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RESEARCH ARTICLE

Enhancing nanofertilizers' performance for improved yield and quality of cotton

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Abstract

Nanofertilizers have shown promise in enhancing nutrient use efficiency, yield and fiber quality in cotton, however, the performance of foliar applied nanofertilizers still requires improvement. Therefore, a two-year field experiment (2016-17 and 2018-19) was conducted at the Central Institute for Cotton Research, Regional Station, Coimbatore, to evaluate the effects of foliar application of different dosages of commercially available nanofertilizers, with and without surfactant, on cotton growth and yield. The ten treatments included T1-control, T2-recommended dose of fertilizer (RDF), T3-100 % Nualgi without surfactant, T4-200 % Nualgi without surfactant, T5-100 % Nualgi with surfactant, T6-200 % Nualgi with surfactant, T7-100 % Nanomol without surfactant, T8-200 % Nanomol without surfactant, T9-100 % Nanomol with surfactant and T10-200 % Nanomol with surfactant were replicated thrice and laid out in randomized block design (RBD). Nanofertilizers (T3-T10) were foliar sprayed at 45 and 90 days after sowing (DAS), i.e., at both vegetative and flowering stage of cotton (var. Suraj). The results revealed that the foliar application of Nualgi nanofertilizer with surfactant significantly increased nitrate reductase (NR) activity, total chlorophyll content, reducing sugar, total potassium content, the number of opened bolls per plant, boll weight and seed cotton yield. Similarly, foliar spraying of Nanomol nanofertilizer without surfactant significantly enhanced the reducing sugar, total nitrogen (N), number of opened bolls per plant, boll weight and seed cotton yield. On average, a 28 % increase in seed cotton yield was recorded with 100 % Nualgi nanofertilizer with surfactant (15.4 q ha^{-1}) and 100 % of Nanomol nanofertilizer without surfactant (15.4 q ha^{-1}) compared to RDF (12.0 q ha^{-1}). However, fibre quality parameters were not significantly affected by the foliar application of nanofertilizers.

Keywords: foliar spray; nanofertilizers; nutrient concentration; physiological attributes; seed cotton yield; surfactant

Introduction

Cotton (*Gossypium* spp., Malvaceae), commonly referred to as 'White Gold', is one of the world's most important fiber and cash crops, playing a vital role in both the agricultural and textile industries. India holds a unique global position, cultivating four major cotton species: *G. hirsutum, G. arboreum*, *G. herbaceum* and *G. barbadense* and employing 60 million people in cotton-related industries, including cultivation, marketing, processing and exports (1). In 2023-24, India ranked first globally in cotton acreage (12.7 million ha) and production (32.5 million bales) (2). Around 62 % of cotton growing areas are rain-fed, while the remaining 38 % are irrigated. The global demand for cotton is increasing, but India's cotton productivity remains low due to poor soil fertility and inefficient nutrient management practices; therefore, sustainable and effective nutrient management solutions are necessary in the coming years. Fertilizers are among the most crucial inputs determining yield and fiber quality in cotton production. Although somewhat effective, traditional fertilizers often have poor nutrient use efficiency and can harm the environment through runoff, leaching and volatilization. In recent years, nanotechnology has the potential to transform agriculture in the modern era by providing new insights, ideas and tools to increase productivity and reduce poverty (3). The unique qualities of nanotechnology, such as its high surface-to-volume ratio, enhanced chemical reactivity, increased solubility, reduced size (1-100 nm in any one dimension) and exceptional magnetic and optical capabilities, have made nanotechnology-based products ubiquitous worldwide (4, 5). Some products based on nanotechnology, such as nanofertilizers and nanopesticides, are currently on the market, while others are awaiting patent approval. Researchers and the fertilizer industry have been interested in nanofertilizers because of their controlled and targeted delivery mechanism, which increases the nutrient uptake ratio and fertilizer use efficiency without causing any nutrient losses (6). This enables the enhancement of crop productivity by stimulating energy metabolism, protein synthesis, photosynthetic activity, seed germination, seedling growth and enzyme-related functions, among others. Nanofertilizers are considered efficient alternatives to conventional fertilizers, as they improve dissolution rates and nutrient use efficiency due to their smaller size. This allows the particles to easily penetrate root and leaf cuticular cells via soil and foliar applications respectively. Farmers are increasingly interested in nanofertilizers due to their potential benefits over traditional fertilizers; however, they are often unaware of the commercially available nanofertilizers and their efficacy in improving plant health. Nanofertilizer efficiency can be improved by surfactants, i.e., surface wetting agents, which can enhance the effectiveness of commonly applied fertilizers. Surfactants allow nanofertilizers to easily pass through cell walls, stomata and cuticular membranes by increasing contact between the leaf and the solution and decreasing surface tension. Furthermore, while a uniform dose of nanofertilizer is often recommended across crops, cotton's high nutrient responsiveness warrants optimization of application rates. Keeping the above facts, the present study was undertaken to evaluate and enhance the effectiveness of nanofertilizers in improving the yield and fibre quality of cotton.

