



## Effect of conventional and nano fertilizers on sunflower (*Helianthus annuus*) in acidic soil

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### ABSTRACT

The present study was carried out during the rainy (*khari*) season of 2021 and 2022 at University of Agricultural Sciences, Gandhi Krishi Vigyana Kendra, Bengaluru, Karnataka to evaluate effect of different doses of conventional and nano-fertilizers on concentration, uptake and use efficiency on sunflower (*Helianthus annuus* L.) in acidic soil. The experiment was laid out in a randomized block design (RBD) with three replications and comprised of 14 treatments, including varying combinations of recommended doses and nano-fertilizer. Results revealed that nitrogen, sulphur and zinc concentrations in sunflower varied significantly with application of treatment T<sub>14</sub> (75% RDN + Nano Urea @ 4 mL/L + 25% ZnSO<sub>4</sub> + Nano Sulphur @200 ppm + Nano Zinc @500 ppm) compared to treatment T<sub>2</sub> [Package of practice (FYM + Bio fertilizers + NPK + Zn + B)], while phosphorus and potassium were non-significant. A similar kind of trend was observed in case of uptake of nitrogen, sulphur and zinc and this treatment recorded a significant improvement over other treatment. Furthermore, these findings underscore the potential for integrated use of conventional and nano formulations at optimal level to boost crop productivity without excessive inputs. Nutrients use efficiency of nitrogen (72.01 kg/kg), phosphorus (26.47 kg/kg) and potassium (35.29 kg/kg) were influenced considerably with application of different levels of conventional and nano fertilizers among different treatment combinations.

**Keywords:** Nitrogen use efficiency, Nutrient concentration, Nutrient efficiency, Zinc uptake

Sunflower (*Helianthus annuus* L.) is a widely cultivated oilseed crop known for its adaptability and versatility (Afshar *et al.* 2014). Nonetheless, the cultivation of sunflower in acidic soils presents notable challenges, primarily due to altered nutrient dynamics (Ma *et al.* 2010). The availability of essential nutrients such as nitrogen (N), sulphur (S), and zinc (Zn) is adversely affected in acidic soils, leading to suboptimal crop performance (Abasalt *et al.* 2015). The significance of nitrogen, sulphur, and zinc in plant nutrition is well established. Nitrogen is a vital component of amino acids, proteins, and chlorophyll, influencing growth and photosynthesis (Fan *et al.* 2012, Sarkar *et al.* 2009). Sulphur supports the synthesis of amino acids and vitamins (Chandana *et al.* 2021), while zinc functions as a cofactor in numerous enzymatic pathways (WAAJ-Juthery *et al.* 2019). Their limited availability under acidic conditions necessitates improved fertilization strategies tailored to such soils.

The advent of nanotechnology in agriculture has opened avenues for addressing nutrient deficiencies and

enhancing nutrient use efficiency (Azamal and Khawaja 2014). Nano-scale nutrient formulations offer increased reactivity, improved solubility, and enhanced plant uptake (Patel *et al.* 2019). This research aims to examine the effects of different levels of nano-nitrogen, nano-sulphur, and nano-zinc on nutrient concentration, uptake mechanisms, and nutrient use efficiency in sunflower grown under acidic soil conditions. By integrating soil chemistry, plant physiology, and nanotechnology, this study seeks to provide evidence-based insights into optimizing nano-nutrient applications for sunflower cultivation in acidic soils. The outcomes are expected to contribute to refined nutrient management strategies that enhance productivity and resilience under such limiting environments.

### MATERIALS AND METHODS

*Experimental details:* The present study was carried out during the rainy (*khari*) season of 2021 and 2022 at University of Agricultural Sciences, Gandhi Krishi Vigyana Kendra, Bengaluru, Karnataka. The pH of the soil during the experimental years 2021 and 2022 was 5.7 and 5.8, respectively. The high yielding variety KBSH-44 of sunflower was used for the experiment with a seed rate of 5 kg/ha and recommended dose of FYM (6.25 t/ha) and

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Table 1 Treatment details of the experiment

