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Conservation Crop Establishment and Foliar Sulphur Nutrition Improve Growth, Photosynthetic Efficiency and Productivity of Rainfed Pearl Millet

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Abstract: The study was undertaken to evaluate the effect of foliar sulphur (S) nutrition through ammonium thiosulphate (ATS) under conservation management on the growth, photosynthetic efficiency and productivity of rainfed pearl millet in dryland and rainfed conditions of New Delhi in 2021 and 2022 crop years. Pearl millet established under conservation management ($ZTCR^{ret}$) achieved significantly higher crop growth rate (CGR) and relative growth rate (RGR) as a result of improved photosynthesis efficiency in terms of net assimilation rate (NAR) and a higher rate of productive tiller production (RPTP). The productivity of rainfed pearl millet under $ZTCR^{ret}$ was improved by 26.6 and 13.5 % during 2021, and by 27.6 and 12.7% over zero tillage ($ZTCR^{rem}$) and conventional tillage (ConTil), respectively. The application of a recommended dose of S at 30 kg ha^{-1} resulted in a dramatic improvement in growth indices and photosynthetic efficiency over control and ATS doses up to 0.5%-twice. Foliar application of ATS at 0.5%-once and successively higher doses were found to improve the growth and productivity of pearl millet over S control, however, the dose of ATS at 1.0%-twice could only achieve statistically similar levels of CGR and RGR to the recommended dose of sulphur (RDS) that led to the higher rate of productive tiller production (RPTP) with higher photosynthetic efficiency but in non-significant yield difference. Therefore, the pearl millet established under zero tilled and crop residue retained plots supplemented with foliar feeding of ATS at 1.0% at 20 DAS (4-6 leaves stage) and 50 DAS (flowering stage) can be practiced under rainfed ecologies with a grain and stover yield increase of 19.5% and 13.2%, respectively over the no S application.

Keywords: Pearl millet, growth, photosynthetic efficiency, rainfed, yield.

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Photosynthetic efficiency (PE) is a primary determinant of crop productivity (Simkin *et al.*, 2019). However, the PE of the major crops in many parts of the world has plateaued so has the year-on-year yield (Brestic *et al.*, 2021). The scope to improve the PE of crops, particularly in dryland and rainfed ecologies through major technological interventions (Yan *et al.*, 2021) is narrow owing to limitations set in by harsh environmental factors such as scarce moisture availability and poor fertility status of the soil along with the socio-economic status of the region. Owing to sub-optimal photosynthetic efficiency in changing climate scenarios, the productivity of the major field crops of India is stagnant over the years (Wang *et al.*, 2018), however, millets could be alternative climate-smart crops as their adaptation to challenging environments is better than the current major crops (O'leary *et al.*,2008; Tiwari *et al.*, 2019). Pearl millet (*Pennisetum glaucum* L.) being the staple food of rainfed area dwellers, is the king crop of the arid and semi-arid regions with 90% coverage of area under millets and occupies about 6.93 mha area of gross cropped area with a production of 9.62 mt and productivity of 1388.2 kg ha^{-1} in the financial year 2021-2022 (Anonymous, 2022). Drought hardiness coupled with low care and management makes the pearl millet a climate-resilient crop. The millet can help the world face the challenges of climate change along with increasing costs of inputs. Realizing the potential of this crop to confront the prevailing challenges of climate change and food and nutritional security and to create awareness about its significance in sustainable agriculture, the Food and Agriculture Organization (FAO) and United Nations General Assembly (UNGA) approved India's proposal to observe 2023 as an International Year of Millets (NCKC, 2022).

The productivity of pearl millet in dryland and rainfed regions is very low because of the scarcity of moisture at critical growth stages and nutrient deficiency. Apart from the deficiency of major nutrients, most of the arid and semi-arid soils are deficient in S with an available S status below 9 mg kg^{-1} soil (Ankit *et al.,* 2021). Pearl millet is reported to be S-responsive crop, hence application may enhance the yield potential (Parihar *et al.,* 1998). The S deficiency not only causes poor productivity of pearl millet owing to its synergistic interaction with nitrogen utilization, the quality of grains in terms of protein content is also affected adversely because it is an essential element for the biosynthesis of cysteine, cystine and methionine amino acids, the building blocks of protein. Keeping in view the upcoming huge requirement of millet, the present study is undertaken to improve the growth, photosynthetic efficiency and productivity of rainfed pearl millet in a sustainable manner.