Materials and Methods

To study the effects of foliar application of different dosages of commercially available nanofertilizers, namely Nualgi and Nanomol, with and without surfactant on cotton growth and yield, field experiments were carried out at Central Institute for Cotton Research, Regional Station, Coimbatore, during 2016-17 and 2018-19 in the same field with test crop cotton (cv. Suraj). The experimental design was laid out in a randomized block design (RBD) with ten treatments and three replications. The soil was clay loam in texture, alkaline in reaction (8.47), non-saline (0.27 ds m^{-1}) with moderate cation exchange capacity (CEC) (21.8 cmol (p^+) kg^{-1} and low organic carbon (4.4 g kg^{-1}) content. Available nitrogen (N) and phosphorus (P) were low (163 and 9.4 kg ha^{-1} respectively) while available potassium (K) was high (655 kg ha^{-1}). Seeds were sown manually in rows 75 cm apart and a plant-to-plant distance of 45 cm. Plot size was 4.5 m in length and 3.75 m in breadth (16.88 m^2). In this experiment, each plot consisted of 5 rows and each row had 10 plants. For all the treatments except for the control (T1), recommended dose of fertilizer (RDF) (60:30:30 kg NPK ha^{-1}) was applied uniformly, where P & K was used as basal (100 %) and N was applied at sowing (50 %), 45 (25 %) and 90 days after sowing (DAS) (25 %). No foliar spray was applied for T2. Commercially available nanofertilizers, such as Nualgi foliar spray from Nualgi Nanobiotech and Nanomol from Alert Biotech were purchased. Nualgi foliar spray contains a balanced mix of essential nutrients including macronutrients phosphate (P_2O_5) and potash (K_2O) fertilizers; secondary nutrients consisting of calcium (Ca), magnesium (Mg) and sulfur (S); micronutrients iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), molybdenum (Mo) and boron (B); and additional nutrients including cobalt (Co) and silica (SiO_2). The particle size of the nanofertilizer ranges from 1 to 100 nm. A Nanomol nanofertilizer contained only micronutrients (Fe, Mn, Zn, Cu, Mo and B) in the form of chelates. Different dosages, viz., 100 (recommended dose as per respective firms) and 200 % (higher dosage) were foliar-sprayed at 45 and 90 DAS i.e., at both the vegetative and flowering stages of the crop (T3-T10). Recommended doses of Nualgi (500 mL 250 L^{-1} of water) and Nanomol (0.75 g L^{-1} of water), as well as higher doses of Nualgi (1000 mL 250 L^{-1} of water) and Nanomol (1.5 g $L^{-1}$of water), were each mixed with a 0.1 % surfactant solution (trade name: Lipstick). Physiological parameters, including total chlorophyll content, reducing sugars and nitrate reductase (NR) activity, were measured at the boll-formation stage (105 DAS - 15 days after the second spray) (7). Yield-related parameters, including the number of opened bolls per plant, boll weight and seed cotton yield, were recorded at the harvest stage. The quality parameters, viz., upper half mean length, uniformity index, fibre strength and micronaire, were analyzed using high-volume instruments (HVI, Statex-Fibrotex model). Total N, P, K, Ca and Mg concentrations were analyzed in whole-plant samples collected at harvest in both years (8).

Statistical analysis

Data were statistically analyzed using standard analysis of variance (ANOVA) and the differences between means of treatments were compared using the least significant difference (LSD) test (9). Statistically significant data are represented by an asterisk for * and ** indicating $p \leq 0.05$ and $p \leq 0.01$ respectively.

