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Role of sulphur and micronutrients spray on accumulation and uptake of nutrients by plant parts of safflower (*Carthamus tinctorius* L.)

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ABSTRACT

A field experiment was conducted to assess the effect of different sources and levels of sulphur, combined with micronutrient foliar spray (MN) having Zn 3.0%, Fe 2.5%, Mn 1.0%, Cu 1.0%, B 0.5%, Mo 0.1% on nutrient content and uptake in safflower (Carthamus tinctorius L.). Eight treatments were applied, including varying doses of elemental sulphur (ES) and gypsum (15, 30, and 45 kg/ha), supplemented with foliar spray of micronutrients. The treatment with 45 kg/ha of elemental sulphur combined with foliar micronutrient spray (T4) significantly enhanced nutrient accumulation across plant parts. In the leaves, nitrogen (4.11 kg/ha), potassium (5.55 kg/ha), iron (712.34 ppm), and boron (66.95 ppm) were highest (p=<0.05), reflecting improved nutrient transport and photosynthetic efficiency. The stems showed significantly elevated sulphur levels (1.19 kg/ha) and iron content (426.99 ppm), enhancing nutrient redistribution. Seeds exhibited the highest zinc accumulation (52.13 ppm), promoting seed quality. Nutrient uptake was maximized in leaves, with the largest quantity of potassium (48.25 kg/ha), Cu, Mn and B (p=<0.05). Additionally, T4 boosted nitrogen (15.80 kg/ha), phosphorus (9.49 kg/ha), and zinc (77.29ppm) uptake in seeds, essential for seed development. This treatment proved to be most effective in optimizing nutrient availability and accumulation, thereby promoting overall crop productivity in sulphur-deficient soils.

Keywords: Safflower, Elemental Sulphur, foliar spray, gypsum, sulphur-deficient soils

INTRODUCTION

Safflower (*Carthamus tinctorius L.)* is an oilseed crop known for producing high-quality oil with wide range of industrial uses (Zanetti *et al.,* 2022). Sulphur is an essential macronutrient that supports vital plant processes such as amino acid production, chlorophyll synthesis and enzymatic activity (Singh *et al.,* 2020). The semi-arid soils of this plant in Maharashtra, India, present unique challenges due to their low organic matter content, high pH levels, and limited availability of essential elements to plant roots, attributed primarily to climatic conditions like low and irregular rainfall (Bhattacharyya *et al.,* 2018). Sulphur levels in the soil can significantly affect nutrient absorption and plant metabolism. Ensuring adequate sulphur availability is crucial for promoting sustainable crop growth and maximizing agricultural productivity (Sharma *et al.,* 2024).

Sulphur (S) is a crucial macronutrient ranking fourth after nitrogen, phosphorus, and potassium (NPK) in terms of its importance and required quantity (Tandon *et al.,* 2002). It plays a vital role in various biological functions, such as the synthesis of key proteinaceous amino acids like cysteine and methionine, and the formation of chlorophyll (Ballabh and Rana, 2012). Additionally, sulphur is integral to the structure of defence molecules like glutathione, sulpholipids in chloroplast membranes, essential vitamins such as biotin and thiamine, and coenzymes involved in fatty acid synthesis and oxidation (Narayan *et al.,* 2023). Besides fulfilling the nutritional needs of plants, sulphur application serves as an effective soil amendment, especially in calcareous soils (Singh *et al.,* 2015). Its ability to oxidize and produce sulphuric acid helps in slightly lowering the soil pH around the sulphur particles, thereby improving plant nutrient uptake. When sulphur fertilizers are applied in the rhizosphere, they facilitate the dissolution of insoluble nutrient compounds, thereby releasing essential elements for plant growth (Patel *et al.,* 2019, Magodia *et al.,* 2024a).