Treatment details	
T <sub>1</sub>	Absolute control
T <sub>2</sub>	Package of practice (FYM + Bio fertilizers + NPK + Zn + B)
T <sub>3</sub>	25% RDN + nU @2 mL/L+ 50% ZnSO <sub>4</sub> + nS @ 100 ppm + nZn @250 ppm
T <sub>4</sub>	25% RDN + nU @4 mL/L+ 50% ZnSO <sub>4</sub> + nS @ 100 ppm + nZn @250 ppm
T <sub>5</sub>	50% RDN + nU @2 mL/L+ 50% ZnSO <sub>4</sub> + nS @ 100 ppm + nZn @250 ppm
T <sub>6</sub>	50% RDN + nU @4 mL/L+ 50% ZnSO <sub>4</sub> + nS @ 100 ppm + nZn @250 ppm
T <sub>7</sub>	75% RDN + nU @2 mL/L+ 50% ZnSO <sub>4</sub> + nS @ 100 ppm + nZn @250 ppm
T <sub>8</sub>	75% RDN + nU @4 mL/L+ 50% ZnSO <sub>4</sub> + nS @ 100 ppm + nZn @250 ppm
T <sub>9</sub>	25% RDN + nU @2 mL/L+ 25% ZnSO <sub>4</sub> + nS @ 200 ppm + nZn @500 ppm
T <sub>10</sub>	25% RDN + nU @4 mL/L+ 25% ZnSO <sub>4</sub> + nS @ 200 ppm+ nZn @500 ppm
T <sub>11</sub>	50% RDN + nU @2 mL/L+ 25% ZnSO <sub>4</sub> + nS @ 200 ppm+ nZn @500 ppm
T <sub>12</sub>	50% RDN + nU @4 mL/L+ 25% ZnSO <sub>4</sub> + nS @ 200 ppm+ nZn @500 ppm
T <sub>13</sub>	75% RDN + nU @2 mL/L+ 25% ZnSO <sub>4</sub> + nS @ 200 ppm+ nZn @500 ppm
T <sub>14</sub>	75% RDN + nU @4 mL/L+ 25% ZnSO <sub>4</sub> + nS @ 200 ppm+ nZn @500 ppm

RDN, Recommended dose of nitrogen; nU, Nano urea; NS, Nano sulphur; nZn, Nano zinc; FYM, Bio fertilizer; Phosphorus, Potassium and Borax is common for all treatments except in absolute control.

fertilizer (37.5:50:37.5 kg/ha of NPK + 10 kg/ha ZnSO<sub>4</sub> + 15 kg/ha Borax + 375 g/ha Azatobactor) was applied according to the treatment. The soil type was sandy loam (Alfisol) in texture and the experiment was laid out in randomized block design (RBD) with 3 replications and comprised of 14 treatments (Table 1).

*Spray schedule and source of nano fertilizers:* Nano urea spray- Vegetative V-4 stage and Pre Bud-initiation stage @20 and 40 DAS + Nano Sulphur and Zinc spray - Ray floret stage @50–55 DAS. The nano fertilizers used in the experiment were nano nitrogen (Nano Urea - 4% N), nano sulphur (Elemental nano sulphur - 98% S) and nano zinc (Nano Zinc-EDTA - 21% Zn).

*Collection of plant samples:* Treatment wise plant samples were collected by uprooting the entire plant carefully. The samples were dried in shade and then oven-dried at 65°C. Then the plant samples were weighed to record dry matter accumulation in different plant parts and then powdered separately into seeds and stalks with the help of a grinder and stored in butter paper bags. The samples

were analyzed for nitrogen, phosphorus, potassium, sulphur and zinc accumulation in seed and stalk at harvest stage, determined by following standard procedures and expressed as concentration and total uptake of nutrients.

*Nitrogen estimation (%):* Seeds and stalk of about 0.5 g of samples were digested with concentrated sulphuric acid (H<sub>2</sub>SO<sub>4</sub>) and digestion mixture (K<sub>2</sub>SO<sub>4</sub>: CuSO<sub>4</sub>.5H<sub>2</sub>O: selenium in the ratio of 100:20:1). The digested content was distilled by the Macro Kjeldhal. The ammonia produced was trapped in boric acid with mixed indicator and was then measured by titrating against standardized sulphuric acid (Piper 1966).

