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Improving the Nutritional Quality of Paddy Straw (*Oryza sativa* L.) through Soil Fertilization with Sulphur and Zinc for Ruminant Feeding

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Abstract
The present study evaluated the effect of sulphur and zinc applied to soil on nutritional quality of paddy straw (Oryza sativa L.) for ruminant feeding. Field experiment was conducted using four levels each of sulphur (0, 15, 30 & 45 kg ha^{-1}) and zinc (0, 3, 6 & 9 kg ha^{-1}) comprising sixteen treatments with three replications in factorial randomized block design. Alone application of zinc showed an antagonistic effect on phosphorus and calcium content while sulphur application significantly improved their concentrations in paddy straw. In comparison to control, combined application of 45 kg S ha^{-1} and 9 kg Zn ha^{-1} significantly influenced N, K, Zn, S, Ca, crude protein, total carbohydrates and reducing sugar contents by 52.78%, 62.50%, 22.22%, 3.68%, 52.80%, 23.91% and 39.13%, respectively exhibited a good improvement in nutritional quality of rice straw. Correlation analyses revealed strong positive relationships among the mineral nutrient concentrations and biochemical constituents of the paddy straw. It was concluded that combined soil application of 45 kg S ha^{-1} and 9 kg Zn ha^{-1} is an effective agronomic strategy for enhancing the nutritive value of rice straw, making it a valuable roughage source particularly during lean season to sustain the normal health and productivity of livestock.
Keywords: *Sulphur, Zinc, Ruminant feed, Rice straw, Mineral nutrients, Crude protein, Carbohydrates*

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I. Introduction

Scarcity of quality feed and fodder is a major constraint in Indian livestock production. India had a deficit of about 23.4% in dry fodder availability, necessitating efficient utilization of residues as alternative feed resources (Roy *et al.*, 2019). Industrialization and increasing human population are causing much pressure on agricultural land and apparently animal production likely would depend on feeding the by-products of food crops. Rice being a major staple food renders energy and protein to nearly half of the global population. Along with rice grain, approximately 731 million tonnes of rice straw are produced globally per year, of which India contributes about 126.6 million tonnes of rice straw with an average harvest index of 0.45 (Malik *et al.*, 2023). Rice straw is used as low-cost roughage for ruminants. It is typically used as a source of roughage, especially during lean season and it is a valuable emergency bulk feed to prevent starvation. Rice straw is generally most appropriate for cattle with relatively low nutritional requirement such as non-lactating cattle or when supplements are inexpensive. The nutritional quality and chemical composition of rice straw vary considerably depending on fertilizer management, soil fertility status, climatic conditions, crop variety, maturity stage, harvesting practices and post-harvest storage conditions (Kumar *et al.,* 2023). Due to limited nutritive value, it is used as a replacement for part of the forage in a ration. However, its quantity in a ration depends on the nutritional quality of the rice straw. Rice straw constitutes nearly 81% of the total roughage fed to ruminants in Bangladesh and accounts for 60-90% of the dry matter intake of ruminants in many Asian countries (Nandjui *et al.*, 2021).

Sulphur and Nitrogen are components of protein forming amino acids which are directly linked to growth and milk production and support rumen bacteria which use ammonical-N to synthesize protein. Zinc contributes to reproductive efficiency mainly in young animals besides improving immune function, protein synthesis, enzyme activities and feed utilization. Zinc deficiency results in stunted growth and delayed sexual maturity. Seasonal scarcity of the fodder during lean period and enhancement of nutrients content in rice straw is demand of the time. However, information about combined influence of sulfur and zinc fertilization on nutritional quality of rice straw remains limited. Thus, the present study was aimed to assess the influence of sulphur and zinc nutrition on structural, non-structural and mineral nutrient concentration in straw of Samba Mahsuri (BPT-5204), grown in Indo-Gangetic plain of Uttar Pradesh, India.

II. Materials and Methods

Experimental Setup and treatment details: Straw used in this study was collected from a field experiment conducted at the Crop Research Farm of Department of Soil Science and Agricultural Chemistry, Naini Agricultural Institute, SHUATS, Prayagraj, U.P. during *kharif* season, 2024. A total of 16 treatments comprising four levels each of sulphur (0, 15, 30 and 45 kg ha^{-1}) through gypsum and zinc (0, 3, 6 and 9 kg ha^{-1}) through zinc oxide were replicated thrice in factorial randomized block design in plots of area 12 m^2. Experimental field had sandy loam texture with pH 7.11, electrical conductivity 0.30 dSm^{-1} (1:2.5, soil:water solution), organic carbon 0.32%, available nitrogen 230.70 kg ha^{-1}, available phosphorus 19.48 kg ha^{-1}, available potassium 195 kg ha^{-1}, sulphur 9.70 mg kg^{-1} and extractable zinc 0.65 mg kg^{-1}. Two 25 days old seedlings were transplanted in each hill at the spacing of 25 x 20 cm. Recommended dose of N, P and K were applied through urea, DAP and MOP, respectively. Half dose of nitrogen and full dose of phosphorus and potassium were applied at transplanting. Remaining half of nitrogen was top dressed in 2 equal splits. Manual weeding was done at 30 and 60 days after transplanting. Crop was irrigated plot wise as and when required. Appropriate agronomical practices were followed to protect the crop from insect and pests.