Materials and methods

A field experiment was undertaken in *Typic Haplustept* sandy loam soil at the research farm of the Division of Agronomy, Indian Agricultural Research Institute, New Delhi for two consecutive seasons of *Kharif* during the years 2021 and 2022. The experimental field lies in the central region of the state within a geographical tract of 28°40′N latitudes and 77°12′ longitudes at an altitude of 228 m above MSL. The field received higher rainfall (195.4 mm) that was evenly distributed over the growing season (July to mid of October 2021) with 45 rainy days during the first year while a scanty rainfall averaging 86.8 mm confined in 33 days was experienced during the second year. A combined analysis of composite samples taken from three permanent strips indicated that the experimental field was low in available N (174.2 kg ha^{-1}) and medium with respect to available P (17.9 kg ha^{-1}) and available K (195.6 kg ha^{-1}) with a soil pH in alkaline range (7.0-7.5). In general, zero tillage with crop residue mulching $ZTCR^{ret}$ (8.66 mg kg^{-1}), zero tillage without mulching $ZTCR^{rem}$ (7.99 mg kg^{-1}) and conventional tillage CT-noR (7.85 mg kg^{-1}) were found below the critical level of 0.15% $CaCl_2$-extractable S (Chesnin and Yien, 1950). Hence, the response of pearl millet to S nutrition strategies is expected in the present experiment.

The experiment comprised of 3 dedicated permanent plots ($ZTCR^{ret}$, $ZTCR^{rem}$ and ConTil as crop establishment methods on which 6 levels of S nutrition strategies *viz.* S control (S_0), soil application of elemental S at 30 kg ha^{-1} (S_{30}) at the time of sowing, one foliar application of ammonium thiosulphate (ATS) at 0.5% (ATS 0.5%-once) and 1.0% (ATS 1.0%-once) at 4-6 leaves stage and two foliar sprays of ATS at 0.5% (ATS 0.5%-twice) and 1.0% (ATS 1.0%-twice), respectively 20 DAS (at 4-6 leaves stage) and 50 DAS (flowering stage) were superimposed.

Since the main plot strips were found low in available nitrogen (N) and phosphorus (P) status and medium in potassium (K), hence, the recommended dose of N, P and K that is 60:40:40 was applied through urea (46% N),

Table 1. Nitrogen schedule followed in pearl millet

S nutrition strategies	N dose deduction at 14.0% (kg ha^{-1})	Basal (Urea + DAP kg ha^{-1})	Top dressing (Urea kg ha^{-1})
S control	0.0	14.35 + 15.65	30
RDS (S_{30})	0.0		
ATS 0.5%-once	0.35		29.65
ATS 1.0%-once	0.70		29.30
ATS 0.5%-twice	0.70		29.30
ATS 1.0%-twice	1.4		28.60

diammonium phosphate (18% N and 46% P_2O_5) and muriate of potash (60% K_2O). The entire quantity of phosphatic and potassic fertilizers and half-split dose of nitrogen (15.65 kg was supplied by DAP and the remaining by urea) was applied as a basal application while the remaining half (30 kg N) was top-dressed at the pre-flowering stage (45 DAS). To ensure the exclusive effect of S foliar feeding, the amount of N that was supplied through ATS (14.0% N) in foliar-treated plots was deducted from the dose of N to be supplied through urea at the time of top dressing (Table 1):

The seeds of a short-duration composite variety of pearl millet namely 'Pusa Composite 443' was shown at 4 kg ha^{-1} during the second week of July with a seed drill that dropped seeds 45 cm apart. The thinning was practiced to maintain the plant rectangularity by adjusting the plant-to-plant spacing of 15 cm at the time of intercultural operations at 10 DAS. The previous season's mixed residues containing leftover of chickpea, cluster bean and fodder pearl millet were applied in $ZTCR^{ret}$ at 3 t ha^{-1} just after the sowing in a way to cover 30% of the surface area by a 5 cm thick residue layer over the soil for effective moisture conservation.

