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RESEARCH PAPER

Assessment of the impact of solid and liquid fertilizer applications on yield and yield components in cotton (*Gossypium hirsutum* L.)

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Abstract

This research aimed to compare the effects of liquid fertilizers on cotton yield and specific yield components relative to traditional solid fertilizers. The study employed 20-20-0, 15-15-15 and Di Ammonium Phosphate- DAP (18-46-0) fertilizers for base fertilization, with solid urea (46%) as top dressing. Liquid fertilizers, including orthophosphate and polyphosphate-based liquid base fertilizers (liquid 20-20-0, liquid 15-15-15 and liquid DAP) were developed and applied. Urea ammonium nitrate (UAN-32% N) was used for all top dressing in treatments. The experiments were conducted at the Eastern Mediterranean Agricultural Research Institute in Doğankent, following a randomized block trial design with three replications. Three separate field trials were established, each corresponding to a different compound fertilizer: 20-20-0, 15-15-15 and DAP. Within each trial, five treatments were applied, using the cotton variety "Karizma" consistently. The results indicated that liquid fertilizers containing phosphorus, particularly in the form of polyphosphate, yielded higher values for the examined properties of cotton cultivation when used for base fertilization. Although statistically insignificant, compared to conventional fertilizer applications (solid 20-20 + Urea, solid 15-15-15 + Urea, solid DAP + Urea), the use of liquid fertilizers with polyphosphate (liquid 20-20 + UAN, liquid 15-15-15 + UAN, liquid DAP + UAN) led to yield increases of 16.5%, 25.1% and 9.9%, respectively. Additionally, in the trials conducted, liquid UAN fertilizer proved to be more effective in enhancing cotton yields than solid urea fertilizer when used for top dressing.

Introduction

Agricultural production, effective land use and increased yield per unit area are of strategic importance for nations worldwide. These factors play a crucial role in ensuring food security, shelter, clothing, trade, and economic stability. Enhancing agricultural production, promoting sustainability, and implementing sound agricultural policies are essential for regional and national development. Therefore, it is necessary to effectively plan plant nutrition management strategies, adopt modern agricultural techniques, align crop patterns with regional and national needs, and address the goals of breeding programs in agricultural products.

Fertilizers play a significant role in increasing crop yield and quality. However, nutrients applied through solid chemical fertilizers are often susceptible to losses, which can vary depending on soil, plant, and fertilizer

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characteristics, as well as the method, timing, and quantity of application. Moreover, the nutrient uptake efficiency by plants is generally low, and influenced by plant specific traits. The rate at which plants utilize nutrients and their concentrations within the plant vary according to species and genus, growth stage and age. Therefore, while fertilization increases the levels of one or more nutrients in the soil, it is essential to maintain a balanced nutrient profile (Erdal, 2021).

The indiscriminate use of fertilizers can lead to nitrogen (N) leaching or lost as gas, while nutrients like phosphorus and potassium can transform into forms that are not accessible to plants (Gyaneshwar et al., 2002, Barlog and Grzebisz, 2004). Some studies have reported that up to 50% of the applied N is lost from the soil (Eickhout et al., 2006), and as much as 90% of phosphorus remain unavailable for plant uptake (Gyaneshwar et al., 2002, Korkmaz et al., 2009). The economic value of N that becomes unavailable amounts to approximately 17.7 billion dollars annually (Brentrup and Palliere, 2010, Karaşahin, 2014). Nitrogen loss from the soil/plant system not only reduces soil fertility and plant yields but also have detrimental environmental consequences. Ammonia emissions into the atmosphere contribute to acid rain, nitrate leaching into rivers and lakes leads to eutrophication, and nitrate contamination of drinking water supplies poses significant health risks. Furthermore, nitrous oxide emissions are a major contributor to ozone depletion and climate change (Cameron et al., 2013). Producing more food with less pollution is a grand challenge, which is crucial for global sustainable development goals (Gerten et al., 2020; van Dijk et al., 2021).

