose of Fertilizers

Fig. 1. Sub plots (Treatments) overview of rice based cropping systems.

the importance of integrated nutrient management strategies to boost the productivity and sustainability of intensive cropping systems while safeguarding soil health.

MATERIALS AND METHODS

Experimental site details

A three-year field experiment (2018–2021) was carried out at the research farm of the Department of Soil Science, Punjab Agricultural University (PAU), Ludhiana, India. The experimental site is located at 30°56′ N latitude and 75°52′ E longitude. The region experiences a semi-arid subtropical climate with an annual rainfall of approximately 700–800 mm.

Experimental design and layout

The experiment was laid out in a split-plot design, comprising main plots and sub-plots. The main plot was assigned three rice based cropping system viz: Rice-wheat (R-W), Rice-potato-spring maize (R-P-Sp), and Rice-raya-summer moong (R-R-Sm). The sub-plots comprise of total eight treatments which includes seven treatment with different NPK fertilizer doses, and one control treatment devoid of any type of fertilizer dose, the details are given below (Fig. 1).

Each treatment was replicated three times in a fixed layout, resulting in a total of 24 treatment combinations. Irrigation was applied as per crop requirements and prevailing weather conditions. The initial physico-chemical properties of the experimental field are provided in Table 1.

Inputs and fertilizer Specifications

Sardar Amin Granules (SAG) and Bentonite Sulfur, manufactured by Gujarat State Fertilizer and Chemical Limited, were utilized in the study. SAG comprises nitrogen, hydrolyzed proteins (amino acids

Table 1. Preliminary physico-chemical characteristics of experimental field.

Parameter	Details	Description
Soil texture	Sandy-loam	Good drainage and moderate nutrient retention
pH	7.85	Suitable for rice cultivation
EC (dS/m)	0.212	Low salinity level
Organic carbon (%)	0.42	Low organic matter content
Nitrogen (kg/ha)	162.8	Moderate nitrogen availability
Phosphorus (kg/ha)	22.7	Low phosphorus levels
Potassium (kg/ha)	152.60	Moderate potassium content

Table 2. Details of the package of practices of different crops.

SI. No.	Crop	Variety	Spacing (cm × cm)	RDF (kg/acre) $N:P_2O_5:K_2O$
1	Rice	PR 129	60 x 10	42:12:12
2	Wheat	Unnat PBW 343	20	50:25
3	Potato	Kufri Pukhraj	Rows (65 × 18.5), tubers (75 × 15)	187.5:62.5:62.5
4	Spring Maize	PMH 2	60 × 20	120:60:0
5	Raya	PHR 126	30 × 10	40:12:0
6	Summer Moong	SML1827	22.5 × 7	30:15:0

such as alanine, glutamic acid, leucine, and serine) derived from plant sources, hydrolyzed carbohydrates, phosphorus, potassium, zinc, iron, and manganese. Bentonite sulfur, applied to the soil, contains 90% sulfur and 10% bentonite clay. Furthermore, various types of crops used in the cropping system are specified with variety, spacing and RDF in Table 2 (Anonymous 2023).

Crop and cropping system

The grain yield (q/ha) of various crops in rice-based cropping systems was calculated each year over a three-year period (2018-2021). Each cropping system's average grain yield per year was converted into rice equivalent yield (REY) based on the crops' minimum support price (Uddin *et al*. 2009). The calculation utilized the following formula:

$$\text{Equivalent yield (EY) (main crop)} = \frac{(YMC*PMC+YSC*PSC)}{PMC}$$

YMC= Main crop yield (q/ha)
YSC= Secondary crop yield (q/ha)
PSC= Secondary crop price (Rs/q)
PMC= Main crop price (Rs/q)

System productivity (SP) was determined annually by dividing the system equivalent yield (kg/ha) by the duration (number of days) of the respective cropping system, expressed in kg/ha/day (Tomar and Tiwari 1990).