Results and Discussion

Physiological parameters

Nitrate reductase a key regulatory enzyme, mediates the conversion of nitrate (NO_3^{2-}) to nitrite (NO_2^-), which is involved in amino acid and protein synthesis (10). Nitrate reductase activity provides the best indication of a plant's N status, which is related to normal growth and development (11). Nitrate reductase activity was significantly increased by foliar application of 100 (22.28 µg NO_2 g^{-1} hr^{-1}) and 200 % (22.30 µg NO_2 g^{-1} hr^{-1}) of Nualgi nanofertilizer with surfactant in comparison with both the dosages without surfactant (22.03 and 21.96 µg NO_2 g^{-1} hr^{-1}) (Table 1). The added surfactants mixed well with the SiO_2-encrusted Nualgi nanofertilizer and were compatible with each other, thereby enhancing the efficiency of the foliar-applied solution. Furthermore, surfactants enhanced the foliar uptake of nutrients by reducing the surface tension between the leaf and solution, facilitating the easy penetration of nutrients through the cuticular membrane, stomata, or cell walls of cotton plants (12, 13).

Table 1. Total chlorophyll content (mg g^{-1}) and nitrate reductase enzyme activity (µg NO_2 $g^{-1}hr^{-1}$) in cotton leaves at the boll formation stage

Treatments	Treatments	Total chlorophyll content (mg g^{-1} tissue)		Nitrate Reductase activity (µg NO_2 g^{-1} hr^{-1})
		2016-17	2018-19	2018-19
T1	Control	0.740	1.098	21.94
T2	NPK (RDF)	0.751	1.172	22.10
T3	100 % Nualgi without surfactant	0.752	1.240	22.03
T4	200 % Nualgi without surfactant	0.757	1.263	21.96
T5	100 % Nualgi with surfactant	0.760	1.333	22.28
T6	200 % Nualgi with surfactant	0.763	1.406	22.30
T7	100 % Nanomol without surfactant	0.754	1.356	21.94
T8	200 % Nanomol without surfactant	0.756	1.338	21.85
T9	100 % Nanomol with surfactant	0.760	1.373	21.86
T10	200 % Nanomol with surfactant	0.759	1.454	21.60
	CD (0.05)	0.014^{NS}	0.181^{*}	0.40^{*}

NS - non significance

But, the lowest activity of NR was observed in Nanomol nanofertilizer with (21.86 and 21.60 µg $NO_2 g^{-1} hr^{-1}$) and without (21.94 and 21.85 µg $NO_2 g^{-1} hr^{-1}$) surfactant foliar application compared to Nualgi nanofertilizer and RDF (22.10 µg $NO_2 g^{-1} hr^{-1}$) and absolute control (21.94 µg $NO_2 g^{-1} hr^{-1}$). Although the surfactant aids in the uptake of nutrients, the main reason for the lowest NR activity is the omission of nutrients that are necessary for the NR synthatase enzyme. Nanomol nanofertilizer contained chelated cationic micronutrients (Zn, Fe, Cu, Mn) along with B and Mo, but lacked macro and micronutrients. The reduced level of NR activity is mainly caused by an insufficient supply of N nutrients, which may be attributable to the limited synthesis of the protein moiety of NR (14).

The physiological attribute of chlorophyll content serves as an index of both photosynthetic potential and plant productivity. Among the two different dosages of Nualgi and Nanomol nanofertilizers, the highest total chlorophyll content was recorded in 200 % (higher dose) of Nualgi with surfactant (0.763 mg g^{-1} fresh tissue for 2016-17 and 1.406 mg g^{-1} fresh tissue for 2018-19) and 200 % of Nanomol with surfactant (0.759 mg g^{-1} fresh tissue for 2016-17 and 1.454 mg g^{-1} fresh tissue for 2018-19) however, it was on par with 100 % (recommended dose) of Nualgi with surfactant (0.760 mg g^{-1} fresh tissue for 2016-17 and 1.333 mg g^{-1} fresh tissue for 2018-19) and 100 % of Nanomol with surfactant (0.760 mg g^{-1}fresh tissue for 2016 -17 and 1.373 mg g^{-1} fresh tissue for 2018-19). The results revealed that an increase in total chlorophyll content was observed under both 100 % and 200 % of Nualgi and Nanomol with surfactant compared to without surfactant (Table 1). The reason might be that foliar spraying of nanofertilizers, along with optimum concentration of surfactant, enhanced the chlorophyll content indirectly by increasing nutrient accumulation in plants. Regarding the different sources of nanofertilizers, viz., Nualgi and Nanomol, the highest total chlorophyll content was registered in both dosages of Nanomol nanofertilizer with (1.373 and 1.454 mg g^{-1} fresh tissue) and without (1.356 and 1.338 mg g^{-1} fresh tissue for 2018-19) surfactant application respectively, as compared to Nualgi nanofertilizer with (1.333 and 1.406 mg g^{-1} fresh tissue) and without (1.240 and 1.263 mg g^{-1} fresh tissue) surfactant application.

