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RESEARCH ARTICLE

Synergistic Effects of Integrated Organic and Mineral Fertilization on Soil Nutrient Dynamics and Cotton Productivity in Irrigated Meadow-Alluvial Soils of Arid Uzbekistan

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ABSTRACT

A field experiment was conducted in 2019–2021 in the Shavat district of the Khorezm region, Uzbekistan, to determine how mineral fertilizers combined with farmyard manure affect nutrient availability and cotton productivity in old-irrigated meadow-alluvial soils. Five fertilizer treatments were tested under furrow irrigation in a randomized complete block design with three replications. Soil nutrient status, nutrient accumulation in cotton organs, growth parameters, and seed cotton yield were evaluated. The treatment $N_{200}P_{150}K_{100}$ + 25 t ha^{-1} manure gave the strongest agronomic response. In this treatment, the 0–30 cm soil layer contained higher nitrate nitrogen, available phosphorus, and exchangeable potassium during the main growth stages, and cotton plants accumulated more N, P, and K in leaves, stems, and bolls. The highest mean yield was 34.8 c ha^{-1}, which exceeded the unfertilized control by 86.1%. A further increase in mineral fertilizer rate did not improve yield. Under the studied conditions, the balanced mineral–organic regime was more effective than the highest mineral fertilizer input.

Keywords: Cotton yield, Farmyard manure, Khorezm region, Meadow-alluvial soil, Nutrient uptake

Introduction

Cotton is widely cultivated for fiber production and also has value as a source of seed oil and feed by-products.[1,2] Among cultivated cotton species, Gossypium hirsutum L. remains the dominant species in global production.[3] In Uzbekistan, cotton continues to be one of the main crops of irrigated agriculture.[4] In the Khorezm region, its productivity is closely linked with irrigation regime, soil fertility, and the availability of mineral nutrients during the growing season.

Under intensive irrigated farming, fertilizer management directly affects cotton yield formation and the maintenance of soil fertility.[5] The use of organic inputs together with mineral fertilizers can improve the humic status of the soil and reduce organic matter depletion under long-term cultivation.[6] At the same time, nutrient management should supply available elements during the main growth stages of cotton without creating excessive nutrient losses under irrigation.[7]

Nitrogen is one of the main yield-forming nutrients in cotton, and its application affects both yield level and nitrogen-use efficiency.[8–10] The optimal nitrogen rate is not universal; it changes depending on soil properties, irrigation conditions, and crop management, with many studies reporting effective rates within the range of 200–300 kg N ha^{-1}.[11–13] However, nitrogen input above crop demand may reduce nitrogen-use efficiency and disturb physiological balance.[14–17] In cotton production

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systems, excessive nitrogen has also been associated with delayed maturation, excessive vegetative growth and less stable yield formation.[18–20] Similar physiological responses to nitrogen imbalance have also been reported in other crop systems, confirming that the nitrogen rate should be adjusted to crop demand and local growing conditions.[21,22]

Other macronutrients, particularly phosphorus and potassium, are also required for stable cotton productivity under irrigated conditions.[23] Phosphorus is involved in root development, energy transfer, and reproductive growth, while organic matter application can influence phosphorus status in calcareous soils.[24–26] Its availability in alkaline irrigated soils can be limited by fixation processes, which makes the response to phosphorus fertilization strongly dependent on local soil conditions.[27,28] When phosphorus input is not balanced with crop demand, its accumulation may also increase environmental risks.[29]

Potassium is important for osmotic regulation, enzyme activity, and stress tolerance in cotton plants.[30–32] Under arid irrigated conditions, potassium uptake may vary during the season because soil moisture, ion mobility, and root-zone conditions are not constant.[33–35] This is particularly relevant for meadow-alluvial soils cultivated under furrow irrigation, where nutrient availability may change between irrigation events.