*Digestion of plant samples for nutrients estimation:* One gram of the dried seeds and stalk samples were pre-digested with 10 ml concentrated HNO<sub>3</sub> for 24 h, the samples were digested with 10 ml di-acid mixture reagent (HNO<sub>3</sub> + HClO<sub>4</sub> in 9:4) and placed on a sand bath until a white precipitate was left at the bottom. The digested samples were cooled and diluted to 100 mL using distilled water, filtered and used for the analysis of all elements except nitrogen.

*Sulphur percentage:* Sulphur content in the sample was determined by the turbidometric method, a widely used analytical technique based on the formation of a suspension of insoluble barium sulphate. The degree of turbidity produced is directly proportional to the concentration of sulphur present in the sample. To quantify this, the intensity of turbidity was measured using a spectrophotometer at a wavelength of 420 nm, where maximum light scattering by the suspended particles occurs. A calibration curve was prepared using standard sulphur solutions, and the sulphur concentration in the sample was determined by comparing its turbidity with that of the standards. This procedure was carried out following the method outlined by Piper (1966), ensuring accuracy and reproducibility in sulphur estimation.

*Micronutrient (Zn in mg/kg):* The digested plant samples were fed to the atomic absorption spectrophotometer using appropriate hallow cathode lamps to estimate the zinc concentration in the plant samples (Lindsay and Norwell 1978).

*Nutrient uptake:* The uptake of nutrients by sunflower crop was calculated after the analysis of nutrients concentrations in sunflower seeds and stalk. For the calculation of uptake of concentration of each nutrient in seeds and stalk were multiplied with their respective dry biomass. The formulas below are used to measure the nutrient uptake for macro and micronutrients:

$$\text{Macronutrient uptake (kg/ha)} = \frac{\text{Nutrient concentration (\%)} \times \text{Dry biomass (kg/ha)}}{100}$$

$$\text{Micronutrient uptake (g/ha)} = \frac{\text{Nutrient concentration (mg/kg)} \times \text{Dry biomass (kg/ha)}}{1000}$$

*Nutrient use efficiency (NUE):* Nutrient use efficiency is a critically important concept in the evaluation of crop production systems. Nutrient use efficiency of nitrogen,

phosphorus and potassium was calculated using the formula:

$$\text{NUE (kg/kg)} = \frac{\text{Grain yield of fertilized plot (kg)} - \text{Grain yield of control plot (kg)}}{\text{Quantity of nutrient applied (kg)}}$$

*Statistical analysis of data:* The experimental data collected on various soil properties, growth and yield parameters of sunflower plant was subjected to Fishers method of Analysis of Variance (ANOVA) as outlined by Gomez and Gomez (1984). The F- test found significant for comparison among treatment means, an appropriate value of critical difference (CD) has been worked out. Otherwise the abbreviation NS is indicated against the CD values. All the data were analyzed and the results are presented and discussed at a probability level of  $p=0.05$  for field experiment and  $p=0.01$  for laboratory experiment.

## RESULTS AND DISCUSSION

### *Effect of different levels of nano nitrogen, sulphur and zinc on nutrients concentration in sunflower*

*Nitrogen percent:* Nitrogen concentration in sunflower differed significantly among treatments (Table 2). Treatment T<sub>14</sub> (75% RDN + nano-urea @4 mL/L + 25% ZnSO<sub>4</sub> + nano-S @200 ppm + nano-Zn @500 ppm) recorded the highest nitrogen concentration (4.59%), which was statistically at par with T<sub>6</sub> (4.54%) and significantly superior to the package of practice (T<sub>2</sub>, 4.00%) and absolute control (T<sub>1</sub>, 3.74%).

The higher nitrogen concentration observed with nano-

nitrogen foliar application is mainly due to its superior solubility and quick absorption through leaves, along with reduced nutrient losses via leaching and volatilization compared to conventional soil-applied fertilizers (Badran and Savin 2017, Chandana *et al.* 2021). Additionally, its improved intracellular mobility and faster translocation to sink tissues (Hafeez *et al.* 2015), coupled with precise application aligned to crop demand, help minimize nitrogen stress and enhance overall nutrient use efficiency (Azamal and Khawaja 2014). These mechanisms collectively improve nitrogen accumulation in seeds and stalk while promoting sustainable nutrient management (Ma *et al.* 2010, Fan *et al.* 2012, Abasalt *et al.* 2015).