Reducing sugar is an important energy source and plays a crucial role in central signaling molecules that regulate processes such as photosynthesis, seed germination, nutrient assimilation, stress response and disease resistance. Application of nanofertilizers through foliar significantly improved the reducing sugar contents in cotton leaves in the range of 10.3 to 13.4 mg/g at boll formation stage as compared to control (Fig. 1). Application of 30 ppm of nanofertilizers increased the nutrient concentration (N, P, Fe, Mn and Zn) in seeds and straw as well as photosynthetic pigments, carotenoids, total carbohydrate, soluble sugars, protein and seed oil as compared to normal plants (15). Among the different types of nanofertilizers, 100 % of Nualgi nanofertilizer with surfactant (12.3 mg g^{-1}) and 100 % of Nanomol without surfactant (13.4 mg g^{-1}) significantly increased the reducing sugar content. This enhancement may be attributed to the optimal nutrient dose provided by nano fertilizer, which improved photosynthetic activity and facilitated the balanced production of reducing sugars (16, 17).

Nutrient concentration

The average of two years of experiments showed that the foliar application of nanofertilizers significantly increased the total N content in the whole plant of cotton, ranging from 1.31 to 1.61 %. Among the two different types of nanofertilizers, total N content was higher in Nanomol nanofertilizers with and without surfactant (1.38 to 1.61 %) than Nualgi nanofertilizer with and without surfactant (1.31 to 1.36 %). Foliar application of nanofertilizer significantly increased the total N content in cotton leaves at the boll formation stage (18). The highest total N content was registered in both 100 and 200 % of Nanomol nanofertilizers with surfactant (1.53 and 1.61 % respectively) as compared to 100 and 200 % of Nualgi nanofertilizer with surfactant (1.36 and 1.33 % respectively). The total N content in cotton was improved due to the interaction effect of foliar application of chelated micronutrient nanofertilizers along with a surfactant (Table 2).

Similarly, a significant increase in total P content was observed in the range of 0.13 to 0.20 % by foliar application of nanofertilizers. The enhanced total P content was observed with Nanomol nanofertilizers containing surfactant at both dosages of 100 % (0.20 %) and 200 % (0.19 %), compared to Nualgi nanofertilizers with and without surfactant. However, 100 % of Nualgi nanofertilizer with surfactant (0.18 %) was the most effective among the Nualgi nanofertilizer treatments in improving P nutrition in cotton.

The total K content was increased by foliar nutrition with nanofertilizers (2.74 to 3.08 %) compared to the control (2.43 %) and RDF (2.73 %). Among the nanofertilizers, total K content was increased in Nualgi nanofertilizer (2.84 to 3.08 %) as compared to Nanomol nanofertilizer (2.74 to 2.89 %), which might be due to the

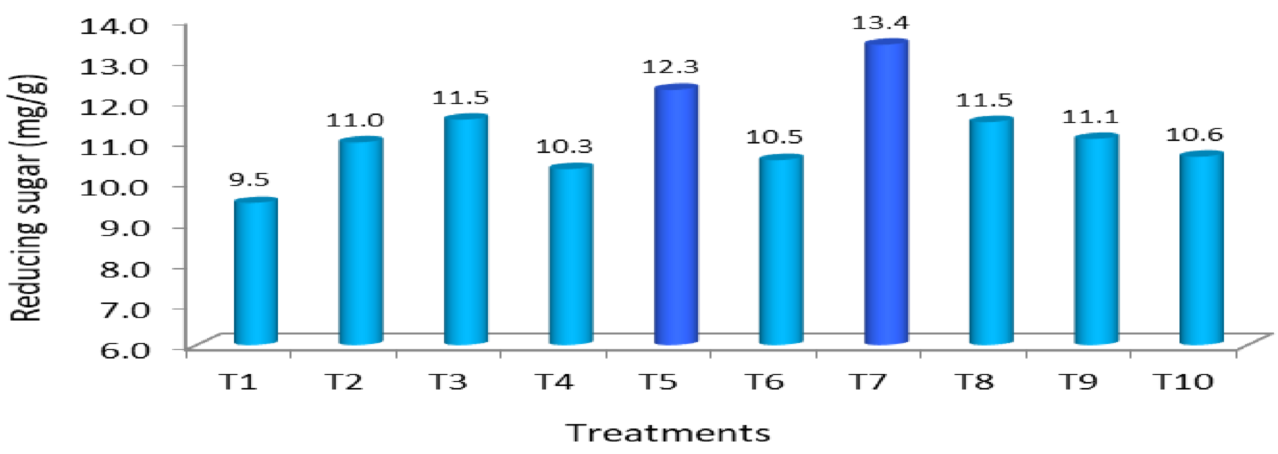

Fig. 1. Average reducing sugar (mg/g) content at the boll development stage of cotton.