Although, adequate sulphur nutrition is important for optimal growth and development of certain crops like Safflower (*Carthamus tinctorius L.)*, ensuring both productivity and

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quality, recent research indicates that application of sulphur in combination with foliar sprays of micronutrients can greatly boost nutrient absorption and content, leading to improved yield and overall quality (Zain *et al.,* 2015). Because, micronutrients play a pivotal role in enhancing crop quality and productivity in the horticulture sector, as they are critical in facilitating the catalytic processes essential for nutrient absorption and maintaining nutrient balance (Tripathi *et al.,* 2015). However, micronutrients exist in smaller quantities compared to macronutrients, and their deficiency in soils can significantly impact plant health and yield, often leading to physiological disorders and reduced quality in agricultural products (Sharma *et al.,* 2016). India, in particular, faces widespread micronutrient deficiencies, especially of zinc (Zn), iron (Fe), Copper (Cu) manganese (Mn), Iron (Fe), boron (B), and Molybdenum (Mo), which are essential for optimal plant growth (Soni *et al.,* 2023). Foliar spry ensures quick nutrient absorption, with most micronutrients entering the plant within hours, making it especially effective in semi-arid and dry regions where soil nutrient deficiencies are more prevalent (Dhiraj and Kumar, 2012). Thus, understanding the role and management of micronutrients is crucial for ensuring sustainable and productive horticultural practices (Monib *et al.,* 2023).

The effect of different sources and levels of sulphur on safflower (*Carthamus tinctorius L.)* nutrient content, along with the impact of micronutrient foliar spray, is essential to optimizing its nutrient management. It will ensure improved nutrient content and uptake, which may lead to efficient and better yield outcomes. This study aimed to evaluate the influence of varying sulphur sources and concentrations, coupled with micronutrient foliar sprays, on safflower nutrient content and uptake. The results could provide valuable insights for improving safflower (*Carthamus tinctorius L.)* cultivation practices, especially in sulphur-deficient soils.

MATERIAL AND METHODS

A field experiment was conducted during the Rabi season of 2024 on safflower (*Carthamus tinctorius L.)* at Narayangaon, a city in Maharashtra, India, located at the latitude of 19.07 and longitude of 73.97. The soil in this region is medium black calcareous with a slightly alkaline pH of 8.1. The experiment followed a randomized block to assess soil physicochemical properties and plant growth parameters. Eight treatments, each with four replications, were implemented in a field each plot measuring approximately 6 square meters (Magodia *et al.,* 2024b). Each replication consisted of 66 plants. The treatments involve the application of different combinations of Recommended Doses of Fertilizer (RDF), elemental sulphur (ES), or gypsum, along with a foliar spray of micronutrients (MN). Treatment T_1 consists solely of 100% RDF, serving as the baseline for comparison. T_2 introduced 15 kg/ha of ES alongside RDF and micronutrient spraying, targeting the improvement of soil sulphur content and plant health. Similarly, T_3 and T_4 increase the ES application to 30 kg/ha and 45 kg/ha, respectively, in addition to the foliar spray, potentially optimizing soil sulphur levels and nutrient availability further. The next set of treatments, T_5 through T_7, substitutes elemental sulphur with gypsum at corresponding levels of 15 kg/ha, 30 kg/ha, and 45 kg/ha, combined with RDF and MN. In T_8, the same RDF level is supplemented with a foliar spray of micronutrients, which aims to address potential nutrient deficiencies and enhance plant uptake at the time of sowing.

The same plants used by Magodia *et al.,* (2024) were used for the present study. The crop was maintained with regular irrigation, consisting of watering on alternate days, along with periodic weeding and protective measures against pests and diseases as required. Sixty days after sowing, Rashtriya Chemical Fertiliser Limited micronutrients spray (Zn 3.0%, Fe 2.5%, Mn 1.0%, Cu 1.0%, B 0.5%, Mo 0.1%) were sprayed twice during the flowering stage. 1ml of MN spray was mixed with 1000ml of water and sprayed on day 45 and day 60 after sowing the seeds. Harvesting was carried out 160 days post-transplanting when plants reached physiological maturity. Plant parts samples were dried in the sun for 8 to 10 days. Nutrients, including nitrogen (N), phosphorus (P), potassium (K), sulphur (S), copper (Cu), zinc (Zn), manganese (Mn), iron (Fe)and boron (B) were extracted from these plant parts using a wet acid digestion method, employing Soxhlet apparatus and petroleum ether as the solvent for extraction of oil. Inductively Coupled Plasma Spectrophotometer (ICP-OES) was used to measure content (Miller *et al.,* 2013). Nutrient uptake from each pant part was calculated by multiplying the nutrient concentration (%) with dry matter yield of plant parts/ hectare. The data collected were statistically analysed according to the methodology outlined by Panse and Sukhatme (1995).