*Sulphur (%):* Sulphur concentration in sunflower differed significantly among treatments (Table 2). The highest value (0.76%) was recorded in T<sub>14</sub> (75% RDN + nano-urea @4 mL/L + 25% ZnSO<sub>4</sub> + nano-S @200 ppm + nano-Zn @500 ppm), which was statistically at par with T<sub>12</sub> (0.74%) and significantly superior to the package of practice (T<sub>2</sub>, 0.58%) and absolute control (T<sub>1</sub>, 0.52%).

The increased sulphur concentration with nano-sulphur foliar sprays is attributable to reduced losses from leaching and volatilization compared to conventional soil-applied forms, precise targeted delivery with minimal wastage (Patel *et al.* 2019), enhanced particle mobility and rapid translocation to seeds and stalk (Sarkar *et al.* 2009, Mandal *et al.* 2015), ability to fine-tune application rates to alleviate sulphur stress (Hafeez *et al.* 2015), and lower risk of excess soil sulphur and consequent acidification. These advantages collectively promote higher sulphur accumulation and

Table 2 Effect of different levels of conventional and nano fertilizers on concentration of nitrogen, sulphur and zinc in sunflower

Treatment	Nitrogen (%)			Sulphur (%)			Zinc (mg/kg)		
	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled
T <sub>1</sub>	3.75	3.73	3.74	0.54	0.49	0.52	133.57	124.86	129.22
T <sub>2</sub>	4.02	3.97	4.00	0.60	0.56	0.58	138.81	127.44	133.13
T <sub>3</sub>	4.17	4.13	4.15	0.63	0.58	0.61	140.84	128.55	134.70
T <sub>4</sub>	4.37	4.34	4.36	0.64	0.62	0.64	140.83	128.64	134.74
T <sub>5</sub>	4.30	4.29	4.29	0.65	0.63	0.64	141.41	129.09	135.25
T <sub>6</sub>	4.56	4.51	4.54	0.66	0.64	0.65	141.36	129.14	135.25
T <sub>7</sub>	4.30	4.25	4.28	0.66	0.64	0.65	142.09	129.63	135.85
T <sub>8</sub>	4.52	4.49	4.51	0.67	0.62	0.65	141.96	129.40	135.68
T <sub>9</sub>	4.20	4.18	4.19	0.72	0.70	0.71	144.73	131.80	138.27
T <sub>10</sub>	4.40	4.34	4.38	0.71	0.69	0.70	145.04	132.10	138.56
T <sub>11</sub>	4.26	4.21	4.23	0.73	0.70	0.71	145.23	133.08	139.15
T <sub>12</sub>	4.49	4.45	4.48	0.75	0.73	0.74	145.84	132.85	139.35
T <sub>13</sub>	4.32	4.28	4.30	0.70	0.73	0.72	145.50	133.03	139.26
T <sub>14</sub>	4.60	4.56	4.59	0.75	0.76	0.76	146.22	133.81	140.01
SEM ±	0.12	0.11	0.11	0.02	0.02	0.02	4.05	3.71	3.88
CD ( $p=0.05$ )	0.36	0.34	0.35	0.06	0.06	0.06	12.08	11.09	11.58

Treatment details are given in Table 1.

support environmentally sustainable nutrition (Afshar *et al.* 2014, Chandana *et al.* 2021).

**Zinc (mg/kg):** Zinc concentration in sunflower seed and stalk differed significantly among treatments (Table 1), ranging from 129.22 mg/kg in the absolute control (T<sub>1</sub>) to 140.01 mg/kg in T<sub>14</sub> (75% RDN + nano-urea @4 mL/L + 25% ZnSO<sub>4</sub> + nano-S @200 ppm + nano-Zn @500 ppm). Treatment T<sub>14</sub> significantly outperformed the package of practice (T<sub>2</sub>, 133.13 mg/kg).