Table 2. Nutrient concentrations of cotton (pooled analysis of two years' data)

	Treatments	Total N (%)	Total P (%)	Total K (%)	Total Ca (%)	Total Mg (%)
T1	Control	0.98	0.13	2.43	1.82	0.93
T2	NPK (RDF)	1.11	0.14	2.73	2.05	1.01
T3	100 % Nualgi without surfactant	1.33	0.15	2.97	2.10	1.00
T4	200 % Nualgi without surfactant	1.31	0.15	3.08	1.98	1.12
T5	100 % Nualgi with surfactant	1.36	0.18	2.90	2.22	0.98
T6	200 % Nualgi with surfactant	1.33	0.13	2.84	2.17	0.94
T7	100 % Nanomol without surfactant	1.38	0.17	2.89	2.27	0.88
T8	200 % Nanomol without surfactant	1.43	0.14	2.86	1.97	0.86
T9	100 % Nanomol with surfactant	1.53	0.20	2.88	2.38	1.22
T10	200 % Nanomol with surfactant	1.61	0.19	2.74	2.67	1.02
CD (0.05)	Year	0.12**	0.012**	0.25**	0.19**	NS
	Treatment	0.27**	0.03**	NS	0.43*	NS
	Year x Treatment	0.39*	0.04**	NS	NS	NS

NS - non significance

presence of SiO_2 in Nualgi nanofertilizer. Silica is an important nutrient for the translocation of K from roots to shoots and the assimilation of K in plant tissues, as it activates K-transporting pathways and helps balance the K/Na ratio, thereby enhancing K uptake by plants (19, 20). A positive interaction between Si supplementation and higher K concentration in cotton leaves has been reported (21).

The secondary nutrient, such as the total Ca content of cotton, was significantly increased by foliar application of nanofertilizers, which ranged from 1.97 to 2.67 %. The higher Ca content was noted in Nanomol nanofertilizers with surfactant dosages of 100 % (2.38 %) and 200 % (2.67 %) compared to Nualgi nanofertilizers. Although the total Mg content was not significantly affected by foliar-applied nanofertilizers over the years, an improvement was observed, similar to the total Ca concentration, which increased by 100 % with the use of Nanomol nanofertilizer with surfactant (1.22 %). The increase in macro and secondary nutrient concentrations (except K) resulting from the application of Nanomol nanofertilizer with a surfactant led to excellent absorption of chelated micronutrients by cotton leaves. This efficient nutrient utilization enhanced the production and translocation of carbohydrates from source to sink, resulting in a higher yield. This result was consistent with previous studies (22, 23). In recent years, nanofertilizers have been widely used and have been proven to be more effective than conventional fertilizers in increasing nutrient use efficiency and improving nutrient concentration in plants (24). The performance of foliar-applied nanoform of chelated micronutrients was the best in delivering nutrients in adequate amounts to enhance the nutritional status of cotton plants (18).

Yield parameters

Numbers of opened bolls per plant and boll weight are the most important and reliable characters of seed cotton yield. On average, two years of data showed that the number of opened bolls per plant was higher in foliar application of the recommended dose (100 %) of Nanomol nanofertilizer without surfactant (18.6), followed by the recommended dose (100 %) of Nualgi with (17.0) and without surfactant (16.8) (Fig. 2). The lowest numbers of opened bolls were recorded in Nanomol nanofertilizer with surfactant (15.6 and 15.4) and higher dosage of Nanomol nanofertilizer in both without (16.1) and with (15.4) surfactant. Similarly, the higher dosage (200 %) of Nualgi nanofertilizer showed very poor performance; i.e., 200 % of Nualgi without (14.3) and with (15.6) surfactant reduced the number of opened bolls, but this was on par with the RDF application. In comparison to Nanomol nanofertilizer, the compatibility of Nualgi nanofertilizer with surfactant is highly impressive, as demonstrated by the results at 100 % and 200 % Nualgi with surfactant. Si nutrients increased the boll mass production per plant in cotton (25).

