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Nano-enabled sulphur nutrition: Impacts on nutrient uptake dynamics and post-harvest soil health in sunflower

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Abstract

A field experiment was conducted during rabi 2024-25 in College of Agriculture, Rajendranagar, PJTAU, Hyderabad, to evaluate the effect of foliar application of synthesized sulphur nanoparticles (SNPs) and conventional sulphur sources on nutrient uptake and post-harvest soil properties of sunflower. The experiment was laid out in a randomized block design with eleven treatments replicated thrice. Treatments included control (RDF), soil application of elemental sulphur, foliar application of ZnSO_4 and SNPs synthesized from pomegranate peel and mango leaf extracts at different concentrations, with and without surfactant (Tween 20) @ 0.5 ml L^{-1} . The results revealed that nutrient uptake (N, P, K and S) was significantly influenced by the treatments. The highest uptake of nitrogen (201.7 kg ha^{-1}), phosphorus (29.4 kg ha^{-1}), potassium (125.4 kg ha^{-1}) and sulphur (34.5 kg ha^{-1}) was recorded with foliar spray of SNPs derived from mango leaf extract @ 500 ppm with Tween 20 @ 0.5 ml L^{-1} , which was statistically at par with pomegranate-based SNPs at the same concentration with surfactant. The enhanced uptake under SNP treatments was attributed to improved foliar absorption, translocation efficiency and better metabolic utilization of nutrients. Post-harvest soil analysis indicated no significant changes in soil pH, electrical conductivity, organic carbon and available N, P, K and S across treatments, suggesting that foliar application of SNPs had minimal residual effect on soil properties. Thus, the study demonstrates that foliar application of green-synthesized sulphur nanoparticles at 500 ppm in combination with surfactant significantly enhances nutrient uptake in sunflower without adversely affecting soil health, highlighting its potential as an efficient and sustainable nutrient management strategy.

Keywords: Nutrient uptake, residual action, soil health, sulphur nanoparticles, sunflower

Introduction

Sunflower (*Helianthus annuus* L.) is one of the most important oilseed crops cultivated worldwide due to its high-quality edible oil, adaptability to diverse agro-climatic conditions and economic significance. In India, sunflower plays a crucial role in bridging the gap between edible oil demand and domestic production. However, its productivity is often constrained by imbalanced nutrient management, particularly deficiencies of secondary nutrients such as sulphur, which is increasingly recognized as a critical element for oilseed crops. Sulphur plays a vital role in plant growth and development as it is a structural component of essential amino acids such as cysteine and methionine, vitamins and coenzymes. It is also involved in chlorophyll formation, enzyme activation and oil synthesis, thereby directly influencing both yield and quality of oilseed crops (Scherer, 2001) [10]. In sunflower, adequate sulphur nutrition is closely associated with improved nutrient uptake, enhanced photosynthetic efficiency and increased oil content. Despite its importance, sulphur deficiency has become widespread in many agricultural soils due to intensive cropping, reduced use of sulphur-containing fertilizers and declining organic matter content.

Conventional methods of sulphur application, particularly soil application, often suffer from limitations such as low use efficiency, leaching losses and delayed availability due to the need for microbial oxidation (Tiwari and Gupta, 2006) [11]. In recent years, foliar fertilization has emerged as an efficient approach to supply nutrients directly to plants, bypassing soil-related

constraints and improving nutrient use efficiency (Fernández and Eichert, 2009) [5]. However, the efficiency of foliar-applied nutrients depends on factors such as leaf absorption, mobility and formulation characteristics. In this context, nanotechnology offers promising opportunities for enhancing nutrient delivery in crop production systems. Nano-fertilizers, particularly sulphur nanoparticles (SNPs), possess unique physicochemical properties such as high surface area, small particle size and greater reactivity, which can improve nutrient absorption, translocation and utilization efficiency (Dimkpa and Bindraban, 2018) [11]. Recent studies have shown that nano-sulphur can enhance plant growth, nutrient uptake and stress tolerance compared to conventional sulphur sources. Additionally, green synthesis of nanoparticles using plant extracts such as pomegranate peel and mango leaves provides an eco-friendly and sustainable approach for nanoparticle production.