The higher zinc concentration achieved with nano-zinc foliar sprays is primarily due to its high solubility and rapid foliar absorption (Afshar *et al.* 2014), reduced immobilization and losses compared to conventional soil-applied Zn (WA Al-Juthery *et al.* 2019), direct and precise delivery to leaves with minimal wastage (Patel *et al.* 2019), faster uptake and translocation kinetics, and lower risk of environmental contamination, collectively enabling greater zinc accumulation in seeds and stover while supporting sustainable nutrient management (Mahajan *et al.* 2013).

*Effect of different levels of nano nitrogen, sulphur and zinc on nutrient uptake by sunflower*

**Nitrogen uptake (kg/ha):** Total nitrogen uptake by sunflower showed significant variation across treatments (Table 3). The maximum uptake was observed in T<sub>14</sub> (75% RDN + nano-urea @4 mL/L + 25% ZnSO<sub>4</sub> + nano-S @200 ppm + nano-Zn @500 ppm) with a value of 132.23 kg/ha, which was statistically comparable to T<sub>8</sub> (128.57 kg/ha) and significantly higher than the absolute control (50.79 kg/ha). Higher nitrogen uptake with nano-nitrogen foliar

sprays is primarily due to greater solubility and rapid foliar absorption, substantially reduced losses from leaching, volatilization and denitrification compared to soil-applied conventional fertilizers (Shailesh *et al.* 2013, Taheri *et al.* 2015, Badran and Savin 2017), enhanced intracellular mobility and faster translocation to seeds and stover (Sedgi *et al.* 2013), precise dose and timing control that matches crop demand and minimizes nitrogen stress (Mahajan *et al.* 2013, Jhanzab *et al.* 2015).

**Sulphur uptake (kg/ha):** Total sulphur uptake by sunflower differed significantly among treatments (Table 3). The highest uptake (23.52 kg/ha) was recorded in T<sub>14</sub> (75% RDN + nano-urea @4 mL/L + 25% ZnSO<sub>4</sub> + nano-S @200 ppm + nano-Zn @500 ppm), which was statistically at par with T<sub>13</sub> (21.01 kg/ha) and significantly superior to the package of practice (T<sub>2</sub>, 13.84 kg/ha) and absolute control (T<sub>1</sub>, 7.31 kg/ha).

The higher sulphur uptake observed with nano-sulphur application can be attributed to its high solubility and rapid absorption by plant tissues (Jhanzab *et al.* 2015), along with significantly lower losses through leaching and volatilization compared to conventional soil-applied sulphur. Its precise and targeted delivery reduces nutrient wastage (Mandal *et al.* 2015), while improved intracellular mobility and quicker translocation to seeds and stover enhance sulphur utilization (Sedgi *et al.* 2013, Abasalt *et al.* 2015, Farnia and Omidi 2015). Moreover, it minimizes the risk of excess sulphur accumulation in soil and associated acidification (Taheri *et al.* 2015), and lowers the chances of nutrient imbalance or plant stress, thereby promoting

Table 3 Nutrients uptake by sunflower as influenced by different treatment levels