The size and weight of bolls directly influenced the yield of seed cotton. Foliar application of nanofertilizers, viz., Nualgi and Nanomol, significantly increased the boll weight as compared to normal RDF and control (Table 3). On average, two years of data

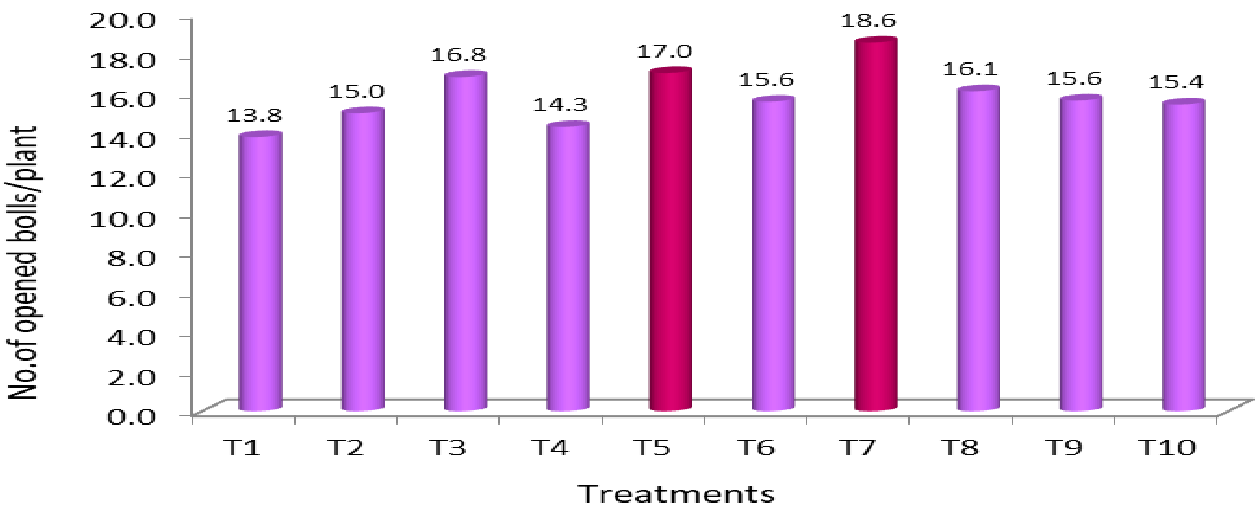

Fig. 2. Average number of opened bolls per plant in cotton.

Table 3. Yield parameters of cotton at the harvest stage

Treatments		Boll weight (g/boll)			Seed cotton yield (kg ha^{-1})		
		2016-17	2018-19	Average	2016-17	2018-19	Average
T1	Control	4.3	4.9	4.6	1034	1209	1122
T2	NPK (RDF)	4.3	5.1	4.7	1043	1349	1196
T3	100 % Nualgi without surfactant	4.4	5.5	5.0	1457	1366	1412
T4	200 % Nualgi without surfactant	4.6	5.2	4.9	1177	1312	1245
T5	100 % Nualgi with surfactant	4.9	5.4	5.2	1409	1662	1535
T6	200 % Nualgi with surfactant	4.7	5.5	5.1	1379	1515	1447
T7	100 % Nanomol without surfactant	4.7	5.4	5.1	1584	1494	1539
T8	200 % Nanomol without surfactant	4.4	5.0	4.7	1198	1470	1334
T9	100 % Nanomol with surfactant	4.8	5.0	4.9	1099	1479	1289
T10	200 % Nanomol with surfactant	4.6	5.3	5.0	1346	1285	1316
	CD (0.05)	NS	0.41*		NS	NS	

NS - non significance

(2016-17 & 2018-19) showed that the increased boll weight was recorded in 100 % Nualgi with surfactant (5.2 g boll^{-1}) and 100 % Nanomol without surfactant (5.1 g boll^{-1}). The lowest boll weight was noted in the normal RDF (4.7 g boll^{-1}) and control (4.6 g boll^{-1}). The two times of foliar application, i.e., 45 and 90 DAS of 100 % of Si-based Nualgi nanofertilizer with surfactant, enhanced the physiological parameters like total chlorophyll content, NR activity and reducing sugar content for producing heavy bolls; simultaneously, the same effect was attributed to 100 % of Nanomol nanofertilizer without surfactant. These findings agreed with another experiment which revealed that nanofertilizers considerably increased the boll weight of cotton (18).