Nitrogen (N) is the main element in crop production. As one of the main building blocks, nitrogen is of special importance in plants because it is an integral part of the proteins from which protoplasm, cells and plant tissues are formed (Malou et al., 2006). The amount of N applied to the soil should be based on the chemical and microbiological characteristics of the soil. In addition, to prevent unused amounts of N by plants from being transported to deeper layers of the soil and causing groundwater eutrophication due to an excessive imbalance of this nutrient, air conditions should be taken into account (Hoffmann and Kluge-Severin, 2011). Improving nitrogen use efficiency can be achieved by using the right combination of nutrients, fertilizing at the right time and avoiding nutrient loss (Yadav et al., 2017). Nitrogen is a highly mobile element and can be lost in various ways. Losses are usually volatile in the air but can also occur through rainfall and groundwater leaching into deeper layers of the soil. Both situations cause economic losses but also lead to environmental problems. Nitrogen losses are influenced by the form of nitrogen (nitrate, ammonium, or urea) and soil properties (pH, texture, temperature, moisture, cation exchange ability, and organic matter) and fertilizer management (time and dosage) (Stevanato et al., 2019; Melino and Tester, 2022). Advanced agronomic management with contemporary technology and environmentally friendly practices should be adopted to achieve the optimum utilization of N fertilizer (Wang et al., 2021). While the global average N uptake efficiency varies depending on production practices and crop varieties, it is generally around 50% (İbrikçi et al., 2012). Similarly, phosphorus uptake efficiency in plants is also low, due to the rapid fixation of phosphorus in the soil, which has a low diffusion coefficient and poor mobility, hindering plant utilization of the remaining phosphorus once the portion in the root zone is depleted (Clarkson, 1981; Bertrand et al., 2006; Lynch, 2007; Balemi and Negisho, 2012). In alkaline or calcareous soils, phosphorus can precipitate into insoluble forms due to the reaction with calcium, aluminum oxides, and iron compounds at subsurface horizons (Bertrand et al., 1999; Alam and Ladha, 2004; Bertrand et al., 2006). Especially pH levels above 7.0, phosphorus tends to combine with cations such as calcium to form insoluble salts (Zhou et al., 2001). Studies using chemical phosphorus fertilizers have reported plant phosphorus uptake efficiency ranging between 10% and 30% (Holloway et al., 2001; Lombi et al., 2004; McBeath et al., 2007; Kusi et al., 2021; Zhao et al., 2021). The processes affecting P fixation in soils are complex and depend on factors such as soil mineralogy, pH, climate, and the form of phosphorus fertilizer added to the soil (Lombi et al., 2005; Degryse et al., 2013; Doydora et al., 2017).

The nutrient losses associated with solid chemical fertilizers and their low nutrient uptake efficiency due to plant characteristics are significant concerns. Furthermore, solid chemical fertilizers can negatively impact seed germination and plant development, primarily due to ammonia toxicity or salt effects. Additionally, the production of these fertilizers often contributes to environmental pollution. To address these issues and enhance fertilizer efficiency, the use of liquid fertilizers-which have significantly lower production costs- has become increasingly common in some countries, particularly developed nations. Liquid fertilizers are being adopted to eliminate the negative effects of solid chemical fertilizers in crop production. Research has shown that liquid phosphorus fertilizers not only improve yield but also enhance phosphorus utilization efficiency (Lombi et al., 2004; McBeath et al., 2005; Bertrand et al., 2006; Montalvo et al., 2015; Erenoğlu and Dündar, 2020).

In our country, solid chemical fertilizers are widely used in cotton farming. In this research, liquid base fertilizers containing orthophosphate and polyphosphate, formulated to match the composition of their solid counterparts, were developed, and applied. The study aimed to investigate the impacts of these novel liquid fertilizers on cotton yield and various yield parameters.

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Material and Methods

Location and Experiments

This study was conducted during the cotton production season on the lands of Eastern Mediterranean Agricultural Research Institute in Adana province, Türkiye. The soil of the experimental field was characterized as clay loam, slightly alkaline, non-saline, highly calcareous and low in organic matter. While zinc, iron, copper, and potassium concentrations were adequate, manganese and phosphorus levels were deficient in the experimental soil (Table 1). Soil samples were collected from a depth of 0-30 cm to determine the concentrations of inorganic N (NO_3+NH_4–N) and phosphorus. The average inorganic N and phosphorus contents in the experimental field were 30.7 mg kg^{-1} and 4.3 mg kg^{-1}, respectively. Based on soil nutrient balance and the requirement of cotton plants, a total of 60 kg P_2O_5 ha^{-1} and 80 kg N ha^{-1} were applied at planting.

Table 1. Soil properties of the experimental site

Saturation	pH	Salt	Lime	O. M.	K_2O	NO_3+NH_4-N	P_2O_5	Zn	Fe	Cu	Mn
(%)	(1:2.5)	(%)	(%)	(%)	(kg da^{-1})	(mg kg^{-1})	(mg kg^{-1})		(mg kg^{-1})		
52.80	7.65	0.46	18.11	1.58	84.06	30.7	4.3	0.73	5.70	1.12	4.90

In this study, commonly used chemical solid fertilizers in cotton agriculture-20-20-0, 15-15-15 and DAP (18-46-0) compound fertilizers, were applied at planting as fertilizer sources. The solid base fertilizers are orthophosphate. For the liquid fertilizers, liquid compound base fertilizers containing the same N-P_2O_5-K_2O ratios as solid fertilizers were developed and applied, utilizing two different forms of phosphorus: orthophosphate and polyphosphate. GÜBRETAŞ developed and provided liquid orthophosphate 20-20-0, liquid orthophosphate 15-15-15, liquid orthophosphate DAP, as well as liquid polyphosphate 20-20-0, liquid polyphosphate 15-15-15 and liquid polyphosphate DAP fertilizers. Solid urea (46% N) and liquid fertilizer urea ammonium nitrate (UAN-32 % N) were used for top dressing. Three separate trials were conducted based on the fertilizer source. Fertilizer applications during sowing and hoeing (50th day) were adjusted according to the inorganic N (NO_3-N) and phosphorus levels in the experimental site, as shown in Table 2. No fertilizers were applied to the control group. The cotton variety "Karizma" was used as plant material in this study.