Collection of straw samples: The crop was harvested manually when grains almost matured and plants had turned yellow. Crop was harvested plot wise, bundled and left for few days to dry. Dried crop bundles were threshed by beating separately. After separation of grain about 200g of straw samples were collected. Samples were thoroughly cleaned through repeated washing followed by rinsing with 0.1N HCl and finally washed with distilled water. The cleaned samples were air dried and then oven dried at 60 $\pm 2^0$C for 48 hours. Once dried, the samples were ground separately using a grinder (Wiley Mill).

Chemical Analysis: Ground rice straw samples were used to analyze the nutrient content in them. Nitrogen, phosphorus and potassium were estimated using modified Kjeldahl method, Vanadomolybdophosphoric yellow color method and using a flame photometer, respectively as described by (Wallinga *et al.,* 1989). Content of sulphur and zinc was determined following the procedure as described by Tandon (1991) and Lindsay and Norvell (1978), respectively. Total carbohydrate and reducing sugar in rice straw was determined by the method described by Weinmann (1947) and (Miller, 1959), respectively. Crude protein content was computed by multiplying per cent straw-N with the factor 6.25 (AOAC, 1990). Content of calcium was analyzed by alternate versenate (EDTA) method as described by Chopra and Kanwar (1976).

Statistical Analysis: Data were statistically analyzed to reach a valid conclusion following the procedure as outlined by Gomez and Gomez (1984). Analysis of variance (ANOVA) was conducted to detect differences in nutrients in rice straw using Statistix 9.0 (Analytical Software, Tallahassee, FL, USA). Significant difference among treatment means were compared using the critical difference at 5% level of significance. Correlation analysis was conducted to test the relationships among the variables (Pearson, 1895).

III. Results and Discussion

Nitrogen, phosphorus and potassium content in paddy straw: Nitrogen content in paddy straw was significantly influenced by increasing levels of sulphur and zinc (Table 1). Individual application of S @ 45 kg ha^{-1} and Zn @ 9 kg ha^{-1} increased 26.83% and 16.28% increase in straw nitrogen content, respectively, over their control. The increase in nitrogen content with zinc application may be attributed to its role in reducing hidden zinc deficiency and enhancing nitrogen uptake and assimilation. Sulphur is essential for the synthesis of sulphur containing amino acids and proteins, thereby improving both the quantity and quality of protein in Straw (Narayana *et al*., 2023). The highest nitrogen content (0.55%) was recorded under Zn_9S_{45}, showing a 52.78% increase over the control. Increased nitrogen concentration is of considerable importance for ruminant nutrition because nitrogen content is directly associated with crude protein content. Thus, the improvement from 0.36% in the control to 0.55% nitrogen content under Zn_9S_{45} is substantially enhance the protein supplying capacity and feeding value of rice straw for cattle.

Phosphorus content in paddy straw increased by 21.52%, 37.97% and 49.37% with the application of 15, 30 and 45 kg S ha^{-1}, respectively over the control, demonstrating strong positive role of sulphur in enhancing P uptake and accumulation in straw (Table 1). Application of zinc exhibited significant depressive influence on straw phosphorus content which declined progressively from 1.20 to 0.75 g kg^{-1} with increasing zinc levels. The interactive effects of zinc and sulphur on phosphorus accumulation showed an antagonism that directly impacts nutritional value of cattle feed. Increasing zinc levels consistently decreased phosphorus content at every sulphur level. The highest phosphorus content (1.30 g kg^{-1}) was recorded in absence of zinc with 45 kg S ha^{-1}, whereas the lowest value (0.60 g kg^{-1}) was observed under Zn_9S_0. Sulphur enhanced phosphorus assimilation by stimulating root activity and organic acid secretion while excessive zinc restricted phosphorus uptake but partially offset by sulphur-induced solubilization. These observations are in conformity to the findings of

Nadeem *et al.,* (2023) who stated that sulphur enhances phosphorus availability through its effect on soil chemical properties and nutrient solubilization, whereas higher zinc levels may restrict phosphorus uptake due to antagonistic interactions between zinc and phosphorus in the soil-plant system.