The seed cotton yield was significantly influenced by growth and physiological attributes, as well as yield-related parameters. During the year 2016-17 under winter irrigated conditions, the highest seed cotton yield was registered by foliar application of 100 % of Nanomol without surfactant (1584 kg ha^{-1}) and 100 % of Nualgi with surfactant (1409 kg ha^{-1}). Still, no significant difference was found between the treatments. Similarly, non-significance was found on seed cotton yield during the year 2018-19 under irrigated conditions, where the highest seed cotton yield was produced in the treatment of 100 % of Nanomol without surfactant (1494 kg ha^{-1}) and 100 % Nualgi with surfactant (1662 kg ha^{-1}). This data indicated that the highest seed cotton yield was attributed to the recommended dose (100 %) of both Nualgi and Nanomol nanofertilizers, rather than a higher dose (200 %) of nanofertilizers.

On an average of two years (2016-17 and 2018-19), more than 28 % of increased seed cotton yield was produced by foliar application 100 % Nualgi nanofertilizer with surfactant (15.4 q ha^{-1}) and 100 % of Nanomol nanofertilizer without surfactant (15.4 q ha^{-1}) as compared to RDF (12.0 q ha^{-1}) (Fig. 3). The performance of Nualgi nanofertilizer was remarkably improved by inclusion of surfactant (0.1 %) that means more seed cotton yield was registered in Nualgi nanofertilizer with surfactant (28.3 %) than Nualgi nanofertilizers without surfactant (18.1 %). Nualgi, a patented nanofertilizer based on SiO_2 nanocomposite, increased chlorophyll content, enhanced photosynthate accumulation and translocated photosynthetic assimilates into sinks, thereby substantially increasing seed cotton yield. Foliar application of nano silica with B increased the seed cotton yield by 12.67 % (26). Similarly, seed treatment and foliar application of nano-silica fertilizer significantly increased the total cotton biomass by 10.6 %, economic yield by 19.4 %, seed yield by 14.3 % and lint yield by 18.2 % compared to the control (21). Moreover, surfactant is more compatible with SiO_2-encrusted Nualgi nanofertilizer, which facilitates better nutrient absorption for healthy physiological processes and enhanced seed cotton yield. (12, 13). Conversely, the maximum seed cotton yield was recorded by Nanomol nanofertilizer without surfactant (28.7 %) than Nanomol nanofertilizer with surfactant (7.8 %), which means the added surfactant did not give any beneficial effect to Nanomol nanofertilizer, as to Nualgi nanofertilizer (Fig. 3). Since foliar-applied chelated micronutrients are efficiently absorbed and utilized by the plant system, plant growth and yield parameters were increased progressively (27). The nutrient demand of the crop was immediately satisfied through foliar spraying of micronutrients, which increased nutrient absorption, photosynthetic assimilation

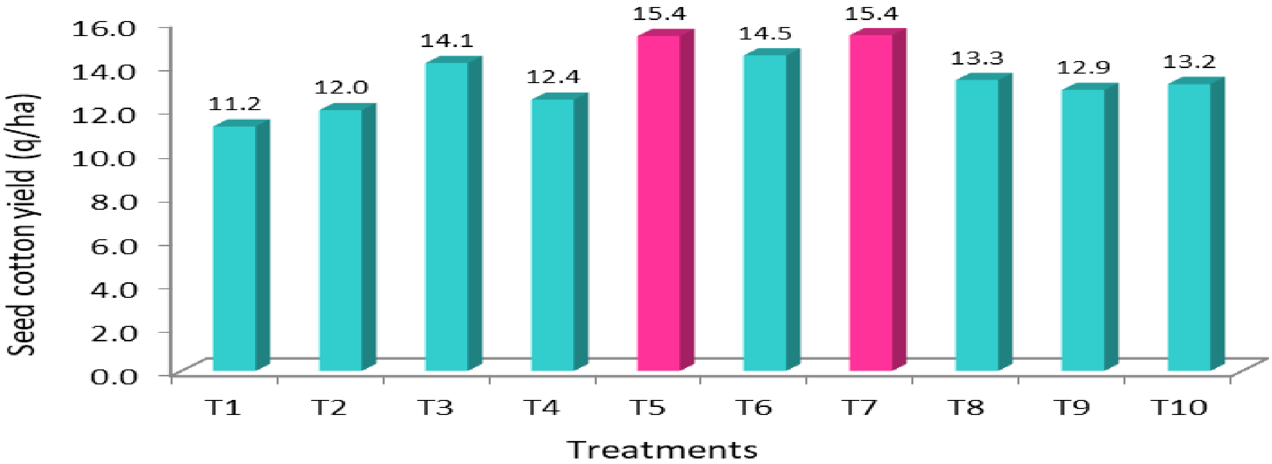

Fig. 3. Seed cotton yield (q/ha) on an average of two years (2016-17 & 2018-19).