The field experiments were designed with 4 rows (2.8 m wide) and a planting density of 70 cm x 12 cm, using a randomized block design with 3 replications.

Table 2. Experimental treatments and amounts of nutrients applied in the experiment

Treatments	Sowing (kg ha^{-1})	50th day (kg N ha^{-1})
20-20+0 Fertilizer Trial		
1. Control	------	-------
2. Solid 20-20-0	60 N-60 P_2O_5	20 N (Solid Urea)
3. Solid 20-20-0	60 N-60 P_2O_5	20 N (Liquid UAN)
4. Liquid 20-20-0 (orthophosphate)	60 N-60 P_2O_5	20 N (Liquid UAN)
5. Liquid 20-20-0 (polyphosphate)	60 N-60 P_2O_5	20 N (Liquid UAN)
15-15-15 Fertilizer Trial		
1. Control	------	-------
2. Solid 15-15-15	60 N-60 P_2O_5-60 K_2O	20 N (Solid Urea)
3. Solid 15-15-15	60 N-60 P_2O_5-60 K_2O	20 N (Liquid UAN)
4. Liquid 15-15-15 orthophosphate)	60 N-60 P_2O_5-60 K_2O	20 N (Liquid UAN)
5. Liquid 15-15-15 (polyphosphate)	60 N-60 P_2O_5-60 K_2O	20 N (Liquid UAN)
DAP Fertilizer Trial		
1. Control	------	-------
2. Solid DAP	23 N-60 P_2O_5	57 N (Solid Urea)
3. Solid DAP	23 N-60 P_2O_5	57 N (Liquid UAN)
4. Liquid DAP (orthophosphate)	23 N-60 P_2O_5	57 N (Liquid UAN)
5. Liquid DAP (polyphosphate)	23 N-60 P_2O_5	57 N (Liquid UAN)

Each plot is 20 m long (56 m^2), with a 1 m distance between plots and 2 m between blocks. Solid fertilizers were applied in bands using a seeder at the time of sowing. For top-dressing with N, urea was manually applied to the soil surface before hoeing and then incorporated into the soil through hoeing.

In liquid fertilizer applications, a combined sowing machine (Figure 1) capable of applying liquid compound fertilizer in bands alongside the seed during sowing was used. For top fertilization, specialized hoeing machines designed for industrial crops such as sugar beet, cotton, corn, and sunflower were used (Figure 2). These machines can apply liquid fertilizer 7.5 cm from the plant rows and at a depth of 12-15 cm. The dosage of liquid fertilizers for each plot was precisely controlled by an electronically controlled dosing unit within the machines. Before each application, the regulator pressure was adjusted, filters were checked, nozzle flow rates were controlled, and the GPS system and tractor feed speed were calibrated.

In the trials, the necessary maintenance procedures and cultural practices were conducted in accordance with standard cotton cultivation on protocols. Observations and measurements were taken before and after harvest to ensure accurate results. To minimize edge effect, one row from the outermost edge of each plot and 1 meter from the beginning of each plot were excluded from the harvest. The cotton plants in the middle 2 rows were then hand-harvested.

When the plants reached the 4-leaf stage (about 10 cm tall), a light thinning was performed, spacing the plants 5-6 cm apart. The first thinning coincided with the first hoeing and the second, more thoroughly thinning occurred during the second hoeing. After planting, weeds were controlled mechanically with a hand hoe and crowbar to eliminate them effectively.

The water requirement of cotton plants ranges from 400 to 600 mm. Given that the total rainfall during cotton growing season is generally insufficient in cotton growing regions, irrigation is necessary to ensure optimal plant development. In this study, drip irrigation was used, with watering conducted at 7-day intervals from the onset of cotton flowering after the second top dressing until the last week of August, when 5-10% of the plant bolls had opened.

To protect against cotton diseases and pests, six chemical sprays were applied through the growing season. The first 2 sprays targeted early pests, such as aphids and fleas, common in the region. Following flowering, 4 additional sprays were applied to control green bollworm and red spider mites. Finally, about 15 days before harvest, defoliating and boll-opening chemicals were applied.

Figure 1. Seeder applying liquid fertilizer to the soil

Figure 2. Machine applying both hoe and liquid fertilizer

Characteristics studied in the Cotton Plants

In the experiments conducted as part of this research, the effects of various treatments were assessed on several key parameters: the number of bolls per plant^{-1}, ginning out-turn percentage, boll mass weight (g), 100 seed weight (g) and cotton yield (kg ha^{-1}).