Despite extensive research on nitrogen, phosphorus and potassium management in cotton production systems, fertilizer response remains highly site-specific and strongly dependent on soil properties and irrigation regimes.[8–13] Therefore, regionally adapted fertilization strategies are required. This is particularly relevant for irrigated meadow-alluvial soils of the Shavat district (Khorezm region), characterized by long-term irrigation history and risks of secondary salinization. Under such conditions, generalized fertilization recommendations and conventional mineral-based fertilizer regimes may be insufficient, because they do not fully account for the specific constraints of old-irrigated meadow-alluvial soils, including alkaline reaction, limited organic matter reserves, reduced phosphorus availability, and nutrient losses under furrow irrigation.[27,28] Moreover, previous studies have mainly emphasized the role of individual mineral nutrients in cotton production, whereas the combined effects of mineral fertilizers and organic manure on soil nutrient dynamics, plant nutrient accumulation, and yield performance under the local conditions of the Shavat district remain insufficiently quantified.

This study contributes to the local literature by providing a three-year field evaluation of integrated mineral and organic fertilization in irrigated meadow-alluvial soils of the Shavat district, with simultaneous assessment of soil nutrient dynamics, plant nutrient accumulation, and cotton yield.

We hypothesized that the combined application of mineral fertilizers and organic manure would improve soil nutrient availability (nitrate N, available P, and exchangeable K), enhance plant nutrient accumulation, and increase cotton yield more effectively than mineral fertilization or manure alone in irrigated meadow-alluvial soils of the Shavat district.

The objective of this study was to evaluate the effects of different rates of mineral fertilizers in combination with organic manure on soil nutrient dynamics, plant nutrient accumulation, and cotton yield in irrigated meadow-alluvial soils of the Shavat district during 2019–2021.

Materials and methods

The field experiment was established on old-irrigated meadow-alluvial soil in the Shavat district of the Khorezm region, Republic of Uzbekistan. Before sowing in spring 2019, composite soil samples were collected from the 0–30 cm and 30–50 cm layers to describe the initial condition of the experimental site. The soil had a loamy texture. In the 0–30 cm layer, soil pH was 7.6 in a 1:2.5 soil-to-water suspension, EC was 1.3 dS m^{-1}, organic matter content was 1.52%, nitrate nitrogen was 7.8 mg kg^{-1}, available P_2O_5 was 28.0 mg kg^{-1}, and exchangeable K_2O was 217 mg kg^{-1}. Total N, P, and K were 0.10%, 0.95% and 1.41%, respectively. These baseline properties are shown in Table 1.

Table 1. Initial physical and chemical properties of the experimental soil before the 2019 growing season.

Parameter	Unit	Value
Soil type	-	Old-irrigated meadow-alluvial soil
Texture	-	Loamy
pH (1:2.5 soil:water)	-	7.6
Electrical conductivity (EC)	dS/m	1.3
Organic matter	%	1.52
Nitrate nitrogen (NO_3^--N)	mg/kg	7.8
Available phosphorus (P_2O_5)	mg/kg	28.0
Exchangeable potassium (K_2O)	mg/kg	217
Total N	%	0.10
Total P	%	0.95
Total K	%	1.41

The cotton variety Khorezm-127 was used throughout the 2019–2021 field experiment. This medium-maturing variety was selected because it is adapted to the irrigated conditions of the Khorezm region. Its vegetation period is about 120–130 days, with a boll weight of 6.0–6.5 g, fiber yield of 36.5–38.4%, and 1000-seed weight of 122–132 g.

Table 2. Field Experiment System (fertilizer application rates and timing).

Experimental Variants	Annual Fertilizer Rate, kg ha^{-1}			Pre-winter Plowing	At Sowing		At the emergence of 3–4 true leaves		Budding	Flowering	
	N	P	K	Manure, t ha^{-1}	P	K	N	P	N	N	K
Control	-	-	-	-	-	-	-	-	-	-	-
$N_{150}P_{150}K_{150}$ + 25 t ha^{-1} manure	150	150	150	25	100	120	60	50	40	50	30
N200P150K100 + 25 t ha^{-1} manure	200	150	100	25	100	75	125	50	20	55	25
$N_{250}P_{175}K_{125}$ + 25 t ha^{-1} manure	250	175	125	25	100	75	100	75	70	80	50
25 t ha^{-1} manure	-	-	-	25	-	-	-	-	-	-	-

The experiment was laid out as a randomized complete block design with three replications. Five fertilizer treatments were tested, and each treatment appeared once in each block. In total, the experiment included 15 plots. Each plot occupied 180 m^2 (7.2 m × 25 m), with 0.9 m between rows. The net plot area was 2700 m^2, while the full experimental area, including guard rows and spaces between plots, was 3240 m^2.