RESULTS AND DISCUSSIONS

Performance of treatments for nutrient content and uptake

The data presented in Table 1-4 indicates nutrient contents and nutrient uptakes. Safflower (*Carthamus tinctorius L.*) was examined across different plant parts—leaves, stems, roots, and seeds—under eight treatments (T_1–T_8). Across all treatments, nutrient content, and uptake showed significant variability, with T_4 treatment (100% RDF+ES 45 kg/ha + MN) consistently outperforming for both macro and micronutrient concentrations and uptake. Whereas some of the macro nutrients in different parts of plant were showing non-significant like nitrogen was found in leaves and seed, phosphorous was in stem and seed, potassium was in root and seed, sulphur was in leaves. Some of the micronutrients were also found to be non-significant in different parts of the plant, like copper in leaves and root, zinc in stem and seed, manganese in leaves and stem, boron was also found in stem and root, and iron in seed.

T_4 consistently enhanced both macro and micronutrient contents in all plant parts, followed closely by T_7, while T_1 and T_8 tended to have the lowest nutrient levels. These findings indicate that specific treatments, particularly $_{T4}$, can significantly influence nutrient allocation within the plant, potentially leading to improved growth and productivity. The stability of nutrient content in these treatments can be attributed to better soil nutrient dynamics and efficient uptake mechanisms.

Table 1: Macronutrient and micronutrient contents of *C. tinctorius* mature leaves

Treatment	N %	P %	K %	S %	Cu ppm	Zn ppm	Mn ppm	Fe ppm	B ppm
T_1	2.80	0.62	4.31	0.24	32.13	24.45	45.55	452.025	40.17012
T_2	3.11	0.71	4.78	0.28	39.43	28.94	53.65	564.300	49.44938
T_3	3.61	0.77	5.02	0.31	41.72	35.41	62.18	626.629	55.12985
T_4	4.11	0.81	5.55	0.34	47.33	39.73	65.51	712.337	66.94886
T_5	3.16	0.72	4.71	0.28	38.56	42.01	52.75	520.219	53.9525
T_6	3.47	0.78	5.07	0.30	43.08	34.39	57.14	627.655	57.69252
T_7	4.00	0.80	5.30	0.30	45.50	41.13	59.99	691.100	60.23088
T_8	3.04	0.74	4.45	0.27	35.95	43.07	49.57	545.134	59.2375
SEM±	0.31	0.02	0.11	0.02	3.81	1.28	4.75	8.76	3.24
CD (.05)	NS	0.07	0.31	NS	NS	3.76	NS	25.77	9.51
CV %	18.24	6.42	4.32	16.88	18.83	7.08	17.03	2.96	11.69

Nutrients content accumulation in different plant parts

The comparative effects of ES and gypsum on the growth and yield of *C. tinctorius* revealed significant insights into their agronomic benefits (Magodia *et al.,* 2024). ES generally enhances vegetative growth and seed yield more effectively than gypsum, although the specific outcomes can vary based on soil type and sulphur levels applied (Renuka, 2023).

The optimal concentrations of micronutrients in foliar sprays are crucial for maximizing crop yields and enhancing plant growth. When it combines with specific soil treatments, combination can significantly improve nutrient contents and uptake, which may lead to enhancing various growth parameters and overall yield across different crops (Ravikumar *et al.,* 2021). Several studies noted that the spray of micronutrients alone or in combination can effectively enhance the yield of plants. Ravi *et al.* (2008) noted ES

(30kg/ha) along with Zn+Fe foliar spray was effective in improving the significant yield of safflower (*Carthamus tinctorius L.)*. However, no known study has compared the effect of varying doses of ES and gypsum with foliar spray and focused on nutrient accumulation and uptake by different plant parts.