Soil and plant analysis

Soil texture was determined using the hydrometer method as described by Bouyoucos (1951). Soil pH was measured following the method outlined by Jackson (1959), total carbonates were determined using the Scheibler calcimeter (Kacar, 2016). Organic matter content (%) was assessed using the Walkey-Black method (Jackson, 1959), and soil salinity was determined by Wheatstone bridge method (U. S. Salinity Laboratory Staff, 1954) through the preparation of a saturation paste. Inorganic N (NH_4+NO_3-N) was measured according to Bremner (1965), and available P concentration was determined in accordance with Olsen et al. (1954). Soil K concentration was measured following Carson (1980), available concentrations of Zn, Fe, Mn, and Cu were determined according to the method by Lindsay and Norvel (1978).

During the peak tassel emergence (flowering) period of the cotton plant, leaf samples were randomly collected from at least 8-10 plants in each plot, which had just reached maturity. These samples were analyzed to determine the N, P and K contents. Nitrogen content in the plant samples was determined using the Dumas Combustion Method (AACC 2004). For K and P analysis, 0.3 g of dried plant samples were digested in a closed-system microwave device (Cem Marsxpress) using 5 ml of 65% HNO_3 and 2 ml of 35% H_2O_2. The final volumes were adjusted to 25 ml with ultra-deionized water, and the solution was filtered through blue banded filter paper. The concentrations P and K in the filtrates were then determined using ICP-AES (Varian, Vista).

Statistical Analysis

All data were analyzed using the JMP statistical software package developed by SAS (SAS Institute, Cary, North Carolina, USA). Analysis of variance (ANOVA) was conducted to examine the differences between the treatments. Following the ANOVA, post-hoc comparisons were conducted to identify statistically significant differences among the means. The Tukey Honesty Significant Difference (HSD) test was employed to perform these multiple comparisons, ensuring a rigorous evaluation of the differences between treatment groups. Statistical significance was assessed at two levels: a threshold of $P<0.05$ (*) indicating moderate significance, and a more stringent threshold of $P<0.01$ (**) indicating strong significance.

Results and Discussion

In this study, the effects of solid and liquid fertilizer applications on cotton plant growth and yield were evaluated and the results presented below.

20-20-0 Compound Fertilizer Trial

In the 20-20-0 compound fertilizer trial, both solid 20-20-0 and liquid 20-20-0 fertilizers- produced using two different forms of phosphorus (orthophosphate and polyphosphate) but containing the same nutrient composition- were used, reflecting common practices in cotton cultivation. The effects of these treatments on cotton yield were found to be statistically insignificant (Figure 3). The lowest yield (3030.08 kgha^{-1}) was recorded in the control treatment, followed by the conventional fertilizer treatment (solid 20-20-0 + Urea) with a yield of 3820.30 kg ha^{-1}. The application of liquid UAN (solid 20-20-0 + UAN) as a top dressing, in comparison to solid urea fertilizer, resulted in a 9.5% yield decrease (Figure 3). Furthermore, the application of orthophosphate and polyphosphate liquid 20-20-0 + UAN, developed as an alternative to solid 20-20-0 fertilizer, resulted in yield increases of 9% and 16.5%, respectively, compared to the conventional fertilizer treatment (Figure 3). Among the treatments, the highest yield was achieved with the liquid 20-20-0 + UAN containing phosphorus in the form of polyphosphate, surpassing the conventional fertilizer application (solid 20-20-0 + Urea) (Figure 3).

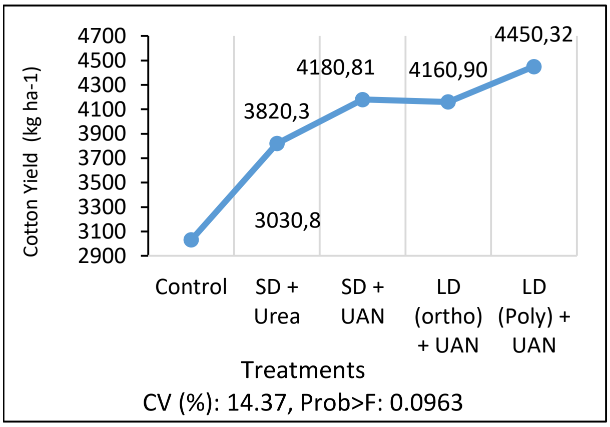

Figure 3. Cotton yield trends across different fertilizer treatments. The treatments are abbreviated on the X-axis as follows: Control (Control), SD+Urea (Solid 20-20-0 + Urea), SD+UAN (Solid 20-20-0 + UAN), LD (Ortho)+UAN (Liquid 20-20-0 with Orthophosphate + UAN), and LD (Poly)+UAN (Liquid 20-20-0 with Polyphosphate + UAN).