Soil analysis

The upper layer (0-15 cm) of surface soil was collected from the experimental site. The samples underwent sieving through a 2 mm mesh for analysis of various physico-chemical parameters. Soil pH and EC (1:2 soil:water suspension) were determined using a glass rod and a conductivity meter, with the conductivity measured in dS/m (Jackson 1967). The available macronutrients nitrogen (N), phosphorus (P), potassium (K), and organic carbon (%) were assessed following established procedures: Subbiah and Asija (1956) for nitrogen, the Walkley and Black method (1934) for organic carbon, 0.5M NaHCO3 (pH 8.5) extraction for phosphorus (Olsen 1954), and neutral ammonium acetate method using a flame photometer for potassium (Merwin and Peech 1950).

Statistical analysis

The ANOVA (Analysis of variance) test was conducted to statistically analyze plant and soil data for selected parameters (GenStat 10^{th} edition, Rothamsted Experimental Station 2000). The treatment means were analyzed for their significance through LSD (least significant difference) at $p \leq 0.05$.

RESULTS

Crop yield

The rice grain yield data (Fig. 2) demonstrated a significant improvement with the application of 100% recommended dose of fertilizers combined with SAG and bentonite sulfur (T_8) compared to 100% recommended fertilizer dose alone (T_4) across all three years. The significant ($p<0.05$) presult was recorded for different crop yield except summer moong and raya during 2018-19 and 2020-21 respectively.

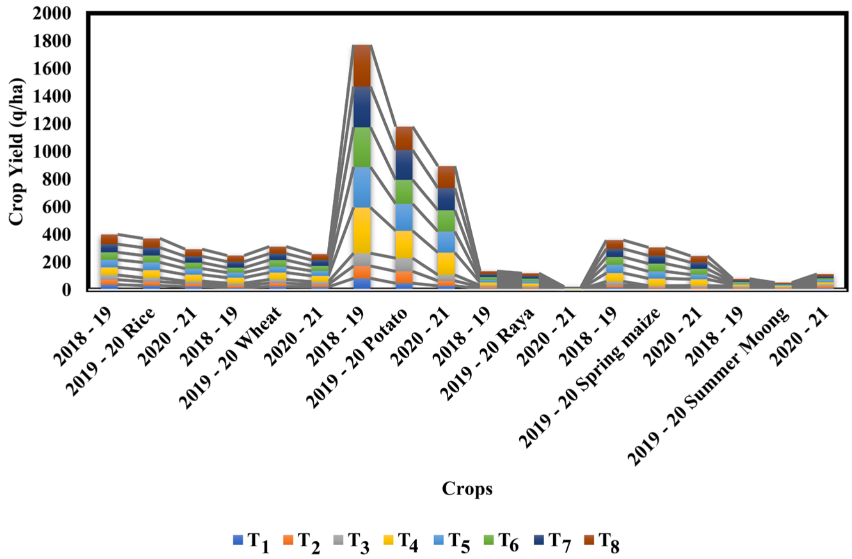


Fig. 2. Effect of SAG-BS application on different crop yield of rice-based cropping system over three years.

Within the rice-based cropping system, a consistent numerical increase in grain yield was recorded under the T_8 treatment compared to T_4 during 2018-19, 2019-20, and 2020-21 for wheat, spring maize, and summer moong. Notably, for spring maize, the addition of SAG to the 100% recommended fertilizer dose (T_7) resulted in a 12.1% increase in mean grain yield during 2019-20 and a 2.82% increase in 2020-21, highlighting the positive impact of this treatment.

The potato crop showed the highest tuber yield under 100% recommended fertilization, reaching 331 q ha^{-1} in 2018-19 and 168.8 q ha^{-1} in 2020-21. In 2019-20, the addition of SAG to the 100% recommended fertilizer dose (T_7) enhanced tuber yield by 8.9% compared to T_4, further emphasizing the benefits of this combined treatment.