Treatment	Nitrogen (kg/ha)			Sulphur (kg/ha)			Zinc (g/ha)		
	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled
T <sub>1</sub>	51.92	49.67	50.79	7.89	6.75	7.31	262.05	234.39	248.05
T <sub>2</sub>	92.94	88.05	90.48	14.67	13.04	13.84	458.26	410.54	434.11
T <sub>3</sub>	81.92	78.95	80.43	13.08	11.76	12.41	391.52	351.50	371.30
T <sub>4</sub>	90.30	85.52	87.90	14.02	12.90	13.45	417.52	369.94	393.39
T <sub>5</sub>	108.56	105.31	106.94	17.34	16.38	16.86	499.14	445.09	471.80
T <sub>6</sub>	120.95	115.54	118.23	18.35	17.39	17.87	533.16	473.31	502.85
T <sub>7</sub>	113.78	109.28	111.52	18.47	17.55	18.00	526.80	472.92	499.59
T <sub>8</sub>	132.14	125.03	128.57	20.46	18.18	19.30	586.28	518.24	551.77
T <sub>9</sub>	88.88	85.81	87.35	16.23	15.33	15.77	435.98	385.18	410.26
T <sub>10</sub>	96.90	92.67	94.78	16.64	15.86	16.25	454.29	406.20	429.98
T <sub>11</sub>	110.37	104.22	107.28	20.81	19.37	20.08	526.62	470.65	498.27
T <sub>12</sub>	122.42	116.27	119.33	21.63	19.96	20.78	559.71	494.59	526.70
T <sub>13</sub>	119.63	114.56	117.09	21.43	20.60	21.01	566.40	501.76	533.66
T <sub>14</sub>	135.08	129.39	132.23	23.74	23.29	23.52	604.49	541.84	572.78
SEM±	2.86	2.74	2.80	0.48	0.46	0.47	13.36	11.91	12.63
CD (p=0.05)	8.32	7.96	8.14	1.41	1.32	1.36	38.85	34.62	36.71

Treatment details are given in Table 1.

Table 4 Nutrient use efficiency by sunflower as influenced by different levels of nano nitrogen, sulphur and zinc application

Treatment	Nutrient use efficiency (kg/kg) by sunflower								
	Nitrogen			Phosphorus			Potassium		
	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled
T <sub>1</sub>	-	-	-	-	-	-	-	-	-
T <sub>2</sub>	21.30	20.14	20.72	15.97	15.10	15.54	21.30	20.14	20.72
T <sub>3</sub>	53.17	52.28	52.72	9.97	9.80	9.89	13.29	13.07	13.18
T <sub>4</sub>	62.59	57.08	59.84	11.74	10.70	11.22	15.65	14.27	14.96
T <sub>5</sub>	52.78	51.37	52.08	19.79	19.27	19.53	26.39	25.69	26.04
T <sub>6</sub>	57.93	55.80	56.86	21.72	20.92	21.32	28.97	27.90	28.43
T <sub>7</sub>	39.18	38.45	38.82	22.04	21.63	21.83	29.39	28.84	29.11
T <sub>8</sub>	45.59	42.85	44.22	25.65	24.10	24.87	34.19	32.14	33.16
T <sub>9</sub>	66.51	65.13	65.82	12.47	12.21	12.34	16.63	16.28	16.45
T <sub>10</sub>	73.36	70.66	72.01	13.76	13.25	13.50	18.34	17.66	18.00
T <sub>11</sub>	55.90	52.24	54.07	20.96	19.59	20.28	27.95	26.12	27.03
T <sub>12</sub>	60.93	57.62	59.28	22.85	21.61	22.23	30.47	28.81	29.64
T <sub>13</sub>	42.79	41.22	42.00	24.07	23.18	23.63	32.09	30.91	31.50
T <sub>14</sub>	48.48	45.63	47.06	27.27	25.67	26.47	36.36	34.22	35.29

Treatment details are given in Table 1.

efficient sulphur use and greater accumulation in harvested biomass (Ma *et al.* 2010, Fan *et al.* 2012, Patel *et al.* 2019).

**Zinc uptake (g/ha):** Total zinc uptake by sunflower differed significantly among treatments (Table 3). The highest value (572.78 g/ha) was recorded in T<sub>14</sub> (75% RDN + nano-urea @4 mL/L + 25% ZnSO<sub>4</sub> + nano-S @200 ppm + nano-Zn @500 ppm), which was statistically at par with T<sub>8</sub> (551.77 g/ha) and markedly superior to the package of practice (T<sub>2</sub>, 434.11 g/ha).

The higher zinc uptake with nano-zinc foliar application is mainly due to its targeted delivery to leaves, rapid absorption and translocation (Chandana *et al.* 2021), and faster assimilation kinetics (Mohsen *et al.* 2016). It also reduces environmental losses (Sarkar *et al.* 2009) and allows precise dose regulation according to crop demand, minimizing nutrient imbalance or stress and resulting in more efficient utilization and greater accumulation in seeds and stover (Mahajan *et al.* 2013, Azamal and Khawaja 2014, Hafeez *et al.* 2015).