Table 3. Effects of Liquid and Solid 20-20-0 Fertilizer Applications on Cotton Yield and Key Yield Parameters

Treatments	Number of bolls (number per plant)	Ginning out-turn (%)	Boll mass weight (g)	100 seed weight (g)
Control	12.60	42.85	4.30	88.33
Solid 20-20-0 + Urea	13.17	41.53	4.54	91.67
Solid 20-20-0 + UAN	15.67	41.23	4.69	91.92
Liquid 20-20-0 (orthophosphate) +UAN	13.07	42.41	4.47	88.17
Liquid 20-20-0 (Polyphosphate) + UAN	14.40	42.65	4.33	86.25
CV (%)	24.05	2.83	8.08	3.72
Prob>F	0.7872	0.4519	0.6919	0.2569

The number of cotton bolls among the treatments was not significantly different. However, all treatments showed an increase compared to the control. Specifically, the number of bolls increased by 24% with solid 20- 20-0 + UAN treatment, by 3.7% with liquid 20-20-0 + UAN treatment, and by 14.3% with liquid 20-20-0 (Polyphosphate) + UAN (Table 3). Similarly, no significant differences were observed among the treatments for cotton ginning yield or boll weight (Table 3). The boll weight ranged from 4.30 to 4.69 g across the different treatments (Table 3). Regarding the 100-seed weight, although no statistical differences were detected among the treatments, there were increases compared to the control. The 100-seed weight ranged from 88.33 to 91.92 g (Table 3). Overall, when evaluating all the traits collectively, the liquid 20-20-0 + UAN application containing phosphorus in polyphosphate form demonstrated an increase in yield, suggesting its potential effectiveness in enhancing cotton production.

15-15-15 Compound Fertilizer Trial

In the 15-15-15 compound fertilizer trial, where both solid and liquid forms with the same content were evaluated, the effects of the treatments on cotton yield were not statistically significant (Figure 4). The control treatment yielded the lowest cotton yield at 2830.27 kg ha^{-1}, while the highest yield of 4130.57 kg ha^{-1} was achieved with the polyphosphate liquid 15-15-15 + UAN treatment (Figure 4). Compared to the conventional fertilizer application (solid 15-15-15 + Urea), the application of liquid UAN (solid 15-15-15 + UAN) for topdressing resulted in an 18.9% increase in cotton yield. Additionally, the liquid orthophosphate and polyphosphate 15-15-15 + UAN and applications led to yield increases of 22.2% and 25.1%, respectively, compared to the conventional fertilizer treatment (Figure 4).

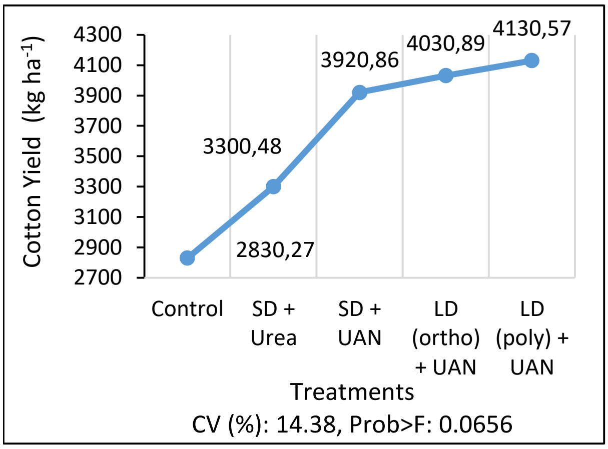

Figure 4. Cotton yield trends across different fertilizer treatments. The treatments are abbreviated on the X-axis as follows: Control (Control), SD+Urea (Solid 15-15-15 + Urea), SD+UAN (Solid 15-15-15 + UAN), LD (Ortho)+UAN (Liquid 15-15-15 with Orthophosphate + UAN), and LD (Poly)+UAN (Liquid 15-15-15 with Polyphosphate + UAN).

Table 4. Effects of Liquid and Solid 15-15-15 Fertilizer Applications on Cotton Yield and Yield Parameters

Treatments	Number of bolls (number per plant)	Ginning out-turn (%)	Boll mass weight (g)	100 seed weight (g)
Control	14.10	43.17	4.11	85.08
Solid 15-15-15 + Urea	14.13	42.63	4.43	85.17
Solid 15-15-15 + UAN	17.27	42.64	4.59	86.92
Liquid 15-15-15 (orthophosphate)+UAN	14.93	41.57	4.51	88.00
Liquid 15-15-15 (Polyphosphate)+UAN	16.33	41.79	4.35	84.83
CV (%)	16.15	1.64	6.43	1.88
Prob>F	0.4796	0.0986	0.3463	0.1570

The effect of liquid and solid 15-15-15 compound fertilizer applications on the number of cotton bolls per plant was not found to be statistically significant. However, all treatments showed an increase in ball numbers compared to the control. In the control treatment, the number of bolls per plant was 14, which increased by 22.4% with the solid 15-15-15 + UAN application, 5.9% with the liquid 15-15-15 + UAN application containing orthophosphate and 15.8% with the liquid 15-15-15 + UAN containing P in polyphosphate form (Table 4). Additionally, compared to the conventional fertilizer application (solid 15-15-15 + urea), the number of bolls per plant increased by 15.6% with the application of liquid 15-15-15 + UAN containing P in polyphosphate form (Table 4). No statistical differences were observed among the treatments in terms of cotton ginning yield or boll weight (Table 4). Boll weight varied between 4.11 and 4.59 g, with the highest values recorded from liquid fertilizer treatments (Table 4). Similarly, no statistical differences were found between the treatments in terms of the 100-seed weight in the liquid and solid 15-15-15 compound fertilizer trials.