Potassium content in rice straw increased steadily from 10.23 to 11.25 g kg^{-1} showing 9.97% increase which is nutritionally beneficial, particularly for high producing animals and those exposed to heat stress. Similarly, increasing levels of sulphur application enhanced potassium content in rice straw from 10.58 to 10.80 g kg^{-1} showed a 2.08% increase over control. The highest potassium content (11.40 g kg^{-1}) was recorded under Zn_9S_{30} showed a 12.87% increase over the lowest value (10.10 g kg^{-1}) with Zn_0S_0. The improvement in potassium accumulation under elevated sulphur and zinc which attributed to enhanced root activity and membrane function which promoted efficiency of NO^{3-} and K^+ uptake (Broadley *et al*., 2012). The simultaneous improvement in nitrogen and potassium concentrations under combined sulphur and zinc application indicates a positive interaction between these nutrients, thereby enhancing the nutritional quality and feeding value of rice straw for ruminants.

Table 1: Influence of S and Zn on content of N, P and K in cattle feed of paddy straw

	N content (%)				
	S_0	S_{15}	S_{30}	S_{45}	Mean
Zn_0	0.36	0.40	0.46	0.48	0.43
Zn_3	0.39	0.45	0.47	0.50	0.45
Zn_6	0.43	0.47	0.49	0.53	0.48
Zn_9	0.46	0.49	0.51	0.55	0.50
Mean	0.41	0.45	0.48	0.52	--
	Zinc	Sulphur	Zn x S		
CD ($P \leq 0.05$)	0.01	0.01	0.02		
	P content (g kg^{-1})				
	S_0	S_{15}	S_{30}	S_{45}	Mean
Zn_0	1.00	1.15	1.25	1.30	1.20
Zn_3	0.80	1.10	1.20	1.25	1.08
Zn_6	0.75	0.90	1.10	1.20	0.99
Zn_9	0.60	0.70	0.80	0.95	0.75
Mean	0.79	0.96	1.09	1.18	--
	Zinc	Sulphur	Zn x S		
CD($P \leq 0.05$)	0.03	0.03	0.05		
	K content (g kg^{-1})				
	S_0	S_{15}	S_{30}	S_{45}	Mean
Zn_0	10.10	10.20	10.30	10.30	10.23
Zn_3	10.40	10.40	10.50	10.60	10.48
Zn_6	10.70	10.80	10.90	11.00	10.85
Zn_9	11.10	11.20	11.40	11.30	11.25
Mean	10.58	10.65	10.78	10.80	----
	Zinc	Sulphur	Zn x S		
CD($P \leq 0.05$)	0.03	0.03	0.07		

Zinc, sulphur and calcium content in paddy straw: Zinc content in paddy straw was significantly influenced by both individual and combined application of sulphur and zinc (Table 2). Zinc content increased from 7.8 to 11.10 mg kg^{-1} by zinc levels showed a 42.31% significant improvement over the control. A consistent significant improvement in mean values of zinc content was observed with increasing levels of sulphur ranged from 8.85 to 10.05 mg kg^{-1} and exhibited 13.56% increase over control. The interaction between sulphur and zinc enhanced zinc accumulation with the highest content (11.7 mg kg^{-1}) with treatment Zn_9S_{45}. This is due to the fact that sulphur enhanced Zn solubility through the formation of sulphuric acid and facilitated more uptake of zinc. These findings corroborate the reports that balanced Zn-S fertilization enhances zinc bioavailability, nutrient uptake and mineral enrichment of cereal residues and forage crops, thereby improving their nutritional value for ruminant feeding (Dhaliwal *et al*., 2023).

Sulphur content in paddy straw increased progressively with increasing sulphur application, indicating a clear dose-dependent response. Mean sulphur content increased from 0.093 to 0.103 mg kg^{-1} and demonstrated a consistent increasing trend. However, highest dose of sulphur only showed a significant increase over 15 kg S ha^{-1}. Application of Zn @ 6 and 9 kg ha^{-1} individually caused 8.89% and 14.44% significant more sulphur in straw than control, respectively indicated that zinc nutrition facilitates sulphur uptake and retention in plant tissues. The combined application of 45 kg S ha^{-1} and 9 kg Zn ha^{-1} showed the highest sulphur content, representing a 22.20% increase over the control. Both elements are required for optimal protein synthesis, creating a positive feedback loop where each nutrient enhances the utilization of the other (Singh *et al.,* 2018). This interaction transforms the nutritional quality of straw beyond what either nutrients could achieve independently.