Table 2: Macronutrient and micronutrient contents of Safflower (*Carthamus tinctorius L.)* mature stem

Treatment	N %	P %	K %	S %	Cu ppm	Zn ppm	Mn ppm	Fe ppm	B ppm
T_1	2.04	0.139	0.48	0.78	10.10	11.30	12.27	267.732	14.68
T_2	2.71	0.148	0.53	0.91	12.87	14.92	14.28	300.843	17.62
T_3	3.00	0.159	0.59	0.99	15.68	16.56	16.80	345.635	19.47
T_4	3.72	0.174	0.62	1.19	17.75	18.63	17.77	426.995	23.06
T_5	2.25	0.153	0.52	0.85	13.64	14.77	12.42	293.470	16.80
T_6	2.71	0.162	0.56	0.95	15.38	16.32	15.94	387.178	19.40
T_7	3.11	0.168	0.59	1.09	16.73	17.55	17.76	432.553	21.61
T_8	2.55	0.151	0.52	0.75	10.97	15.48	13.90	290.575	16.51
SEM±	0.11	0.01	0.01	0.05	0.38	1.45	1.42	14.86	1.769
CD (.05)	0.31	NS	0.03	0.14	1.12	N.S	N.S	43.70	NS
CV %	7.70	13.44	4.05	9.84	5.39	18.51	18.76	8.66	18.973

The findings of the present study demonstrate that the T_4 treatment in *C. tinctorius* significantly boosted the accumulation of essential nutrients across various plant parts, revealing its overall effectiveness (Table 2-5). In leaves, T_4 treatment resulted in the highest levels of nitrogen (4.11 kg/ha), potassium (5.55 kg/ha), and micronutrients like copper (47.33 ppm), zinc (39.73 ppm), manganese (65.51 ppm), iron (712.337 ppm), and boron (66.95 ppm) (Table 1). These accumulated nutrients are significantly higher (p=<0.05) and maximum in leaves compared to other plant parts, might be due to T_4 treatment improved safflower (*Carthamus tinctorius L.)* nutrient transport system. Additionally, the leaf's extensive surface area facilitated greater exposure to foliar spray containing micronutrients. This exposure also enhanced the photosynthetic process, which in turn drives increased nutrient demand and uptake through root activity (Monib *et al.,* 2023).

Table 3: Macronutrient and micronutrient contents of Safflower (*Carthamus tinctorius L.)* mature roots

Treatment	N %	P %	K %	S %	Cu ppm	Zn ppm	Mn ppm	Fe ppm	B ppm
T_1	5.64	0.09	0.75	0.0512	14.55	18.54	24.70	194.505	21.40
T_2	6.52	0.10	0.87	0.0607	16.73	25.13	31.77	210.935	28.86
T_3	6.93	0.12	0.98	0.0768	20.56	31.73	39.72	224.355	33.15
T_4	7.31	0.14	1.04	0.0895	22.46	39.12	44.19	244.615	36.13
T_5	6.16	0.09	0.89	0.0663	16.27	24.34	27.11	217.190	26.67
T_6	6.76	0.13	0.95	0.0780	19.32	32.03	32.30	228.198	31.07
T_7	7.09	0.14	0.93	0.0842	20.91	36.10	45.68	241.228	34.49
T_8	6.07	0.11	0.82	0.0560	16.94	19.13	30.86	204.308	29.68
SEM+_	0.13	0.01	0.06	0.00	1.75	2.19	1.20	16.94	2.986
CD (.05)	0.39	0.02	NS	0.01	NS	6.44	3.53	NS	NS
CV %	4.03	11.21	13.58	13.00	18.95	15.50	6.95	15.35	19.789

Stems also showed substantial nutrient accumulation (Table 3), particularly sulphur(1.19 kg/ha), maximum among all parts, along with iron content reaching 426.995 ppm (p=<0.05). This suggests that T4 having elemental S (45kg/ha) improved nutrient storage capabilities in the stems, which are pivotal for nutrient redistribution throughout the plant (Jagasia *et al.,* 2024). Seeds of Safflower (*Carthamus tinctorius L.)* showed considerable nutrient accumulation, with maximum zinc (52.13 ppm), emphasizing the effectiveness of

T_4 treatment in channelling essential nutrients towards reproductive tissues to enhance seed development and quality (Table 5). Although roots were not the primary site for nutrient storage, they accumulated high amounts of nitrogen (7.31 kg/ha) in T4 plants (Table 4) and low levels of other nutrients, indicating their role in nutrient uptake and initial assimilation (Zanetti *et al.,* 2024).