Farmyard manure was incorporated before the first growing season, and its residual effect was followed in 2020 and 2021. Mineral fertilizers were applied with a cultivator in split doses. At the early growth stage, fertilizers were placed 15–18 cm from the plant row. During flowering, they were placed 25–30 cm from the stem and 3–5 cm below the bottom of the irrigation furrow.

Statistical analysis. Treatment effects were tested by one-way ANOVA, using fertilizer treatment as the main factor. Before analysis, the data were checked for normal distribution and homogeneity of variance. When significant differences were found, treatment means were separated by the LSD test at $P \leq 0.05$. Results are presented as mean ± standard error (SE).

The experiment was carried out under arid continental conditions. According to the Urgench meteorological station, the mean air temperature during the cotton-growing period from April to September in 2019–2021 was 23.0 °C, and total precipitation was 42.6 mm. July was the hottest and driest month, with a mean temperature of 29.9 °C and only 1.8 mm of precipitation. Because rainfall was not sufficient for cotton growth, furrow irrigation was applied 5–6 times per season, depending on soil moisture and crop development.

Fertilizers were applied in split doses according to the cotton growth stage. Phosphorus and potassium were mainly applied before sowing or at sowing. Nitrogen was supplied during early vegetative growth, budding and flowering. The detailed rates and timing of fertilizer application for each treatment are given in Table 2.

Plant observations included plant height, number of fruiting branches, buds, flowers, and bolls, and final seed cotton yield. The last fertilizer application was made during flowering and repeated after 12–14 days according to the treatment schedule.

The analyses of soil and plant samples were carried out according to standard procedures described in Arinushkina's Manual on Soil Chemical Analysis. Field experiments followed the relevant methodological guidelines for cotton field trials under irrigated conditions. Soil pH was determined potentiometrically in a 1:2.5 soil-to-water suspension (unitless). Electrical conductivity (EC) was measured in the soil-water extract and expressed in dS m^{-1}. Organic matter content was determined by the Tyurin method and expressed as %. Nitrate nitrogen (NO_3^--N) was determined colorimetrically and expressed as mg kg^{-1}. Available phosphorus was determined as P_2O_5 by the Machigin method (extraction with ammonium carbonate solution) and expressed as mg kg^{-1}. Exchangeable potassium was extracted with 1 N ammonium acetate and determined by flame photometry as K_2O (mg kg^{-1}).

Results and discussion

The study area is located in the Shavat district of the Khorezm region, northwestern Uzbekistan. Uzbekistan is situated in Central Asia between the Amu Darya and Syr Darya rivers and is characterized by arid continental climatic conditions that strongly influence agricultural production systems.[36]

Irrigated meadow-alluvial soils are classified into old-irrigated and newly irrigated soils based on the duration of irrigation. Morphological features of old-irrigated soils include an upper layer (60–70 cm, sometimes more) composed of agro-irrigation deposits, usually having a uniform color and a homogeneous loamy structure. Newly irrigated soils exhibit a recently developed soil layer beneath the plow layer, with horizons differing in mechanical composition and consisting of various lithological deposits.

These soils show modern signs of moisture influence, such as rusty and dark gray shades, and in some cases, salt accumulation.

Experiments were conducted on old-irrigated meadow-alluvial soils using the Khorezm-127 cotton variety under five differentiated fertilizer application variants: a control variant (without fertilizers), variant 2 - $N_{150}P_{150}K_{150}$ + 25 t ha^{-1} manure, variant 3 - $N_{200}P_{150}K_{100}$ + 25 t ha^{-1} manure, variant 4 - $N_{250}P_{175}K_{125}$ + 25 t ha^{-1} manure, and variant 5 - manure only (25 t ha^{-1}).