An index of plant development has been calculated by dividing the number of productive tillers, the tillers bearing robust ear, per meter row by the total number of tillers per meter row at 60 days stage of crop growth (adaptation of the formula devised by Kondic *et al.*, 2016).

$$\text{RPTP} = \frac{\text{Number of productive tillers per m row}}{\text{Total number of tillers per m row}}$$

The growth in terms of mean crop growth rate and relative growth rate (RGR) were calculated for 30-60 DAS and 60 DAS-harvest during both seasons using the following formulae and expressed as mg $g^{-1}day^{-1}$ (Watson *et al.*, 1952).

$$\text{CGR (g m}^{-2}\text{ day}^{-1}) = \frac{1}{p} \times \frac{W_2 - W_1}{T_2 - T_1}$$

where p is plant spacing of 45 cm between rows and 15 cm among the plants.

$$\text{RGR (mg g}^{-1}\text{ day}^{-1}) = \frac{\log W_2 - \log W_1}{T_2 - T_1}$$

where, W_1 and W_2 are the dry weights of plant (gram) of plants at time T_1 and T_2, respectively and p denotes the ground area occupied by the individual plant (45 × 15 cm).

The photosynthetic efficiency of pearl millet leaves in terms of net gain of assimilate per unit leaf area per unit time, that is, mean NAR value was estimated for vegetative phase to flowering phase (30-60 DAS) by the expression suggested by Watson, (1958):

$$\text{NAR (g m}^{-2}\text{ day}^{-1}) = \frac{(W_2 - W_1)(\ln LA_2 - \ln LA_1)}{(T_2 - T_1)(LA_2 - LA_1)}$$

where, W_1 and W_2 are the dry weights (g $plant^{-1}$) and LA_1 and LA_2 are leaf area (m^2) per plant at time T_1 (days) and T_2 (days), respectively. *Ln* denotes natural logarithm.

The plants from the net plot excluding 50 cm borders from each side were harvested from the ground level and were left for sun drying *in- situ*. The ear heads were separated from the pearl millet plant and threshed with a Pullman thresher. Grains were cleaned and weighed for expressing yield in t ha^{-1}. The weight of the stover was recorded separately and used for estimating the stover yield. The harvest index was worked out by the expression suggested by Donald and Hamblin (1976):

$$\text{HI (\%)} = \frac{\text{Economic yield (t ha}^{-1})}{\text{Biological yield (t ha}^{-1})} \times 100$$

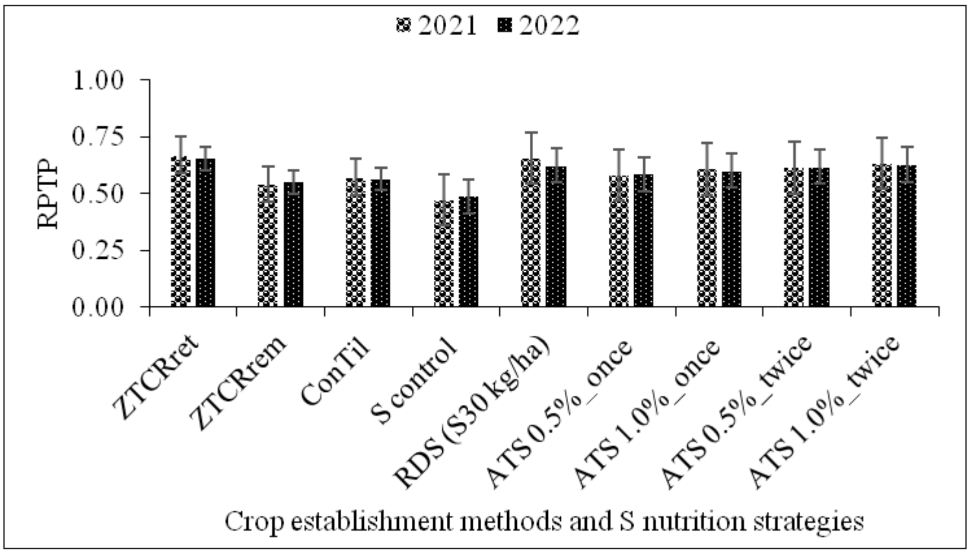

Fig. 1. Rate of productive tiller production at 60 DAS. Vertical bars showing LSD values (p= 0.05).

where grain yield (t ha^{-1}) was considered as economic yield and biological yield (t ha^{-1}) was computed by summation of grain and stover yield across the main and sub-plot treatments.

The statistical analysis of the experimental data was carried out in a split-plot design with 3 replications by two-way Analysis of Variance (ANOVA) at $p<0.05$ using the standard procedures (Gomez and Gomez, 1984) to draw valid inferences.