Table 4: Macronutrient and micronutrient contents of Safflower (*Carthamus tinctorius L.)* mature seeds

Treatment	N %	P %	K %	S %	Cu ppm	Zn ppm	Mn ppm	Fe ppm	B ppm
T_1	2.82	0.48	0.69	0.19	18.87	40.05	18.13	119.289	9.78
T_2	3.22	0.57	0.84	0.21	22.53	44.42	21.38	130.465	13.34
T_3	3.57	0.59	0.90	0.24	25.27	47.44	25.01	137.421	16.38
T_4	3.69	0.64	0.90	0.25	27.61	52.13	30.05	143.690	21.55
T_5	2.95	0.48	0.80	0.20	20.86	43.61	22.29	126.363	13.51
T_6	3.31	0.55	0.86	0.21	23.12	45.43	24.62	131.802	16.04
T_7	3.65	0.61	0.88	0.24	27.70	49.41	26.28	140.063	19.21
T_8	3.14	0.52	0.79	0.21	20.52	43.90	22.78	127.480	13.05
SEM±	0.25	0.04	0.06	0.01	0.82	2.80	1.30	5.33	0.78
CD (.05)	NS	NS	NS	0.02	2.40	N.S	3.82	NS	2.30
CV %	15.13	13.89	14.38	6.54	7.01	12.23	10.90	8.08	10.18

In Table 4 the uptake of total of total macro and micronutrients by safflower increased with increasing the doses of sulphur. Among all the treatments T_4 has recorded the maximum total uptake and the lowest with T_1 (only RDF), combinations of sulphur and micronutrients had significant influence on overall uptake of nutrients, the increase in uptake maybe due to the interaction effect of sulphur and micronutrients which are synergistic, same results are observed in (Ravishankar *et al.,* 2021). The uptake of nutrients increased with an increased in levels of NPK, sulphur, and zinc; same results are in conformity with those Jagasia *et al.,* (2024) in groundnut and Babulkar *et al.,* (2000) in safflower.

Foliar spray of several micronutrients has been noted to be effective for many crops. Zinc at concentrations around 1000 ppm (0.1%), particularly when combined with Boron (B) at 200 ppm (0.02%) and Molybdenum (Mo) at 50 ppm (0.05%), which enhances head diameter and chlorophyll content in cabbage (Soni *et al.,* 2023). A concentration of 250 ppm has been shown to positively influence fruit weight and seed germination in sweet pepper (Soni *et al.,* 2023). Foliar application of Fe at 0.5% has demonstrated significant improvements in yield parameters for crops like cauliflower (Tirkey *et al.,* 2024). Another study says when combined with Zn and Fe, Cu enhances yield components in wheat, particularly at the booting stage (Ijaz *et al.,* 2023). However, the impact of the combination of Zn 3.0%, Fe 2.5%, Mn 1.0%, Cu 1.0%, B 0.5%, Mo 0.1% is not yet studied.

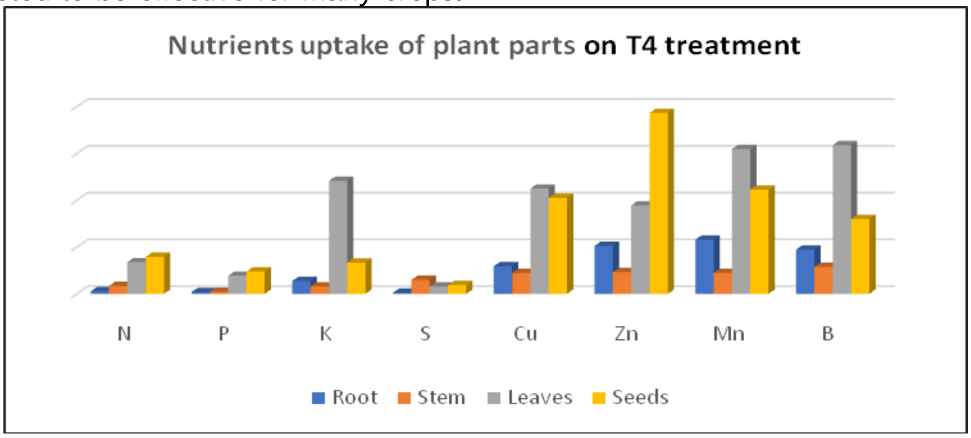

Figure 1: Nutrient uptake by Safflower (*Carthamus tinctorius L.)* plant parts on treatment with 45 kg/ha of elemental sulphur and foliar spray of micronutrients (T_4 treatment)