Sulphur and zinc interacted significantly in influencing the content of calcium in paddy straw (Table 2). Calcium content increased significantly with increasing sulphur levels from 2.33 to 3.50 g kg^{-1}. In contrast, zinc application significantly decreased calcium content which declined from 3.50 to 2.39 g kg^{-1} showed a reduction of 31.7%. Effect of zinc fundamentally depends on sulphur status as evidenced by the significant interaction between them. The antagonistic effect of zinc became pronounced and systematic only at adequate sulphur levels. This interaction was particularly evident under 45 kg S ha^{-1} where increasing zinc application from Zn_0 to Zn_9 suppressed calcium content from 3.98 to 2.82 g kg^{-1} being a decrease of 29.15%. This pattern reveals that sulphur sufficiency establishes a physiological context in which zinc strongly inhibits calcium accumulation in plant tissues. The enhancement of calcium content by sulphur is nutritionally advantageous. Sulphur improves root proliferation and enhances the soil exploration and cation exchange capacity, facilitate greater uptake and accumulation of calcium in plant tissues. Conversely, the depressive effect of zinc showed a significant nutrient antagonism under high sulphur levels. This might be due to the competition of divalent cations Zn^{2+} and Ca^{2+} for shared transport proteins and membrane binding sites on root epidermal cells (Broadley *et al*., 2012).

Table 2: Influence of S and Zn on content of Zn, S and Ca in cattle feed of paddy straw

			Zn content (mg kg^{-1})		
	S_0	S_{15}	S_{30}	S_{45}	Mean
Zn_0	7.2	7.6	8.0	8.4	7.8
Zn_3	8.3	8.7	9.1	9.5	8.9
Zn_6	9.4	9.8	10.2	10.6	10.0
Zn_9	10.5	10.9	11.3	11.7	11.10
Mean	8.85	9.25	9.65	10.05	--
	Zinc	Sulphur	Zn x S		
CD(P≤ 0.05)	0.52	0.52	NS		
			Sulphur content (mg kg^{-1})		
	S_0	S_{15}	S_{30}	S_{45}	Mean
Zn_0	0.090	0.080	0.100	0.090	0.090
Zn_3	0.090	0.090	0.100	0.100	0.095
Zn_6	0.090	0.090	0.100	0.110	0.098
Zn_9	0.100	0.110	0.090	0.110	0.103
Mean	0.093	0.093	0.098	0.103	--
	Zinc	Sulphur	Zn x S		
CD(P≤ 0.05)	0.006	0.006	0.012		
			Calcium content (g kg^{-1})		
	S_0	S_{15}	S_{30}	S_{45}	Mean
Zn_0	2.72	3.48	3.80	3.98	3.50
Zn_3	2.40	3.30	3.48	3.67	3.21
Zn_6	2.13	2.75	3.19	3.56	2.91
Zn_9	2.06	2.25	2.42	2.82	2.39
Mean	2.33	2.95	3.22	3.50	--
	Zinc	Sulphur	Zn x S		
CD(P≤ 0.05)	0.05	0.05	0.11		

Total carbohydrate, reducing sugar and crude protein in paddy straw: Total carbohydrate, reducing sugar and crude protein content in rice straw were significantly improved with increasing levels of sulphur and zinc (Table 3). Maximum total carbohydrate 54.0%, reducing sugar 8.53 g kg^{-1} and crude protein content 3.14% was observed with Zn_9 which showed an increment of 10.20%, 16.05% and 19.61% over their respective control, respectively. Application of sulphur @ 45 kg ha^{-1} showed 54.5% total carbohydrate, 8.85 g kg^{-1} reducing sugar and 3.22% crude protein content which were 12.37%, 21.23% and 25.78% more than their corresponding control, receptively. Adequate supply of sulphur and zinc might improve photosynthetic efficiency, nitrogen metabolism and assimilate translocation which play vital roles in the synthesis of proteins and other biomolecules, thereby improving straw quality (Baral *et al.,* 2023). Application of adequate quantity of sulphur greatly contributed in biosynthesis of these biomolecules than application of zinc.

Table 3: Main effect of sulphur and zinc on crude protein, total carbohydrate and reducing sugar in cattle feed of paddy straw

Nutrient	Crude protein (%)	Total carbohydrate (%)	Reducing sugar (g kg^{-1})
Zn_0	2.63	49.0	7.35
Zn_3	2.81	51.5	7.98
Zn_6	3.00	52.5	8.20
Zn_9	3.14	54.0	8.53
CD (P≤ 0.05)	0.03	1.3	0.22
S_0	2.56	48.5	7.30
S_{15}	2.83	51.0	7.68
S_{30}	3.02	53.0	8.23
S_{45}	3.22	54.5	8.85
CD (P≤ 0.05)	0.03	1.3	0.22

Non-significant interaction between sulphur and zinc indicated that their effect on carbohydrate and reducing sugar accumulation were primarily additive rather than synergistic (Figure 1 and 2). However, their judicious use significantly influenced crude protein content in rice straw (Figure 3), which may enhance rumen microbial activity and feed digestibility (Drewnoski *et al.,* 2014). Maximum content of these biomolecules recorded under the combined application of Zn_9S_{45} showed synergism between the nutrients. Across all sulphur levels, zinc application progressively increased total carbohydrate from 46.0 to 57.0%, reducing sugar from 6.90 to 9.60 g kg^{-1} and crude protein from 2.25 to 3.44%, indicating that balanced sulphur and zinc fertilization substantially improves the biochemical quality and feeding value of rice straw.