DAP (18-46-0) Compound Fertilizer Trial

The liquid fertilizer applications demonstrated more positive effects in both base fertilization and top fertilization compared to traditional solid fertilizer applications. In the solid and liquid forms of DAP fertilizer trials, the treatments' effect on cotton yields were not found to be statistically significant (Figure 5). However, the lowest cotton yield (3220.06 kg ha^{-1}) was recorded in the control treatment, followed by the conventional fertilizer application (solid DAP + Urea), with a yield of 3740.29 kg ha^{-1}. The highest cotton yield (4110.43 kg ha^{-1}) was obtained from liquid DAP + UAN application containing phosphorus in the form of polyphosphate (Figure 5). Compared to the conventional fertilizer application (solid DAP + Urea), the solid DAP + UAN treatment resulted in a 9.2% yield increase, while the liquid DAP + UAN application with orthophosphate led to an 8.4% increase. The liquid DAP + UAN application containing phosphorus in polyphosphate form provided the highest increase (9.9%) in cotton yield (Figure 5).

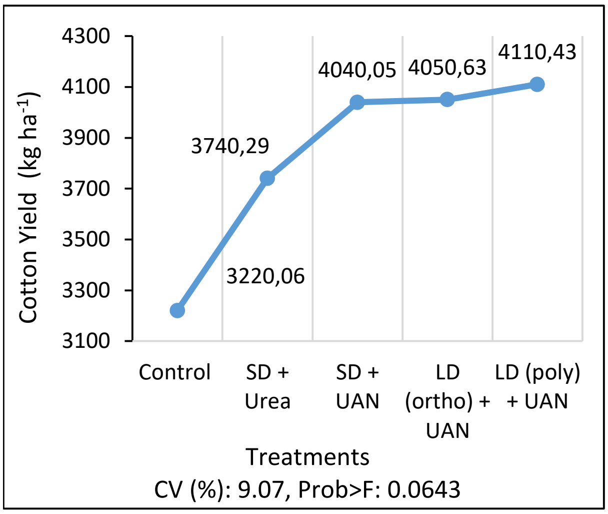

Figure 5. Cotton yield trends across different fertilizer treatments. The treatments are abbreviated on the X-axis as follows: Control (Control), SD+Urea (Solid DAP + Urea), SD+UAN (Solid DAP + UAN), LD (Ortho)+UAN (Liquid DAP with Orthophosphate + UAN), and LD (Poly)+UAN (Liquid DAP with Polyphosphate + UAN)

Table 5. Effects of Liquid and Solid DAP Fertilizer Applications on Cotton Yield and Key Yield Parameters

Treatments	Number of bolls (number per plant)	Ginning out-turn (%)	Boll mass weight (g)	100-seed weight (g)
Control	14.17 b	42.72	4.41	84.75
Solid DAP + Urea	16.67 ab	42.14	4.63	77.58
Solid DAP + UAN	22.33 a	41.29	4.78	73.92
Liquid DAP (orthophosphate) +UAN	16.03 ab	42.31	4.27	74.67
Liquid DAP (Polyphosphate) + UAN	17.13 ab	41.88	4.82	75.25
CV (%)	14.80	2.08	8.14	7.21
Prob>F	0.0386*	0.4171	0.3894	0.2077

The effect of liquid and solid DAP compound fertilizer applications on the number of bolls per cotton plant was found to be statistically significant ($p<0.01$). The lowest number of bolls per plant (14 bolls) was recorded in the control treatment. The other treatments did not show statistically significant differences from each other in terms of boll numbers per plant (Table 5). Specifically, compared to control, the number of bolls per plant increased by 17.6% with conventional fertilizer application (solid DAP + Urea), by 57.6% with the solid DAP + UAN application, by 13.1% with the liquid DAP + UAN application containing orthophosphate, and by 20.9% with the liquid DAP + UAN application containing P in polyphosphate (Table 5). No significant differences were observed among the treatments for cotton ginning yield and boll weight (Table 5). Boll weight ranged from 4.11 to 4.82 g with the highest values recorded in the liquid DAP + UAN treatment containing P in polyphosphate form (Table 5). Similarly, no statistical differences were found among the treatments for the 100-seed weight in the liquid and solid DAP compound fertilizer trials.