Moreover, the use of surfactants in foliar application can further enhance nutrient uptake by improving spreadability, adhesion and penetration of spray solutions on leaf surfaces (Hong *et al.*, 2021) [13]. However, limited field-level information is available on the comparative effectiveness of green-synthesized SNPs from different botanical sources, their interaction with surfactants in foliar application and their influence on nutrient uptake and post-harvest soil properties in sunflower. Therefore, the present study was undertaken to evaluate the effect of foliar application of synthesized sulphur nanoparticles from different plant sources, with and without surfactant, on nutrient uptake (N, P, K and S) in sunflower, to compare their performance with conventional sulphur sources and to assess their residual impact on post-harvest.

Materials and Methods

The field study was carried out during *rabi*, 2024-25 in College farm, College of Agriculture, Rajendranagar of Professor Jayashankar Telangana Agricultural University, Hyderabad. The farm is geographically situated 17° 19' 20" N latitude and 78° 24' 37" E longitude and at an altitude of 542.6 m above mean sea level. The experimental site is located in the Southern Telangana Agro-climatic zone of Telangana. According to Troll's climate classification, it falls under semi-arid tropic region. Sunflower (*Helianthus annuus* L.) hybrid NDSH-1012 was used in the experiment. Initial soil analysis showed that soil is of sandy loam texture with neutral pH, low EC, low organic carbon, low available nitrogen and phosphorus and medium in available potassium and sulphur. The experiment was conducted using Randomised block design with eleven treatments replicated thrice. The treatment details included as follows, T₁: Control (RDF NPK), T₂: Soil application of Elemental S @ 45 kg ha⁻¹, T₃: Foliar spray of ZnSO₄ @ 0.5%, T₄: Foliar spray of SNPs from pomegranate fruit peel extract @ 500 ppm, T₅: Foliar spray of SNPs from mango tree leaf extract @ 500 ppm, T₆: Foliar spray of SNPs from pomegranate fruit peel extract @ 750 ppm, T₇: Foliar spray of SNPs from mango tree leaf extract @ 750 ppm, T₈: Foliar spray of SNPs from pomegranate fruit peel extract @ 500 ppm with tween 20 @ 0.5 ml l⁻¹, T₉: Foliar spray of SNPs from mango tree leaf extract @ 500 ppm with tween 20 @ 0.5 ml l⁻¹, T₁₀: Foliar spray of SNPs from pomegranate fruit peel extract @ 250 ppm with tween 20 @ 0.5 ml l⁻¹ and T₁₁: Foliar spray of SNPs from mango tree leaf extract @ 250 ppm with tween 20 @ 0.5 ml l⁻¹. The recommended dose of fertilizers (RDF) was applied at a rate of 75:90:30 kg ha⁻¹ of N, P₂O₅ and K₂O, respectively. Nitrogen, phosphorus, and potassium were supplied by urea, diammonium phosphate and muriate of potash. Synthesized SNPs were applied as foliar sprays using a power-

operated backpack sprayer twice during the crop growth period: first at the head initiation stage and again fifteen days later. The parameters on nutrient uptake of N, P, K and sulphur were recorded. Post harvest analysis of soil was carried out and recorded data on pH, EC, Organic carbon, available N, P₂O₅, K₂O and sulphur.

Results and Discussion

Nutrient uptake represents the combined outcome of nutrient concentration in plant tissues and overall biomass, making it a more comprehensive indicator of plant nutritional status. Uptake values reflect the plant's efficiency in absorbing, translocating and utilizing nutrients throughout the growing period, thereby linking physiological responses directly to agronomic performance. In sunflower, the uptake of NPK and S is closely associated with seed development, oil biosynthesis and structural growth. Evaluating nutrient uptake thus provides valuable insight into how different sulphur treatments, especially nano formulated foliar sprays affect whole plant nutrient assimilation and contribute to yield and quality improvements. The data presented in Table 1 revealed significant variations in nutrient uptake (N, P, K and S) of sunflower as influenced by foliar application of synthesized sulphur nanoparticles (SNPs) and conventional sulphur sources.