Results and Discussion

Rate of productive tiller production

The rate of productive tiller production (RPTP) was maximum under $ZTCR^{ret}$ (0.67) which was significantly higher over the rest during both the years of experimentation (Fig. 1). An increase of 23.7% and 17.2% in RPTP under conservation crop establishment system was observed over $ZTCR^{rem}$ (0.54) and ConTil (0.57), respectively. The mulching and least disturbance of soil might have conserved the soil moisture efficiently ensuring a continuous and adequate supply of moisture (Choudhary *et al.*, 2016) that sustained the cell turgidity which eventually maintained a high meristematic activity leading to more foliage development, greater photosynthetic activity (Amgain and Sharma, 2021) and consequently improved RPTP.

Growth indices and photosynthetic efficiency

The effect of the crop establishment method on mean crop growth rate (CGR) of pearl millet influenced significantly as the plants attained reproductive growth during 30-60 DAS (Table 2). The establishment of pearl millet crop under $ZTCR^{ret}$ practice led to 11% increase in mean CGR during the panicle initiation to ear head blooming phase, over the NoTill and remained significantly higher. NoTill and ConTil practices with respect to CGR remained at par with each other during the year 2021, however, the latter registered significantly higher mean CGR over the former during 2022. The mean relative growth rate (RGR) of pearl millet during both the years and net assimilation rate (NAR) during the first year of study were not affected significantly due to crop establishment methods. However, the photosynthetic efficiency (NAR) was found to increase by up to 4.5% over $ZTCR^{rem}$ practice. Though the NAR under $ZTCR^{ret}$ over ConTil was not improved considerably during the first year, however, an increase of 3.5% in photosynthetic efficiency was recorded during the drought year (2022). The nonsignificant growth rates during the first year might be due to abundant rainfall during the first year whereas the second year was a drought year in which conservation of soil moisture under $ZTCR^{ret}$ practices resulted in sustained growth rates.

The response of foliar S application on mean CGR of pearl millet was observed even with single spray of ATS at 0.5% as this practice registered significantly higher values over S control during 2021 and 2022. Furthermore, with a nonsignificant increase in mean CGR,

Table 2. Effect of crop establishment methods and S nutrition strategies on mean growth indices and photosynthetic efficiency of pearl millet at 30-60 DAS

Treatment	Mean CGR (g $m^{-2}day^{-1}$)		Mean RGR (mg $g^{-1}day^{-1}$)		Mean NAR mg $cm^{-2}day^{-1}$	
	2021	2022	2021	2022	2021	2022
Crop establishment systems						
$ZTCR^{ret}$	25.17	26.52	57.07	55.07	7.84	7.67
$ZTCR^{rem}$	22.62	23.89	55.05	52.71	7.51	7.34
ConTil	23.56	25.62	55.81	54.20	7.82	7.41
SEm±	0.37	0.29	0.56	0.61	0.10	0.06
LSD (p=0.05)	1.49	1.16	NS	NS	NS	0.25
S nutrition strategies						
S control	19.18	21.47	53.76	51.60	7.16	6.48
RDS (S_{30})	27.71	28.70	58.29	56.37	8.28	8.37
ATS 0.5%-once	21.09	23.29	54.00	52.47	7.54	6.91
ATS 1.0%-once	23.63	25.21	54.45	53.53	7.53	7.35
ATS 0.5%-twice	24.62	25.64	58.16	54.32	7.69	7.70
ATS 1.0%-twice	26.48	27.75	57.17	55.66	8.11	8.04
SEm±	0.58	0.40	0.97	0.69	0.16	0.22
LSD (p=0.05)	1.69	1.17	2.80	2.02	0.47	0.65

the foliar feeding practice of spraying ATS 0.5%-twice remained at par to ATS 1.0% once during both the years of investigation. However, the foliar feeding practice of ATS 1.0%-twice with 38% and 27.3% higher mean CGR values over S control during 2021 and 2022, respectively remained at par with RDS.

Likewise, RDS recorded significantly higher mean RGR over control and the practice of spraying ATS 0.5% once and ATS 1.0% once during reproductive phase. However, the foliar feeding of ATS 0.5%-twice and ATS 1.0%-twice registered a mean RGR at par with RDS during 2021 and 2022.

Similarly, S nutrition strategies brought out increase in photosynthetic efficiency of pearl millet that followed a similar pattern to RGR. RDS maintained a higher photosynthetic rate hence, resulted in the highest NAR which remained significantly higher over control and ATS doses upto 5 ml l^{-1} twice. Only ATS 1.0%-twice could achieve a statistically similar level of NAR to RDS. It is well documented that S deficiency can cause stunted growth with short stem height due to its highly efficient role in photosynthesis (Aarabi *et al.*, 2021).