Figure 1: Effect of sulphur and zinc on total carbohydrate (%) on cattle feed of paddy straw

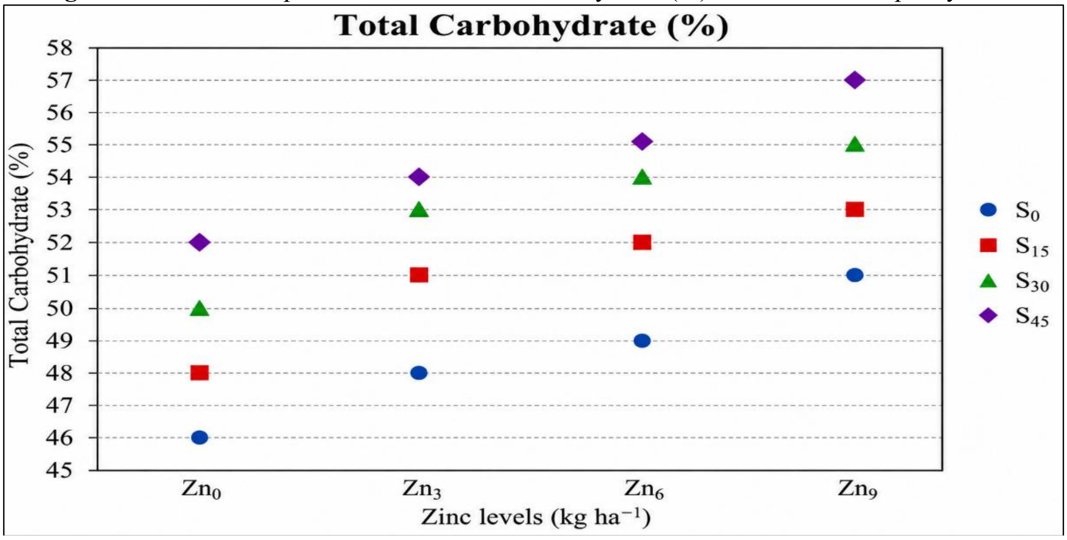


Figure 2: Effect of sulphur and zinc on reducing sugar (g kg^{-1}) in cattle feed of paddy straw