Nitrogen uptake: Nitrogen uptake exhibited strong differentiation among treatments, reflecting the combined influence of nutrient concentration and biomass. The nitrogen uptake ranged from 76.4 kg ha⁻¹ recorded in the control to the maximum uptake occurred under surfactant added SNPs derived from mango 201.7 kg ha⁻¹ (T₉), followed closely (194.9 kg ha⁻¹) by SNPs derived from pomegranate peel extract (T₈). The substantial increase in nitrogen uptake under surfactant-assisted SNP treatments clearly demonstrates enhanced foliar absorption and nutrient translocation efficiency. The improvement in nitrogen uptake can be attributed to the close physiological relationship between sulphur and nitrogen metabolism. Sulphur is essential for the synthesis of sulphur-containing amino acids such as cysteine and methionine, which are critical for protein synthesis and enzyme activity (Fazili *et al.*, 2008; ul Haq *et al.*, 2019) [4, 12]. Adequate sulphur supply enhances nitrate reductase activity and promotes efficient nitrogen assimilation. Furthermore, sulphur deficiency has been shown to restrict nitrogen uptake and utilization even when nitrogen is adequately supplied, indicating that nitrogen use efficiency is strongly dependent on sulphur availability (Hawkesford, 2014) [6].

Phosphorus uptake: Phosphorus uptake ranged from 14.9 kg ha⁻¹ to 29.4 kg ha⁻¹. Treatments which received the 500 ppm of SNPs aided by surfactant recorded the highest P uptake of 29.4 kg ha⁻¹ (T₉) and 28.5 kg ha⁻¹ (T₈). Conventional sulphur sources such as elemental sulphur (T₂: 20.8 kg ha⁻¹) and ZnSO₄ (T₃: 23.1 kg ha⁻¹) improved phosphorus uptake compared to control but remained inferior to SNPs treatments with surfactant. The enhanced phosphorus uptake under nano-sulphur treatments may be attributed to increased root activity and improved metabolic processes. Sulphur plays a key role in chlorophyll synthesis and photosynthesis, leading to increased carbohydrate production, which in turn enhances root growth and phosphorus acquisition (Scherer, 2001) [10]. Additionally, improved sulphur nutrition enhances ATP synthesis and energy transfer processes, which are essential for active uptake and translocation of phosphorus within the plant (Tiwari and Gupta, 2006) [11]. The synergistic interaction between sulphur and phosphorus has also been

reported to improve nutrient uptake efficiency through better physiological functioning (Pruthviraj, 2022) [9].

Potassium uptake: Potassium uptake ranging from 75.4 kg ha⁻¹ to 125.4 kg ha⁻¹. The highest K uptake (125.4 kg ha⁻¹) was recorded under mango derived SNPs application (T₉) followed by 120.1 kg ha⁻¹ (T₈) and the lower concentrated (250 ppm) SNPs + surfactant treatments recorded considerable uptake as 106.0 kg ha⁻¹ (T₁₁) and 106.2 kg ha⁻¹ (T₁₀), while SNPs without surfactant and conventional sulphur treatments showed comparatively moderate values. The increased potassium uptake under SNPs treatments can be attributed to enhanced plant growth and physiological efficiency. Potassium is involved in enzyme activation, osmotic regulation, stomatal movement and assimilate transport, all of which are closely linked with plant growth and biomass production (Marschner, 2012) [7]. Improved sulphur nutrition enhances overall metabolic activity and photosynthetic efficiency, thereby increasing the demand for potassium and its subsequent uptake (Fageria *et al.*, 2009) [3]. The combined effect of improved nutrient balance and increased biomass under SNPs treatments resulted in higher potassium accumulation.

Sulphur uptake: In the present investigation, sulphur uptake by sunflower showed considerable variability across treatments, strongly influenced by the form and application method of sulphur (Table 1). Sulphur uptake showed a marked increase

from 8.2 kg ha⁻¹ in control to 34.5 kg ha⁻¹ in T₉, followed by T₈ (32.7 kg ha⁻¹). The significantly higher uptake under SNPs + surfactant treatments indicates superior efficiency of nano-sulphur formulations over conventional sulphur sources. This enhanced uptake can be attributed to the small particle size, higher surface area and better adherence of nanoparticles to leaf surfaces, which facilitate improved absorption and translocation. The addition of surfactant (Tween 20 @ 0.5 ml L⁻¹) further enhances foliar uptake by reducing surface tension and improving spreadability on leaf surfaces. These results indicate superior nutrient use efficiency under nano sulphur + surfactant combinations, likely due to more efficient phloem loading, enhanced sulphur mobility and improved metabolic utilization within tissues (Fernandez and Eichert, 2009) [5].