For raya grain yield, no significant differences were observed between T_7 and T_8 treatments compared to T_4 in most years. However, in 2018-19, a modest increase was recorded, with yields improving by 2.3% and 0.5% under T_7 and T_8, respectively, over T_4. While the differences were not statistically significant, these results suggest a slight yield advantage from the inclusion of SAG and bentonite sulfur in certain conditions.

These findings underline the role of integrated fertilizer management in improving crop yields across

Table 3. Effect of SAG-BS application on rice equivalent yield and system productivity (2018-19).

Fertilizer treatments	Rice equivalent yield (q ha^{-1}) R-W	R-P-Sp	R-R-Sm	System productivity (kg/ha/day) R-W	R-P-Sp	R-R-Sm
T_1	52.5	72.9	98.7	17.8	21.2	29.4
T_2	55.0	74.3	98.2	18.6	21.6	29.2
T_3	54.0	75.3	117.3	18.3	21.9	34.9
T_4	101.1	187.8	138.8	34.3	54.6	41.3
T_5	101.7	177.2	129.2	34.5	51.5	38.5
T_6	92.8	172.4	143.7	31.4	50.1	42.8
T_7	110.9	184.8	143.7	37.6	53.7	42.8
T_8	113.4	190.3	125.7	38.4	55.3	37.4
Mean	85.2	141.9	124.4	28.9	41.2	37.0

Table 4. Effect of SAG-BS application on rice equivalent yield and system productivity (2019-20).

Fertilizer treatments	Rice equivalent yield (q ha^{-1})			System productivity (kg/ha/day)		
	R-W	R-P-Sp	R-R-Sm	R-W	R-P-Sp	R-R-Sm
T_1	54.5	52.6	74.9	19.0	15.6	21.0
T_2	52.8	56.2	77.3	18.5	16.6	21.6
T_3	56.2	56.8	77.1	19.7	16.8	21.6
T_4	102.1	151.1	142.8	35.7	44.7	40.0
T_5	108.9	141.0	124.3	38.1	41.7	34.8
T_6	87.0	151.9	110.5	30.4	44.9	31.0
T_7	97.9	166.9	125.2	34.2	49.4	35.1
T_8	119.4	161.4	147.9	41.7	47.8	41.4
Mean	84.9	117.2	110.0	29.7	34.7	30.8

rice-based cropping systems.

Equivalent yield and system productivity

The trends in equivalent yield and system productivity, averaged over each year for various rice-based multiple cropping systems under different fertilizer treatments, are illustrated in Tables 3-5. The recorded data were found significant ($p<0.05$) for all three years. The combined application of SAG (soil amendment gypsum) and bentonite sulfur, along with 100% of the recommended dose of fertilizers (RDF), that is, T_8 exhibited consistently higher equivalent yield and system productivity compared to the application of 100% RDF (T_4) alone across all three years. This trend was particularly evident in the R-P-Sp, followed by R-R-Sm cropping system during 2018–19 and 2019–20. However, in the third year (2020–21), the highest equivalent yield was observed in R-R-Sm, followed by R-P-Sp while system productivity was recorded at par for R-P-Sp and R-R-Sm cropping systems.

The maximum mean system productivity across the three years was achieved with the combined application of SAG and 100% RDF (T_8), highlighting the synergistic effect of soil amendments and balanced fertilization on enhancing yield performance.

Soil fertility status in rice-based cropping system

No significant changes in soil pH, electrical conductivity (EC), or organic carbon were observed after the wheat, spring maize, and summer moong harvest under the rice-wheat cropping system (Tables 6–8).

After the harvest of wheat at the end of rice-wheat cropping system, NPK differed significantly (Table 6). The highest soil available nitrogen (175.4 kg ha^{-1}) and phosphorus (29.9 kg ha^{-1}) levels were recorded in treatments receiving 75% of the recommended dose of fertilizers combined with SAG (T_5). There were no significant differences in soil available nitrogen and phosphorus levels between treatments with 100% recommended dose of fertilizers alone (T_4)

Table 5. Effect of SAG-BS application on rice equivalent yield and system productivity (2020-21).