Table 4. Fibre quality parameters of cotton

	Treatments	UHML (mm)			Uniformity index (%)			Fibre strength (g tex^{-1})			Micronaire (μ $inch^{-1}$)		
		2016-17	2018-19	Mean	2016-17	2018-19	Mean	2016-17	2018-19	Mean	2016-17	2018-19	Mean
T1	Control	30.8	30.0	30.4	82.6	83.7	83.2	30.1	32.1	31.1	4.4	4.2	4.3
T2	NPK (RDF)	31.0	30.1	30.5	82.6	84.7	83.6	29.8	32.3	31.1	4.4	4.2	4.3
T3	100 % Nualgi without surfactant	32.1	29.3	30.7	82.8	85.7	84.2	30.0	31.1	30.6	4.5	4.4	4.5
T4	200 % Nualgi without surfactant	32.0	30.1	31.1	82.7	85.3	84.0	29.8	31.7	30.8	4.6	4.5	4.5
T5	100 % Nualgi with surfactant	31.1	30.4	30.7	82.8	85.7	84.2	29.9	32.3	31.1	4.3	4.2	4.2
T6	200 % Nualgi with surfactant	31.2	32.1	31.7	82.7	85.0	83.9	30.8	34.2	32.5	4.3	3.7	4.0
T7	100 % Nanomol without surfactant	31.7	28.2	29.9	82.7	84.0	83.4	29.7	32.9	31.3	4.6	4.3	4.5
T8	200 % Nanomol without surfactant	31.9	30.5	31.2	82.8	85.3	84.0	30.6	32.1	31.4	4.2	4.4	4.3
T9	100 % Nanomol with surfactant	31.6	30.0	30.8	82.7	85.7	84.2	30.5	32.0	31.3	4.3	4.6	4.5
T10	200 % Nanomol with surfactant	32.1	31.0	31.6	82.8	85.0	83.9	28.8	32.3	30.5	4.3	4.2	4.3
	CD (0.05)	NS	NS		NS	NS		NS	NS		NS	0.32**	

NS - non significance

and translocation of assimilates from vegetative to reproductive parts of the plant (28).

Fibre quality parameters

During 2016-17 and 2018-19, fibre quality parameters such as upper half mean length (UHML), uniformity ratio, fibre strength and micronaire value were not significantly influenced by the foliar application of nanofertilizers (Table 4); however, micronaire value was affected considerably during the second year of the experiment. On average, UHML was increased at the higher dosage (200 %) of Nualgi nanofertilizer with surfactant (4.0 %) and Nanomol nanofertilizer with surfactant (3.6 %) compared to the recommended dose of NPK fertilizers. Similar to UHML, the fiber strength of cotton was also improved by a higher dosage (200 %) of Nualgi nanofertilizer with surfactant (4.5 %). Improvement in fibre length and fibre strength of cotton due to foliar spraying with micronutrients (Zn, Fe, Cu, Mn, B, Mo) has been reported (29, 30). However, the uniformity index was improved by the recommended dosage (100 %) of Nualgi and Nanomol nanofertilizer with surfactant (0.72 %). Regarding the micronaire content of cotton, both the dosages of Nualgi and Nanomol without surfactant were more effective (4.7 %) in increasing the micronaire value than the generally applied RDFs. The micronaire content was increased by 4.8 % due to foliar spraying of Nualgi (NF 3) nanofertilizer in cotton (18). Although the fibre quality parameters, such as fibre length, fibre strength, uniformity index and micronaire, were slightly improved by foliar application of nanofertilizers with and without surfactant, these fibre quality parameters are mostly cultivar-dependent (31).

Conclusion

Foliar application of nanofertilizers, with or without surfactant and regardless of dosage, improved growth and physiological parameters, enhanced nutrient concentration and increased yield and fibre quality attributes of cotton. Among the two different types of nanofertilizers, the recommended dose of Nualgi nanofertilizer with surfactant significantly increased the physiological and yield parameters of cotton. The addition of surfactant enhanced the efficiency of Nualgi nanofertilizer compared to its use without surfactant. However, the performance of the recommended dose of Nanomol nanofertilizer without surfactant was better in improving the physiological parameters, nutrient concentration, yield and fibre quality parameters of cotton. This research revealed that nanofertilizers are a potential alternative to conventional fertilizers and that the addition of surfactants could enhance their effectiveness.

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Authors' contributions

DK conducted the research trial, made observations, analyzed nutrients, performed data analysis and addressed reviewers' comments. JAS analyzed the physiological parameters, assisted with data analysis and contributed to the write-up and grammar check. SU reviewed and edited the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

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