Overall, the results clearly indicate that foliar application of SNPs at 500 ppm combined with Tween 20 @ 0.5 ml L⁻¹ significantly enhanced the uptake of N, P, K and S compared to control and conventional sulphur sources. Among the treatments, foliar spray of SNPs prepared from mango tree leaf extract @ 500 ppm + Tween 20 @ 0.5 ml L⁻¹ (T₉) consistently recorded the highest nutrient uptake, though it remained statistically at par with T₈. The superior performance of SNPs + surfactant treatments can be attributed to improved foliar absorption, enhanced metabolic activity and better nutrient use efficiency. These findings confirm that nano-enabled sulphur fertilization can serve as an effective strategy for improving nutrient uptake and productivity in sunflower.

Table 1: Influence of foliar spray of synthesized sulphur nanoparticles (SNPs) and conventional sulphur sources on nitrogen, phosphorous, potassium and sulphur uptake (kg ha⁻¹) sunflower

Treatments	N uptake	P uptake	P uptake	S uptake
T ₁ : Control (RDF NPK)	76.4	14.9	75.4	8.2
T ₂ : Soil application of Elemental S @ 45 kg ha ⁻¹	121.5	20.8	95.4	19.4
T ₃ : Foliar spray of ZnSO ₄ @ 0.5%	128.9	23.1	95.5	21.9
T ₄ : FS of SNPs from pomegranate fruit peel extract @ 500 ppm	104.1	18.9	89.0	14.8
T ₅ : FS of SNPs from mango tree leaf extract @ 500 ppm	109.1	19.2	90.8	16.6
T ₆ : FS of SNPs from pomegranate fruit peel extract @ 750 ppm	91.1	16.0	86.4	12.0
T ₇ : FS of SNPs from mango tree leaf extract @ 750 ppm	95.4	18.4	86.8	13.4
T ₈ : FS of SNPs from pomegranate fruit peel extract @ 500 ppm with tween 20 @ 0.5 ml l ⁻¹	194.9	28.5	120.1	32.7
T ₉ : FS of SNPs from mango tree leaf extract @ 500 ppm with tween 20 @ 0.5 ml l ⁻¹	201.7	29.4	125.4	34.5
T ₁₀ : FS of SNPs from pomegranate fruit peel extract @ 250 ppm with tween 20 @ 0.5 ml l ⁻¹	140.2	23.6	106.2	24.3
T ₁₁ : FS of SNPs from mango tree leaf extract @ 250 ppm with tween 20 @ 0.5 ml l ⁻¹	145.6	25.7	106.0	25.5
SEm ±	10.3	1.6	7.1	1.2
CD (P=0.05)	30.4	4.7	20.9	3.7
CV (%)	13.9	12.8	12.5	10.6

Post harvest soil analysis: The post-harvest analysis was carried out to assess whether foliar application of synthesized SNPs and other sulphur sources produced any residual effects on soil chemical characteristics. As the results indicate, the treatments did not impose significant changes on soil pH, EC, organic carbon or available nutrients, suggesting minimal post-harvest alteration of soil properties (Table 2). This observation is consistent with recent findings that foliar fertilization, particularly with nano-formulations, involves direct nutrient absorption through leaves with minimal interaction with soil systems (Ding *et al.*, 2023) [2].

Soil pH values after harvest ranged from 6.90 to 7.75, remaining very close to the initial pH of 7.01. The slight numerical fluctuations observed among treatments did not follow any clear pattern and were statistically non-significant. This stability indicates that the sulphur supplied through foliar application did not alter soil acidity. Even where variations appeared, they were within normal soil variability and do not suggest any treatment-

induced shifts. Unlike soil-applied sulphur, which can acidify soil through microbial oxidation, foliar-applied nutrients largely bypass soil buffering systems (Scherer, 2001) [10]. Electrical conductivity after harvest varied between 0.43 and 0.56 dS m⁻¹. No treatment showed a tendency for increased salinity and the values remained well within acceptable limits for sunflower cultivation and thus the effect of sulphur application found non-significant. This agrees with reports that foliar fertilization supplies nutrients in small quantities and reduces the risk of salt build-up in soil compared to soil fertilization (Niu *et al.*, 2021) [8]. Organic carbon content remained stable (0.41 - 0.50%), which is expected since foliar nutrient application does not contribute organic residues to soil. Soil organic carbon is primarily governed by organic matter inputs and decomposition processes rather than foliar nutrient supply (Marschner, 2012) [7]. Post-harvest analysis of soil nutrients showed that available nitrogen, phosphorus and potassium and sulphur did not follow any consistent trend and were statistically non-significant. The