Nitrogen, phosphorus, and potassium play different roles in cotton growth, but their effect in this experiment depended on fertilizer balance and soil moisture conditions. Under arid irrigated conditions, nutrient availability may change during the season because soil moisture and ion mobility are not constant. This explains why the combined mineral–organic treatments showed stronger responses than the control and manure-only treatment. Its deficiency slows plant development and delays maturation. According to some data, cotton requires an average of 7 to 10 kg of P_2O_5 per bale of fiber, corresponding to the recommended fertilizer application rates of 50 to 75 kg ha^{-1}.[37] Phosphorus uptake occurs similarly to nitrogen absorption and runs parallel to dry matter accumulation. The primary phosphorus reservoir in plants is seeds, which contain about half of the total phosphorus content.

Under phosphorus deficiency, cotton reproductive development is affected more strongly than vegetative growth, because boll formation requires a continuous supply of this element. Potassium is also important under arid conditions, as it helps maintain cell water balance and supports plant resistance to moisture stress.

Potassium can be applied in the form of potassium chloride (KCl) or potassium sulfate (K_2SO_4), with the method of application (broadcast or banding) having little effect on fertilizer efficiency. However, cotton roots grow less actively towards potassium sources than towards phosphorus and nitrogen. Therefore, for maximum absorption, potassium should be applied in the same band as phosphorus or nitrogen.

The study examined the effects of fertilizer rates on cotton growth, development, and yield. The application of mineral and organic fertilizers influenced the nitrate nitrogen, available phosphorus, and exchangeable potassium content in soil layers of 0-30 cm and 30-50 cm. In the first year of the experiment (2019), nitrate nitrogen content in the 3-4 true leaf phase was: in the control variant (without fertilizers) - 7.4 mg/kg (0-30 cm) and 5.1 mg/kg (30-50 cm); in variant 2 ($N_{150}P_{150}K_{150}$ + 25 t ha^{-1} manure) - 9.6 and 7.1 mg/kg, respectively; in variant 3 ($N_{200}P_{150}K_{100}$ + 25 t ha^{-1} manure) - 9.5 and 6.7 mg/kg; in variant 4 ($N_{250}P_{175}K_{125}$ + 25 t ha^{-1} manure) - 9.8 and 6.5 mg/kg; in variant 5 (25 t ha^{-1} manure only) - 9.1 and 6.1 mg/kg. During the budding phase, nitrate nitrogen content increased: in the control variant - up to 8.6 and 5.4 mg/kg, in variant 2 - 11.2 and 7.3 mg/kg, in variant 3 - 11.9 and 7.6 mg/kg, in variant 4 - 11.5 and 7.4 mg/kg, in variant 5 - 9.5 and 6.8 mg/kg. In the flowering phase, maximum values were recorded in variants 3 ($N_{200}P_{150}K_{100}$ + 25 t ha^{-1} manure) - 13.8 and 8.4 mg/kg and 4 ($N_{250}P_{175}K_{125}$ + 25 t ha^{-1} manure) - 13.6 and 8.1 mg/kg. By the end of the growing season, nitrate nitrogen levels decreased: in the control variant - 7.1 and 4.9 mg/kg, in variant 2 - 9.5 and 6.9 mg/kg, in variant 3 - 9.7 and 6.9 mg/kg, in variant 4 - 9.6 and 6.6 mg/kg, in variant 5 - 8.4 and 5.8 mg/kg. In the second and third years of the experiment, changes in available phosphorus and exchangeable potassium content in the soil were studied. The seasonal pattern recorded in 2019 was comparable with reports from irrigated cotton systems, where nitrate availability usually increases during active growth and then decreases toward maturity as a result of plant uptake, irrigation movement and possible leaching.13,20 In the present experiment, the increase at budding and flowering and the subsequent decline at the end of vegetation indicate that the fertilizer effect was strongest during the period of high nutrient demand. Changes in topsoil (0–30 cm) properties before and after fertilizer application are presented in Table 3.

Table 3. Changes in topsoil (0–30 cm) properties before and after fertilizer application.