Fertilizer treatments	Rice equivalent yield (q ha^{-1})			System productivity (kg/ha/day)		
	R-W	R-P-Sp	R-R-Sm	R-W	R-P-Sp	R-R-Sm
T_1	40.3	35.0	67.7	14.9	10.4	19.2
T_2	36.6	38.9	73.2	13.6	11.5	20.7
T_3	34.3	37.3	79.0	12.7	11.1	22.4
T_4	83.6	113.0	110.6	30.9	33.5	31.3
T_5	74.9	104.6	102.2	27.7	31.0	28.9
T_6	74.7	111.6	89.8	27.7	33.1	25.4
T_7	85.1	119.5	96.2	31.5	35.5	27.3
T_8	87.4	125.6	111.1	32.4	37.3	31.5
Mean	64.6	85.7	91.2	23.9	25.4	25.8

R-W: Rice-Wheat; R-P-Sp: Rice-Potato-Spring maize; R-R-Sm: Rice-Raya-Summer moong.

Table 6. Soil fertility status examined after the harvesting of wheat under rice based cropping system in 2020-21.

Fertilizer treatments	pH	EC (dS m^{-1})	OC (%)	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
T_1	7.85	0.246	0.37	91.9	19.3	118.6
T_2	7.83	0.249	0.37	108.7	16.9	113.5
T_3	7.93	0.264	0.38	87.8	28.1	115.9
T_4	7.80	0.234	0.38	162.8	22.7	141.5
T_5	7.84	0.258	0.37	175.4	29.9	122.2
T_6	7.75	0.248	0.32	156.5	22.1	109.4
T_7	7.88	0.283	0.38	152.8	22.3	105.5
T_8	7.94	0.284	0.32	154.5	23.8	121.1
LSD (p= 0.05)	NS	NS	NS	45.2	3.74	9.43

Table 7. Soil fertility status examined after the harvesting of spring maize under rice based cropping system in 2020-21.

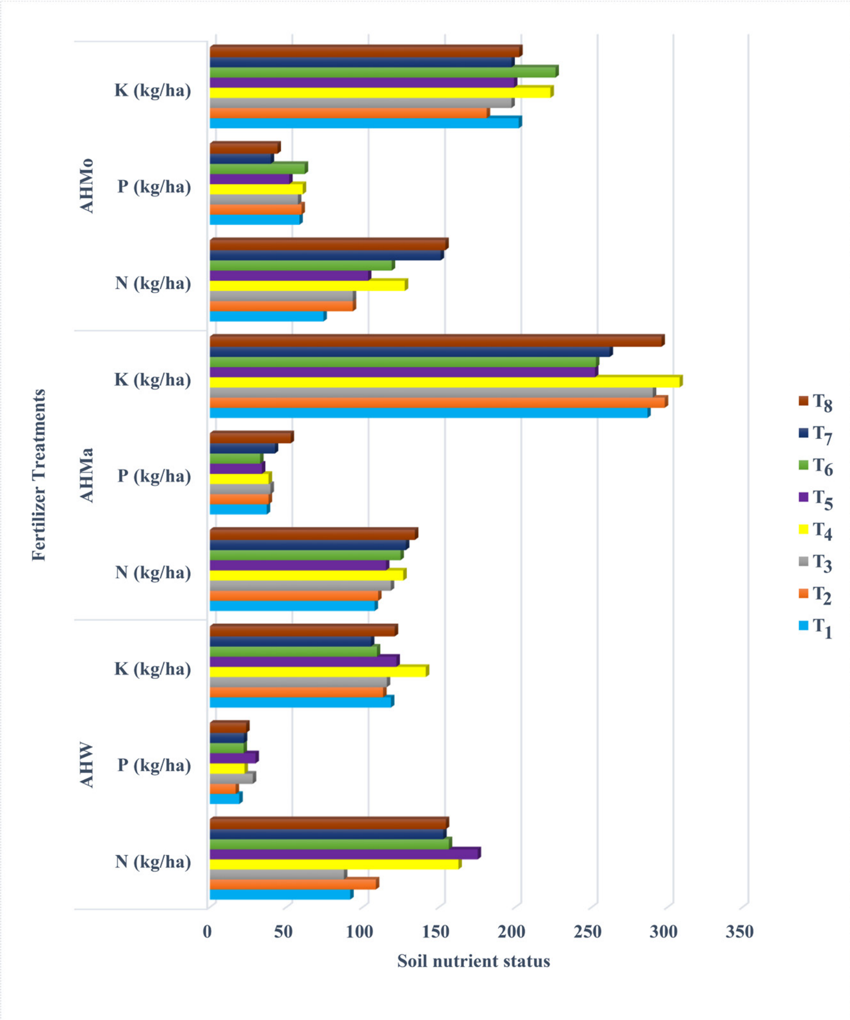
Fertilizer treatments	pH	EC (dS m^{-1})	OC (%)	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
T_1	8.00	0.281	0.64	107.87	37.3	286.6
T_2	7.98	0.222	0.67	110.20	38.5	298.2
T_3	7.86	0.216	0.59	118.53	39.7	290.2
T_4	7.90	0.233	0.64	126.71	38.5	308.1
T_5	7.88	0.204	0.61	115.35	34.1	252.2
T_6	7.99	0.250	0.67	124.87	32.9	252.9
T_7	7.84	0.319	0.66	128.35	42.6	261.8
T_8	7.50	0.305	0.65	134.32	52.9	296.0
LSD (p= 0.05)	NS	NS	NS	9.06	8.77	13.69