Effect of Fertilizers on Macronutrient Uptake in Cotton

Leaf sample analysis revealed significant increases in macronutrient concentrations in the leaves when treated with both solid and liquid fertilizers, compared to the control treatments (Table 6).

In all trials, the macronutrient contents of the plant leaves were within the adequacy limits for cotton reported by Jones et al. (1991) (Table 6). The nitrogen content was 2.62% in the control of 20-20 fertilizer trial, 2.59% in the control of 15-15-15 fertilizer trial, and 2.91% in the control of DAP fertilizer trial. These values, initially indicating a deficiency (<3%), were increased to sufficient levels (>3%) with the application of fertilizers. The increases in nitrogen content were more pronounced in the treatments with UAN compared to those with urea (Table 6). These results suggest that that the developed liquid base fertilizers effectively provided nutrition to the cotton plants.

Table 6. Effects of Fertilizer Applications on Macronutrient (N, P, K) Concentrations of Cotton Leaves.

Treatment	N	P	K
		(%)	
20-20-0 Fertilizer Trial			
Control	2.62	0.40	1.33
Solid 20-20-0 + Urea	4.11	0.45	1.81
Solid 20-20-0 + UAN	4.69	0.41	1.68
Liquid 20-20-0 (orthophosphate) + UAN	4.18	0.48	1.56
Liquid 20-20-0 (polyphosphate)+ UAN	4.52	0.44	1.72
15-15-15 Fertilizer Trial			
Control	2.59	0.38	1.59
Solid 15-15-15 + Urea	2.86	0.44	1.69
Solid 15-15-15 + UAN	3.88	0.46	1.68
Liquid 15-15-15 (orthophosphate) + UAN	3.33	0.46	1.77
Liquid 15-15-15 (polyphosphate)+ UAN	3.37	0.46	1.83
DAP Fertilizer Trial			
Control	2.91	0.44	1.53
Solid DAP + Urea	3.17	0.48	1.59
Solid DAP + UAN	3.59	0.48	1.87
Liquid DAP (orthophosphate) + UAN	3.31	0.45	1.65
Liquid DAP (polyphosphate)+ UAN	3.68	0.47	1.70
Threshold Limits for Sufficiency (Jones et al. 1991)	3.00-4.30	0.25-0.45	0.90-2.00

Discussion

Liquid base fertilizers containing phosphorus in the form of orthophosphate and polyphosphate-matching the nutrient content of traditional solid chemical fertilizers were evaluated as alternatives to solid chemical fertilizers. For top dressing, the study compared the use of solid urea, which is traditionally used in cotton cultivation, and liquid UAN fertilizers, which represent a potential alternative. While the treatments did not yield statistically significant differences in cotton yields across the 20-20-0, 15-15-15, and DAP trials, increases in yield were observed in all three trials when compared to both control and conventional solid fertilizer applications.

In the 20-20-0 fertilizer trial, the application of orthophosphate and polyphosphate liquid 20-20-0 + UAN resulted in cotton yield increases of 9% and 16.5%, respectively, compared to the conventional solid 20-20-0 + urea application. Furthermore, using liquid UAN for top dressing, as opposed to solid urea fertilizer led to a 9.5% increase in cotton yield. In the 15-15-15 fertilizer trial, both the orthophosphate liquid 15-15-15 + UAN and polyphosphate liquid 15-15-15 + UAN applications increased cotton yield by 22.2% and 25.1%, respectively, compared to the conventional solid 15-15-15 + urea application. The application of liquid UAN in top dressing, compared to the conventional solid 15-15-15 + urea fertilizer, resulted in an 18.9% increase in cotton yield. In the DAP fertilizer trial, the solid DAP + UAN application resulted in a 9.2% increase, liquid DAP + UAN application with orthophosphate increased yield by 8.4%, and the liquid DAP + UAN (polyphosphate) application provided a 9.9% increase compared to the conventional solid DAP + Urea application. The effects of liquid fertilizer applications on cotton cultivation were found to be more favorable than those of traditional solid fertilizer applications in both base fertilization and top fertilization. This aligns with previous research, where liquid fertilizers have been reported to increase plant yields more effectively than solid fertilizers (McBeath et al., 2005 and 2007; Wang and Chu, 2015; Akhtar et al., 2016; Erenoğlu and Dündar, 2020; Kusi et al., 2021). The positive effects on yield and yield parameters observed with liquid phosphorus fertilizers are likely due to their higher phosphorus uptake efficiency compared to traditional solid phosphorus fertilizers (Holloway et al., 2001; Bertrand et al., 2006; 2012; Erenoğlu and Dündar, 2020; Zhao et al., 2021; Kusi et al., 2021). Lombi et al. (2005) demonstrated, through x-ray, spectroscopy, and laboratory-based chemical analysis, that phosphorus supplied in liquid form improved phosphorus use efficiency in Australian soils compared to conventional granular products. Similarly, Hashmi et al. (2017) reported phosphorus uptake efficiency increased by 17% when applied as a liquid fertilizer, compared to solid fertilizer application. Previous studies have suggested that this increased efficiency with liquid phosphorus fertilizers may be due to reduced phosphorus fixation in the soil, as well as enhanced mobility and diffusion (Clarkson, 1981; Lombi et al., 2004). The slow diffusion of phosphorus from solid fertilizers, particularly from granular forms, creates a high concentration in the narrow zone, which facilitates precipitation as calcium-phosphate compounds, thus reducing availability (Bertrand et al., 2006). For instance, in a study conducted by Kulluk