**Nutrients use efficiency (kg/kg) by sunflower as influenced by different levels of conventional and fertilizer application:** Nutrient use efficiency (NUE) of sunflower varied markedly among treatments (Table 4 and Fig. 1). Nitrogen use efficiency was highest in T<sub>10</sub> (25% RDN + nano-urea @4 mL/L + 25% ZnSO<sub>4</sub> + nano-S @200 ppm + nano-Zn @500 ppm) at 72.01 kg/kg,

followed closely by T<sub>9</sub> (65.82 kg/kg), both substantially superior to the package of practice (T<sub>2</sub>, 20.72 kg/kg). Phosphorus and potassium use efficiencies were highest in T<sub>14</sub> (26.47 and 35.29 kg/kg, respectively), which performed statistically at par with T<sub>8</sub> (24.87 and 33.16 kg/kg) and significantly outperformed T<sub>2</sub> (15.54 and 20.72 kg/kg).

The markedly higher NUE obtained with combined soil application of reduced conventional fertilizers and foliar nano-nutrients is mainly due to better synchrony and balanced supply of N, P, K, and Zn (Badran and Savin 2017, WA Al-juthery *et al.* 2019). This is further supported by improved penetration and rapid assimilation of nano-sized particles (Sumathi and Koteswara Rao 2007), enhanced

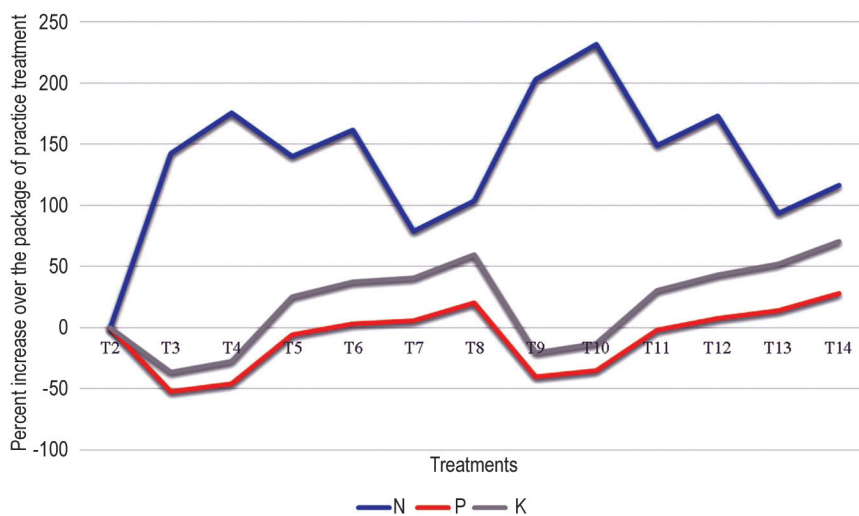


Fig. 1 Graphical representation of percent increase over the package of practice treatment. Treatment details are given in Table 1.

enzymatic and microbial activity promoting nutrient mineralization and uptake (Jhazab *et al.* 2015), and reduced nutrient losses through runoff and leaching (Burmana *et al.* 2013). These mechanisms collectively enabled sunflower plants to produce more grain per unit of applied nutrient compared with conventional full-dose practices.

The present study demonstrates that foliar application of nano-nitrogen, nano-sulphur and nano-zinc in combination with reduced soil-applied conventional fertilizers significantly improved nutrient concentration, total uptake and use efficiency of N, P, K, S and Zn in sunflower grown on acidic soils. Treatment T<sub>14</sub> (75% recommended dose of nitrogen + nano-urea @4 mL/L + 25% ZnSO<sub>4</sub> + nano-S @ 200 ppm + nano-Zn @500 ppm) consistently outperformed the conventional package of practice by enhancing nutrient availability, minimizing immobilization and losses typical of low-pH environments, and achieving superior nutrient translocation and assimilation. These results highlight the ability of nano-scale formulations to overcome acidity-induced nutrient constraints, thereby increasing nutrient-use efficiency and offering a more sustainable fertilization strategy. The findings open promising avenues for precision nano-nutrient management in sunflower and other crops cultivated on acidic soils.

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