and those with 100% recommended dose combined with SAG and bentonite sulfur (T_8). Soil available potassium was highest (141.5 kg ha^{-1}) in the treatment with 100% recommended dose of fertilizers, significantly exceeding the levels in treatments with SAG and bentonite sulfur, T_8 (121.1 kg ha^{-1}).

At the end of the rice-potato-spring maize cropping system, a significant difference in soil available N, P, and K content was observed (Table 7). The additional application of SAG with 100% recommended dose of fertilizers (T_7) and its combination with bentonite sulfur (T_8) resulted in higher soil available nitrogen and phosphorus levels compared to 100% recommended dose alone (T_4). Soil available nitrogen increased to 134.32 kg ha^{-1} with the application of 100% recommended dose + SAG + bentonite sulfur (T_8) compared to 126.71 kg ha^{-1}

Table 8. Soil fertility status examined after the harvesting of summer moong under rice based cropping system in 2020-21.

Fertilizer treatments	pH	EC (dS m^{-1})	OC (%)	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
T_1	7.58	0.50	0.30	74.4	58.6	202.3
T_2	7.61	0.51	0.27	93.6	60.0	181.3
T_3	7.63	0.42	0.38	93.6	57.6	197.5
T_4	7.68	0.48	0.26	127.7	60.8	223.1
T_5	7.66	0.49	0.24	103.6	51.9	199.2
T_6	7.63	0.50	0.37	119.1	62.1	226.4
T_7	7.51	0.61	0.34	151.1	39.8	197.5
T_8	7.69	0.62	0.36	154.2	44.3	202.6
LSD (p= 0.05)	NS	NS	NS	11.47	6.41	15.8



AHW: After harvest of wheat
AHMa: After harvest of spring maize
AHMo: After harvest of summer moong

Fig. 3. Soil NPK status examined at the end of R-W, R-P-Sp, and R-R-Sm rice based cropping system.

with 100% recommended dose alone (T_4). Similarly, soil available phosphorus was highest (52.9 kg ha^{-1}) in T_8, followed by 42.6 kg ha^{-1} in T_7. However, soil available potassium content was higher in plots with 100% recommended dose alone (308.1 kg ha^{-1}) than in those with SAG and bentonite sulfur (296.0 kg ha^{-1}), though the difference was non-significant.