(2022) on calcareous soil, the effects of orthophosphate solid fertilizer (solid 10-25-20, 8% S, 1% Zn + Urea) and liquid fertilizers in orthophosphate and polyphosphate forms (liquid orthophosphate 10-25-20, 8% S, 1% Zn + UAN and liquid polyphosphate 10-25-20, 8% S, 1% Zn + UAN) were examined in base fertilization in sugar beet plants. The highest yield and quality values were obtained from the application of liquid fertilizer containing phosphorus in polyphosphate form + UAN.

The effect of the application of liquid UAN in top dressing was more effective on traits examined in cotton compared to the traditionally used urea fertilizer. This finding is consistent with other studies (Cai et al., 2002; Schelegel et al., 2003; Rochette et al., 2009), where liquid UAN applications in top dressing were shown to improve yields, positively by reducing N losses and increasing N uptake efficiency through subsurface injection of UAN. Schelegel et al. (2003) reported that subsurface injection of UAN in wheat resulted in higher N uptake efficiency compared to surface application, leading to an average yield increase of 8%. It is well known that N losses occur with urea fertilizers, depending on the application method. Rochette et al. (2009) reported that under high temperature and drought conditions, N losses as ammonia increased to 64% when urea was surface-applied, compared to 34% with banded applications. Furthermore, studies by Kelly et al. (2004), Bryant-Schlobohm et al. (2020), and Milyutkin et al. (2021) have also indicated that subsurface N application can significantly reduce N losses.

In the conducted trials (20-20-0, 15-15-15 and DAP), the highest yield values were obtained from polyphosphate liquid fertilizer forms as phosphorus source (Figure 3, 4 and 5). Higher Yield with Liquid Fertilizers: As indicated by the trends, liquid fertilizers (especially those containing polyphosphate) have been shown to improve cotton yields compared to traditional solid fertilizers. Higher yields translate directly to higher revenue, which can offset the higher initial costs of liquid fertilizers. The increased efficiency in nutrient uptake with liquid fertilizers reduces the amount of fertilizer required, which can further mitigate the higher cost per unit. Over time, the reduced need for frequent applications and potential decreases in fertilizer quantity can lead to cost savings. Liquid fertilizers offer several sustainability advantages compared to traditional solid fertilizers. However, their sustainability profile also depends on factors like production methods, application techniques, and overall farm management practices. Liquid fertilizers can be precisely applied through various methods, such as drip irrigation, foliar spraying, or subsurface injections. This targeted application reduces nutrient losses through leaching, volatilization, or runoff, ensuring that more of the applied nutrients are utilized by the crops. Because of their precision, liquid fertilizers minimize the risk of over-application, which can lead to nutrient imbalances in the soil and reduce the need for corrective measures later on. Several other crops might benefit similarly from the use of liquid fertilizers, particularly those with high nutrient demands or those that are sensitive to nutrient availability. Corn has a high demand for nitrogen, particularly during the early growth stages. Liquid nitrogen fertilizers, like UAN (Urea Ammonium Nitrate), can provide a more consistent supply of nitrogen, leading to improved growth and yield. Corn also requires significant phosphorus, especially for root development. Liquid phosphorus fertilizers (e.g., polyphosphate-based) can enhance phosphorus availability, improving early root growth and overall plant health.

Conclusion

The use of liquid fertilizers place of the traditional solid fertilizers had a positive impact on cotton yield and key yield parameters of cotton plants. Although the three trials conducted showed that the effects of traditional fertilizer applications on cotton yield were statistically similar, the newly developed liquid polyphosphate-based fertilizers (liquid 20-20, liquid 15-15-15 and liquid DAP) resulted in yield increases of 16.5%, 25.1% and 9.9%, respectively. The results, including improvements in yield and yield parameters and macronutrient concentrations demonstrate that these liquid base fertilizers are viable alternatives for cotton cultivation. For liquid base and top fertilizer applications to become widespread, it is important to ensure the availability and use of agricultural tools and machinery capable of applying liquid fertilizers during both planting and top fertilization stages. Additionally, further research is needed to evaluate the effects of liquid fertilizers on cotton across different locations and growing seasons, as well as their economic viability.

Conflict of Interest

The authors declare that they have no known competing financial or non-financial, professional, or personal conflicts that might appear to influence the work reported in this paper.

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