Yields and harvest index

$ZTCR^{ret}$ resulted in a significantly higher grain and stover yield compared to $ZTCR^{rem}$, and similar observations were recorded for the harvest index (Table 3). Although the practice of $ZTCR^{ret}$ and ConTil produced statistically similar stover yields, the grain yield of the former was found to be significantly higher than that of the latter. Moreover, with a dip of approximately 7.1% in 2022, the drought year, the loss in biological yield under ConvTil (8.08 t ha^{-1}) were higher as compared to $ZTCR^{ret}$ (8.65 t ha^{-1}) Likewise, the HI was found highest under $ZTCR^{ret}$ which remained significantly higher than the rest methods of crop establishment across the years.

RDS enhanced the grain and stover yields by 22.0% and 14.1%, respectively, over the control. The grain and stover yields in foliar-applied ATS 1.0%-twice were statistically on par with those of RDS, with a yield increase of 19.5% and 13.2%, respectively, which is comparable to the yield increase in RDS. The grain and stover yield levels under foliar-applied ATS 1.0%-once and 0.5%-twice were on par but significantly higher than those under control and ATS 0.5%-once. The HI under S nutrition strategies was found to vary significantly only during the first year of study due to significantly higher vegetative growth, which became non-significant in the second year due to proportionately less stover yield compared to the first year. The improved yield and HI of pearl millet might be due to the favourable effect of these practices on

Table 3. Effect of crop establishment systems and S nutrition strategies on yields and harvest index of pearl millet

Treatment	Grain yield (t ha^{-1})		Stover yield (t ha^{-1})		Biological yield (t ha^{-1})		Harvest index (%)	
	2021	2022	2021	2022	2021	2022	2021	2022
Crop establishment systems								
ZTCR^{ret}	2.43	2.22	7.72	6.44	10.1	8.65	23.9	25.6
ZTCR^{rem}	1.95	1.74	6.85	5.58	8.79	7.32	22.1	23.8
ConTil	2.14	1.97	7.49	6.11	9.63	8.08	22.1	24.4
SEm±	0.03	0.02	0.03	0.04	0.02	0.03	0.30	0.29
LSD (p=0.05)	0.13	0.08	0.12	0.15	0.11	0.10	1.22	1.19
S management strategies								
S control	1.73	1.67	6.53	5.35	8.26	7.02	20.9	23.8
RDS (S_{30})	2.44	2.19	7.85	6.45	10.3	8.64	23.7	25.3
ATS 0.5%-once	2.04	1.89	7.06	5.82	9.10	7.71	22.3	24.5
ATS 1.0%-once	2.17	1.98	7.44	6.12	9.61	8.10	22.6	24.4
ATS 0.5%-twice	2.26	2.02	7.49	6.16	9.75	8.18	23.2	24.7
ATS 1.0%-twice	2.38	2.11	7.74	6.33	10.11	8.43	23.5	24.9
SEm±	0.05	0.04	0.10	0.11	0.11	0.10	0.55	0.66
LSD (p=0.05)	0.15	0.14	0.30	0.32	0.31	0.29	1.59	NS

growth and photosynthetic efficiency through an adequate supply of moisture, leading to greater nutrient uptake, efficient partitioning of metabolites and adequate accumulation and translocation of photosynthates, resulting in improved yields and harvest index. The results are congruent with the work of Ankit *et al.*, (2021).

Conclusion

The demand for millets is predicted to increase in days to come owing to India led international push to include this nutrient dense food in the diets of human. However, the growth and photosynthetic efficiency of pearl millet in dryland rainfed areas need to improve through new technological interventions to keep the pace with the needs of the burgeoning population. The foliar application of ATS at 1.0%-twice under the aegis of conservation crop establishment system (ZTCR^{ret}) evidenced better growth in terms of rate of productive tillers production, CGR and RGR, photosynthetic efficiency in terms of NAR which culminated in improved yield of pearl millet over the ZTCR^{rem} and ConTil. Hence, the low volume foliar application of ATS at 1.0%-twice 20 days growth stage (4-6 leaves stage) and 50 days stage (flowering stage) in pearl millet established under zero tilled field with crop residue retention at 3 t ha^{-1} (ZTCR^{ret}) can be practiced as a promising alternative of existing conventional cultivation systems and RDS under rainfed ecologies for the sustainable production levels of this nutri-cereal.

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