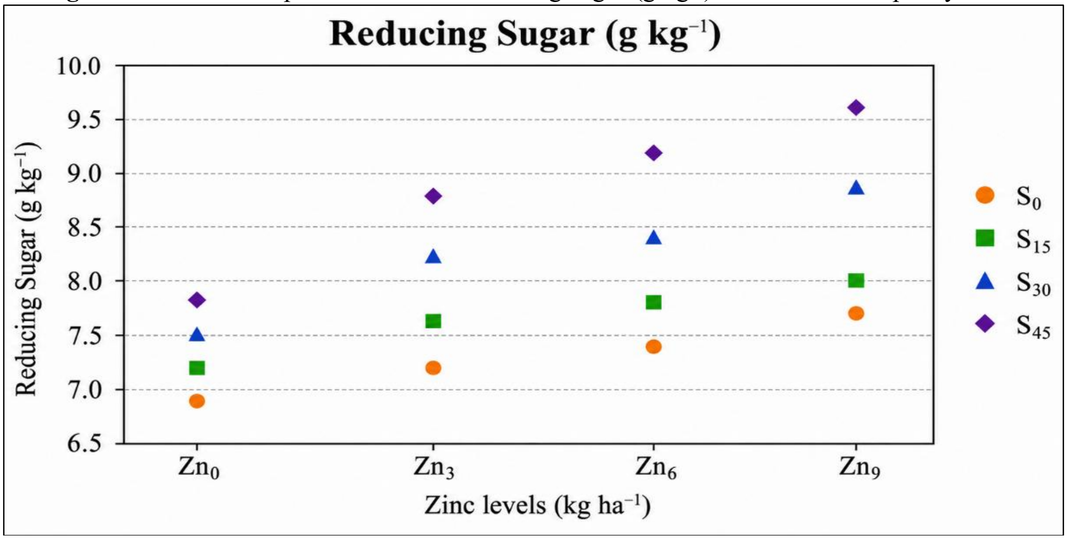
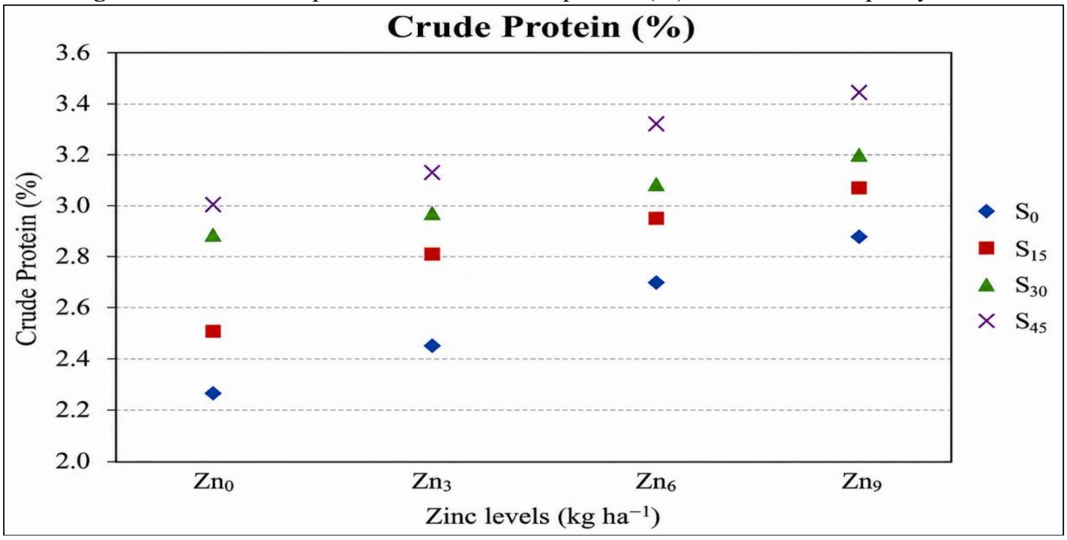
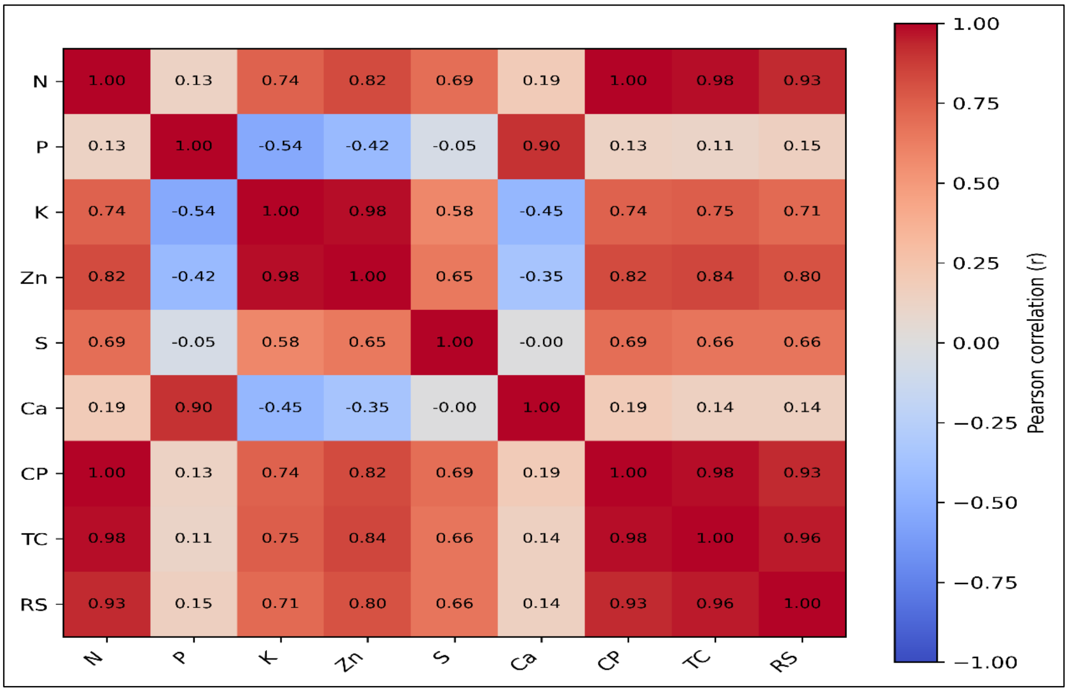


Figure 3: Effect of sulphur and zinc on crude protein (%) in cattle feed of paddy straw