stability of N, P, K and S across treatments indicates that the foliar application of sulphur, whether in conventional form or as nanoparticles, did not alter the nutrient reserves in the soil. Since foliar sprays interact primarily with plant foliage rather than the soil profile, the overall NPKS status remained essentially unchanged after harvest. This is supported by recent studies

indicating that foliar-applied nutrients are largely utilized by plants with minimal contribution to soil nutrient pools (Dimkpa and Bindraban, 2018) ^[1]. These results depicted the understanding that foliar nano-fertilizers are applied in low doses and exhibit higher nutrient uptake efficiency with reduced environmental residue (Ding *et al.*, 2023) ^[2].

Table 2: Influence of foliar spray (FS) of synthesized sulphur nanoparticles (SNPs) and conventional sulphur sources on post harvest soil chemical properties of sunflower

Treatments	pH	EC (dS m ⁻¹)	Organic Carbon (%)	Available N (kg ha ⁻¹)	Available P (kg ha ⁻¹)	Available K (kg ha ⁻¹)	Available S (mg kg ⁻¹)
T ₁ : Control (RDF NPK)	7.19	0.45	0.43	182.1	48.3	185.1	10.0
T ₂ : Soil application of Elemental S @ 45 kg ha ⁻¹	6.90	0.53	0.41	179.1	54.1	210.6	12.8
T ₃ : Foliar spray of ZnSO ₄ @ 0.5%	7.75	0.52	0.47	166.9	51.2	197.8	10.8
T ₄ : FS of SNPs from pomegranate fruit peel extract @ 500 ppm	7.40	0.44	0.46	179.3	49.7	188.4	9.9
T ₅ : FS of SNPs from mango tree leaf extract @ 500 ppm	7.33	0.43	0.50	171.3	45.8	208.3	10.0
T ₆ : FS of SNPs from pomegranate fruit peel extract @ 750 ppm	6.93	0.47	0.49	179.9	43.1	179.3	9.6
T ₇ : FS of SNPs from mango tree leaf extract @ 750 ppm	7.24	0.45	0.45	167.0	52.6	177.7	9.8
T ₈ : FS of SNPs from pomegranate fruit peel extract @ 500 ppm with tween 20 @ 0.5 ml l ⁻¹	7.15	0.51	0.41	181.1	47.0	178.4	11.0
T ₉ : FS of SNPs from mango tree leaf extract @ 500 ppm with tween 20 @ 0.5 ml l ⁻¹	6.93	0.45	0.48	175.9	50.8	180.5	10.3
T ₁₀ : FS of SNPs from pomegranate fruit peel extract @ 250 ppm with tween 20 @ 0.5 ml l ⁻¹	7.26	0.56	0.44	170.1	42.4	215.9	10.3
T ₁₁ : FS of SNPs from mango tree leaf extract @ 250 ppm with tween 20 @ 0.5 ml l ⁻¹	7.16	0.44	0.42	174.0	41.2	195.4	9.8
SEm ±	0.43	0.03	0.03	11.4	2.9	11.6	0.6
CD (P=0.05)	NS	NS	NS	NS	NS	NS	NS
CV (%)	10.3	10.7	11.3	11.3	10.6	10.4	10.1

Conclusion

Nano-enabled sulphur nutrition through foliar application of green-synthesized sulphur nanoparticles (SNPs) effectively improved nutrient uptake dynamics in sunflower. Application of SNPs at 500 ppm with Tween 20 @ 0.5 ml L⁻¹, particularly those derived from mango leaf extract, resulted in superior uptake of N, P, K and S, performing on par with pomegranate-based SNPs at the same level. The enhanced response reflects improved foliar absorption, translocation and nutrient use efficiency compared to conventional sulphur sources. The non-significant variation in post-harvest soil pH, electrical conductivity, organic carbon and available nutrients indicates minimal residual impact on soil, suggesting that foliar-applied nano-sulphur functions primarily through plant-mediated processes without altering soil fertility status. Finally, the study establishes green synthesized SNPs as a promising, eco-friendly and sustainable nutrient management strategy for sunflower, capable of improving nutrient uptake and use efficiency while maintaining soil health. Future research should focus on long-term effects on soil biological properties and exploration of optimized nano-formulations for large-scale agricultural applications.

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