For the rice-raya-summer moong cropping system, soil available nitrogen content (Table 8) was significantly higher with the application of 100% recommended dose + SAG + bentonite sulfur (154.2 kg ha^{-1}), followed by 100% recommended dose + SAG (151.1 kg ha^{-1}), compared to 100% recommended dose alone (127.7 kg ha^{-1}). The significant highest soil phosphorus and potassium contents (62.1 kg ha^{-1} and 226.4 kg ha^{-1}, respectively) were recorded with 75% of the recommended dose of fertilizers combined with SAG and bentonite sulfur. Figure 3 represents the comparative soil NPK status after the harvest of wheat, spring maize, summer moong.

DISCUSSION

Crop yield

The results of this study underscore the significant role of integrated nutrient management in enhancing crop productivity across rice-based cropping systems. The observed increase in rice grain yield under the combined application of 100% recommended dose of fertilizers with SAG and bentonite sulfur (T_8) compared to 100% recommended dose alone (T_4) aligns with previous findings that emphasize the benefits of supplementing conventional fertilizers with soil amendments to improve nutrient availability and plant uptake (Rastogi *et al*. 2023, Selim 2020). SAG and bentonite sulfur have been shown to enhance nutrient use efficiency by improving soil nutrient retention and promoting sustained nutrient release, which likely contributed to the higher yields observed in this study.

The consistent numerical increase in grain yield across wheat, spring maize, and summer moong under T_8 and T_7 treatments highlights the synergistic effects of these amendments. The significant increase in spring maize yield during 2019-20 (12.1%) and 2020-21 (2.82%) under T_7 supports previous reports of improved crop response to sulfur and gypsum-based amendments, particularly in sulfur-deficient soils (Rashmi *et al.* 2024). This effect is attributed to the role of sulfur in protein synthesis and enzymatic activity, which are critical for crop growth and development (Narayan *et al.* 2023).

Potato tuber yield was also positively influenced by the integrated nutrient management strategy. The highest yields were recorded under T_7 during 2019-20, with an 8.9% increase over T_4, indicating that SAG application can effectively enhance tuber growth. This finding corroborates earlier studies by Klikocka (2020), who reported improved potato yields with sulfur supplementation, as sulfur plays a vital role in starch formation and tuber quality.

Raya grain yield, however, showed no significant differences between treatments, except in 2018-19, where slight increases were observed under T_7 and T_8. This suggests that the nutrient demands of raya may not be as responsive to sulfur or gypsum amendments as other crops in the system, which aligns with findings by Singh (2019), indicating varying crop-specific responses to nutrient management practices.

Equivalent yield and system productivity

The trends observed in equivalent yield and system productivity across the rice-based cropping systems under various fertilizer treatments highlight the critical role of integrated nutrient management in enhancing agricultural productivity. The significant ($p > 0.05$) differences recorded over the three years indicate that fertilizer treatments, specifically the combined application of soil amendment gypsum (SAG) and bentonite sulfur along with 100% of the recommended dose of fertilizers (RDF), significantly influenced crop performance in rice-based cropping systems.

The consistent improvement in equivalent yield and system productivity under T_8 (SAG + bentonite sulfur + 100% RDF) across all years suggests a synergistic effect of these inputs on nutrient availability and uptake efficiency. Gypsum, as a source of calcium and sulfur, enhances soil structure and promotes better root growth, while bentonite sulfur improves sulfur availability, critical for protein synthesis and chlorophyll formation (Majhi *et al*. 2021, Rathore *et al.* 2022). These factors likely contributed to improved crop performance, particularly in nutrient-demanding systems such as rice-potato-spring maize (R-P-Sp).

During 2018–19 and 2019–20, the R-P-Sp system exhibited the highest equivalent yield and system productivity under T_8. This could be attributed to the complementary nutrient dynamics and efficient resource utilization in this cropping sequence. For instance, the inclusion of potato as a high-value crop and spring maize, a nutrient-exhaustive cereal, may have benefited from the balanced nutrient application provided by T_8 (Sahoo *et al.* 2024). However, in the third year (2020–21), the R-R-Sm (rice-raya-summer moong) system surpassed R-P-Sp in terms of equivalent yield while maintaining parity in system productivity. The inclusion of legumes such as summer moong in the R-R-Sm system likely improved soil fertility through biological nitrogen fixation, contributing to higher yields in subsequent crops (Ali *et al.* 2022).