Correlation among the variables: The correlation analyses (Figure 4) revealed strong positive associations among mineral nutrients and biochemical parameters. Nitrogen showed strong positive correlations with potassium (r = 0.738), zinc (r = 0.825), sulphur (r = 0.698), crude protein (r = 1.000), sugar (r = 0.928) and total carbohydrate (r = 0.977) reflecting its pivotal role in photosynthesis, amino acid synthesis and carbohydrate metabolism. Potassium was highly correlated with zinc (r = 0.983), sulphur (r = 0.584), crude protein (r = 0.738), reducing sugar (r = 0.709) and total carbohydrate (r = 0.753), suggesting coordinated nutrient uptake and enzyme-mediated metabolic activity amongst the parameters. Likewise, zinc and sulphur showed positive associations with biomolecules, demonstrating their synergistic role in protein synthesis and assimilate accumulation. Weak correlations of calcium with biochemical traits, indicating a limited contribution under the present conditions. These findings are in agreement with Sangnak *et al.,* (2025) and Reddy *et al.,* (2026) who reported that balanced sulphur and zinc nutrition enhances nutrient assimilation, nitrogen use efficiency and nutritional quality of rice straw.

Figure 4: Correlation coefficient among various rice straw parameters



	N	P	K	Zn	S	Ca	CP	TC	RS
N	1.00	0.13	0.74	0.82	0.69	0.19	1.00	0.98	0.93
P	0.13	1.00	-0.54	-0.42	-0.05	0.90	0.13	0.11	0.15
K	0.74	-0.54	1.00	0.98	0.58	-0.45	0.74	0.75	0.71
Zn	0.82	-0.42	0.98	1.00	0.65	-0.35	0.82	0.84	0.80
S	0.69	-0.05	0.58	0.65	1.00	-0.00	0.69	0.66	0.66
Ca	0.19	0.90	-0.45	-0.35	-0.00	1.00	0.19	0.14	0.14
CP	1.00	0.13	0.74	0.82	0.69	0.19	1.00	0.98	0.93
TC	0.98	0.11	0.75	0.84	0.66	0.14	0.98	1.00	0.96
RS	0.93	0.15	0.71	0.80	0.66	0.14	0.93	0.96	1.00

IV. Conclusion

From the findings of the study, it can be concluded that through soil application of sulphur and zinc nutritional values of nitrogen, potassium, sulphur, zinc, total carbohydrate, reducing sugar and crude protein content in rice straw can be improved. Combined use of sulphur @ 45 kg ha^{-1} and zinc @ 9 kg ha^{-1} exhibited highest quantity of most of the nutrients under study. However, zinc either alone or in combination with sulphur significantly lowered the phosphorus and calcium content in rice straw. The significant interaction confirms that by adopting their integrated fertilization practice, farmers can produce a nutritionally rich straw for normal health and productivity of livestock. Moreover, promoting the utilization of nutrient-enriched rice straw as animal feed may reduce residue burning and its associated environmental pollution.

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Conflict of Interest

The authors declare that they do not have any competing interest.

References

[1]. AOAC. (1990). *Official Methods of Analysis* (15th edition). Association of Official Analytical Chemists, Arlington, Virginia, USA.

[2]. Baral, K. B., Shivay, Y. S., Prasanna, R., Kumar, D., Srinivasarao, C., Mandi, S., Nayak, S., & Reddy, K. S. (2023). Enhancing physiological metrics, yield, zinc bioavailability and economic viability of Basmati rice through nano zinc fertilization and summer green manuring in semi-arid South Asian ecosystem. *Frontiers in Plant Science,* **14**, 1283588. https://doi.org/10.3389/fpls.2023.1283588

[3]. Broadley, M. R., Brown, P. H., Cakmak, I., Rengel, Z., & Zhao, F. J. (2012). Function of nutrients: Micronutrients. In P. Marschner (Ed.), *Marschner's Mineral Nutrition of Higher Plants* (3rd edition). Academic Press. Page 191-248. https://doi.org/10.1016/B978-0-12-384905-2.00007-8

[4]. Chopra, S. L., & Kanwar, J. S. (1976). *Analytical Agricultural Chemistry*. Kalyani Publishers, New Delhi, India.

[5]. Dhaliwal, S. S., Sharma, V., Shukla, A. K., Shivay, Y. S., Hossain, A., Verma, V., Gill, M. K., Singh, J., Bhatti, S. S., Verma, G., Singh, J., & Singh, P. (2023). Agronomic biofortification of forage crops with zinc and copper for enhancing nutritive potential: A systematic review. *Journal of the Science of Food and Agriculture,* **103**(4), 1631-1643. https://doi.org/10.1002/jsfa.12353

[6]. Drewnoski, M. E., Pogge, D. J., & Hansen, S. L. (2014). High-sulfur in beef cattle diets: A review. *Journal of Animal Science,* **92**(9), 3763-3780. https://doi.org/10.2527/jas.2013-7242

[7]. Gomez, K. A., & Gomez, A. A. (1984). *Statistical Procedures for Agricultural Research* (2nd ed.). John Wiley & Sons, New York, USA.