When we compared the uptake of different plant parts like root, stem, leaves and seed grown on T_4 treatment, micronutrient spray significantly enhanced nutrient uptake across various parts of the *C tinctorius* plant, demonstrating its effectiveness in optimizing nutrient distribution (Figure 1). As maximum surface area of leaves was exposed to foliar spray, theyexhibited the highest uptake of several key nutrients, notably nitrogen (13.50 kg/ha), potassium (48.25 kg/ha), and boron (63.54 mg/kg), reflecting their central role in photosynthesis and metabolic activity (Shekhawat and Sivay., 2008; Salve *et al.,* 2018). This suggests that the T_4 treatment along with foliar spray, effectively met the nutrient demands of photosynthetic tissues, improving the overall physiological efficiency of the plant (Singh and Singh, 2013). Additionally, the leaves also recorded substantial uptake of micronutrients such as copper (44.96 mg/kg), manganese (61.90 mg/kg), and iron (676.430 mg/kg), indicate an enhanced capacity for metabolic and enzymatic processes essential for growth (Ijaz *et al.,* 2023).

Table 5: Total nutrient uptake by *C. tinctorius* plant after different treatments

Treatment	N kg/ha	P kg/ha	K kg/ha	S kg/ha	Cu g/ha	Zn g/ha	Mn g/ha	Fe g/ha	B g/ha
T_1	17.904	9.38	32.24	5.49	41.7	58.55	51.91	563.951	48.08
T_2	22.890	12.73	48.13	7.82	66.2	88.13	81.87	757.831	69.42
T_3	27.146	14.96	55.60	9.92	82.5	110.53	108.03	939.585	89.67
T_4	33.703	18.79	70.16	13.28	106.6	144.82	138.51	1231.129	125.91
T_5	19.163	10.73	54.75	7.31	57.7	86.60	74.73	651.970	63.66
T_6	24.576	13.86	54.93	8.74	75.0	101.61	94.79	875.455	74.39
T_7	29.974	16.99	62.90	11.35	96.3	130.13	120.16	1120.912	104.86
T_8	21.264	12.38	47.49	6.77	60.1	93.31	79.23	732.232	76.87
SEM±	0.59	0.39	1.77	0.280	1.85	2.800	2.22	23.00	2.216
CD (.05)	1.75	1.155	5.20	0.82	5.45	8.234	6.55	67.666	6.518
CV %	19.35	22.89	26.60	25.35	20.25	22.021	19.036	21.424	21.726

As seeds contain oil, they showed the highest nitrogen (15.80 kg/ha), phosphorus (9.49 kg/ha), and zinc (77.29 mg/kg) uptake ($p=<0.05$), highlighting the importance of nutrient allocation to reproductive parts upon T_5 treatment, which is critical for seed development and quality. Iron accumulation was particularly significant in both leaves and seeds, with values of 676.430 mg/kg and 213.358 mg/kg, respectively (Figure 1), which might be due to the higher biomass of seeds per hectare (Rao and Reddy 2018).

The roots and stems, while not reaching the peak values observed in leaves and seeds, still exhibited substantial nutrient uptakes, particularly in sulphur (5.95kg/ha) in stem, which are vital for nutrient transport and structural integrity (Singh *et al.,* 2024). Overall, the T_4 treatment successfully enhanced nutrient uptake, uptake of macronutrients and micronutrients, and allocation within the safflower (*Carthamus tinctorius L.)* plant, supporting improved growth, seed development, and overall crop quality.

CONCLUSION

The study demonstrates that applying 45 kg/ha of elemental Sulphur combined with foliar spray of micronutrients significantly enhanced nutrient content and uptake in safflower, resulting in improved plant growth and higher seed yields. This treatment proved to be most effective in optimizing nutrient availability and accumulation, thereby promoting overall crop productivity in sulphur-deficient soils. Further research should explore the long-term effects of repeated sulphur applications on soil health and investigate the scalability of this nutrient management strategy across diverse agro-climatic regions for sustainable safflower cultivation.

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