The maximum mean system productivity achieved with T_8 across all three years emphasizes the importance of integrated nutrient management practices. Combining SAG with RDF ensures balanced fertilization, addressing both macro- and micro-nutrient deficiencies in the soil. This finding aligns with earlier studies that underscore the benefits of soil amendments and sulfur-based fertilizers in enhancing crop yield and soil health (Sahu *et al.* 2017, Singh *et al.* 2022).

Soil fertility status in rice-based cropping system

The results of this study indicate that integrated nutrient management strategies significantly influence soil nutrient status under different cropping systems. The lack of significant changes in soil pH, electrical conductivity (EC), and organic carbon across treatments under the rice-wheat cropping system suggests that these parameters were relatively stable and not strongly affected by the amendments or fertilizer applications during the study period. This aligns with the findings of Sharma *et al.* (2019), who reported that short-term cropping system interventions often have minimal effects on soil pH and organic carbon.

The significant differences in soil available nitrogen, phosphorus, and potassium observed at the end of the rice-wheat cropping system underscore the role of integrated nutrient management in enhancing soil fertility. The highest levels of soil nitrogen (175.4 kg ha^{-1}) and phosphorus (29.9 kg ha^{-1}) in T_5 (75% recommended dose + SAG) highlight the potential of SAG in improving nutrient retention and reducing losses through leaching or volatilization, consistent with findings by Rastogi *et al.* (2023). However, soil potassium content was highest in the treatment with 100% recommended dose alone (141.5 kg ha^{-1}), suggesting that SAG and bentonite sulfur may influence potassium availability differently, as previously noted by Singh (2019).

In the rice-potato-spring maize cropping system, the application of SAG combined with the recommended dose of fertilizers (T_7 and T_8) resulted in improved soil nitrogen and phosphorus levels. The highest soil nitrogen content (134.32 kg ha^{-1}) in T_8 can be attributed to the enhanced nitrogen use efficiency and slower nutrient release provided by SAG and bentonite sulfur, as reported by Sikka *et al.* (2024). The elevated phosphorus levels in T_8 (52.9 kg ha^{-1}) further corroborate the role of these amendments in improving phosphorus availability by reducing fixation in soils, as observed by Selim *et al.* (2020). However, the higher potassium content in T_4 (308.1 kg ha^{-1}) compared to treatments with SAG and bentonite sulfur indicates that potassium availability may be less influenced by these amendments under this cropping system.

For the rice-raya-summer moong cropping system, the significant improvement in soil nitrogen (154.2 kg ha^{-1}) and phosphorus (62.1 kg ha^{-1}) content with T_8 reflects the cumulative benefits of combining SAG and bentonite sulfur with the recommended dose of fertilizers. This is consistent with Rashmi *et al.* (2024), who demonstrated that sulfur and gypsum-based amendments can enhance nutrient availability in legume-based cropping systems. The highest potassium content (226.4 kg ha^{-1}) observed in the treatment with 75% recommended dose + SAG and bentonite sulfur suggests that these amendments can maintain potassium levels even at reduced fertilizer rates, as also reported by Narayan *et al.* (2023).

CONCLUSION

The findings highlight the importance of integrating SAG and bentonite sulfur into conventional fertilization programs to enhance productivity and sustain soil fertility in rice-based cropping systems. The synergistic effects of these amendments, particularly in improving nitrogen and phosphorus availability, underscore their potential as effective tools for intensive cropping systems. Future research should focus on the long-term impacts of such nutrient management strategies on soil health, crop quality, and economic viability across diverse agro-climatic conditions to ensure sustainable agricultural practices and their widespread adoption by farmers.

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