[8]. Kumar, A., Nayak, A. K., Sharma, S., Senapati, A., Mitra, D., Mohanty, B., Prabhukarthikeyan, S. R., Sabarinathan, K. G., Mani, I., Garhwal, R. S., Thankappan, S., Sagarika, M. S., de los Santos-Villalobos, S., & Panneerselvam, P. (2023). Rice straw recycling: A sustainable approach for ensuring environmental quality and economic security. *Pedosphere,* **33**(1), 34-48. https://doi.org/10.1016/j.pedsph.2022.06.036

[9]. Lindsay, W. L., & Norvell, W. A. (1978). Development of a DTPA soil test for zinc, iron, manganese and copper. *Soil Science Society of America Journal,* **42**(3), 421-428. https://doi.org/10.2136/sssaj1978.03615995004200030009x

[10]. Malik, K., Sharma, A., Harikarthik, D., Rani, V., Arya, N., Malik, A., Rani, S., Sangwan, P., & Bhatia, T. (2023). Deciphering the biochemical and functional characterization of rice straw cultivars for industrial applications. *Heliyon,* **9**(6), e16339. https://doi.org/10.1016/j.heliyon.2023.e16339

[11]. Miller, G. L. (1959). Use of dinitrosalicylic acid reagent for determination of reducing sugar. *Analytical Chemistry,* **31**(3), 426-428. https://doi.org/10.1021/ac60147a030

[12]. Nadeem, S. M., Hanif, A., Khan,M. Y., Waqas, M. R., Ahmad, Z., Ashraf, M. R., & Naveed, M. (2023). Elemental sulphur with sulphur oxidizing bacteria enhances phosphorus availability and improves growth and yield of wheat in calcareous soil. *Archives of Agronomy and Soil Science,* **69**(9), 1494-1502. https://doi.org/10.1080/03650340.2022.2099541

[13]. Nandjui, J., Chiripasi, S. C., Hamudikuwanda, H., & Mutisi, C. (2021). Nutritional assessment of three baled rice straw varieties intended for use as ruminant feed in Namibia. *Cogent Food & Agriculture,* **7**(1), 1950402. https://doi.org/10.1080/23311932.2021.1950402

[14]. Narayana, O. P., Kumar, P., Yadav, B., Dua, M., & Johri, A. K. (2023). Sulphur nutrition and its role in plant growth and development. *Plant Signaling & Behavior,* **18**(1), 2030082. https://doi.org/10.1080/15592324.2022.2030082

[15]. Pearson, K. (1895). Notes on regression and inheritance in the case of two parents. *Proceedings of the Royal Society of London,* **58**, 240–242. https://doi.org/10.1098/rspl.1895.0041

[16]. Reddy, K. S., Shivay, Y. S., Prasanna, R., Nayak, S., Baral, K. B., Mandi, S., Kokila, V., Alekhya, G., Reddy, K. S., & Borate, R. B. (2026). Augmenting nitrogen and zinc fertilization to enhance productivity, nutrient uptake and nutrient use efficiency in rice. *Frontiers in Sustainable Food Systems,* **10**, 1793826. https://doi.org/10.3389/fsufs.2026.1793826

[17]. Roy, A. K., Agrawal, R. K., Bhardwaj, N. R., & Mishra, A. K. (2019). *Revisiting National Forage Demand and Availability Scenario in India*. ICAR-Indian Grassland and Fodder Research Institute, Jhansi, Uttar Pradesh, India.

[18]. Sangnak, S., Veeradittakit, J., & Prom-u-thai, C. (2025). Comparative impacts of nitrogen, sulfur and zinc fertilization on grain yield, protein content, antioxidant capacity and its loss during polishing process among rice varieties. *Frontiers in Agronomy,* **7**, Article 1725441. https://doi.org/10.3389/fagro.2025.1725441

[19]. Singh, M. V., Takkar, P. N., & Shukla, A. K. (2018). Effect of sulphur and zinc nutrition on yield, nutrient uptake and quality of rice. *Journal of the Indian Society of Soil Science,* **66**(2), 204-210.

[20]. Tandon, H. L. S. (1991). *Sulphur Research and Agricultural Production in India* (3rd rev. & enl. ed.). Fertiliser Development and Consultation Organisation (FDCO), New Delhi, India.

[21]. Wallinga, I., Vanmark, W., Houba, V. J. G., Vender Lee, J. J. 1989. Soil and Plant Analysis Procedures, Part 7, Published by Department of Soil Science and Plant Nutrition, Wageningen Agriculture University. The Netherlands.

[22]. Weinmann, H. (1947). Determination of total available carbohydrates in plants. *Plant Physiology,* **22**(3), 279-290. https://doi.org/10.1104/pp.22.3.279