Parameter	Before experiment	After experiment
Humus (%)	1.52	1.63
Total N (%)	0.10	0.11
Total P (%)	0.95	0.88
Total K (%)	1.41	1.31
Available P_2O_5 (mg/kg)	28.0	35.0
Available K_2O (mg/kg)	217	231

As shown in Table 3, the integrated application of mineral fertilizers and manure improved the nutrient availability in the plow layer (0–30 cm). Humus content increased, and the available forms of phosphorus (P_2O_5) and potassium (K_2O) also increased, indicating enhanced soil fertility status under irrigated conditions. In contrast, total P and total K showed slight reductions, which may be attributed to intensive nutrient uptake by cotton and redistribution of nutrients in the soil profile under furrow irrigation; moreover, total nutrient pools are relatively conservative and may not increase over a short-term period compared with the more responsive available fractions. The observed increase in humus

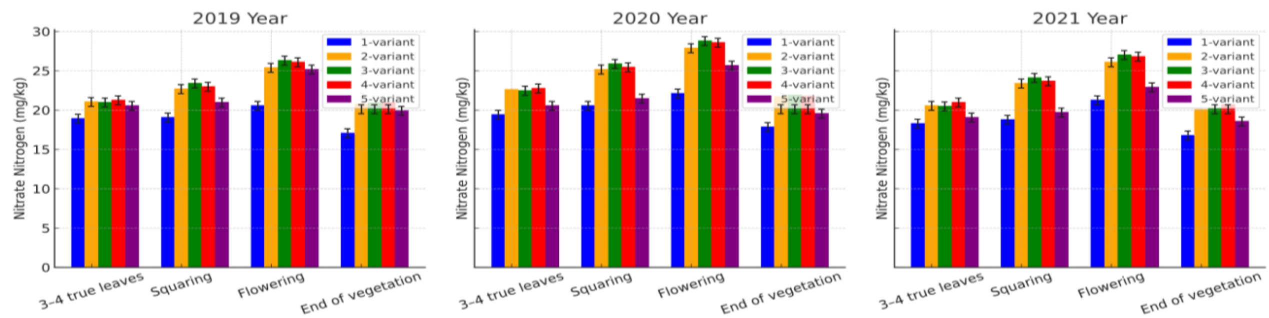

Fig. 1. Seasonal dynamics of soil nitrate nitrogen (NO_3^--N, mg kg^{-1}) in the 0–30 cm layer of meadow-alluvial soil under different fertilizer treatments during 2019–2021. Values represent treatment means based on three replications. Statistical significance was assessed by ANOVA followed by the LSD test at $P \leq 0.05$.

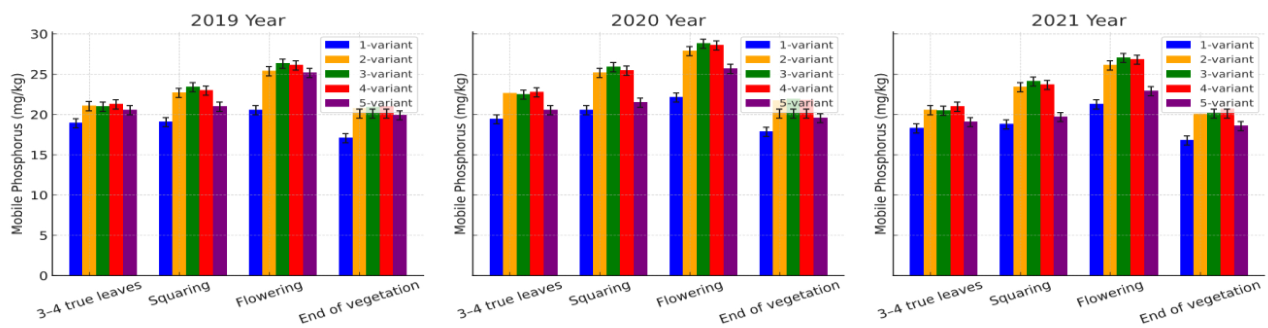

Fig. 2. Seasonal changes in available phosphorus (P_2O_5, mg kg^{-1}) in the 0–30 cm soil layer under different fertilizer treatments during 2019–2021. Values represent treatment means based on three replications. Statistical significance was assessed by ANOVA followed by the LSD test at $P \leq 0.05$.

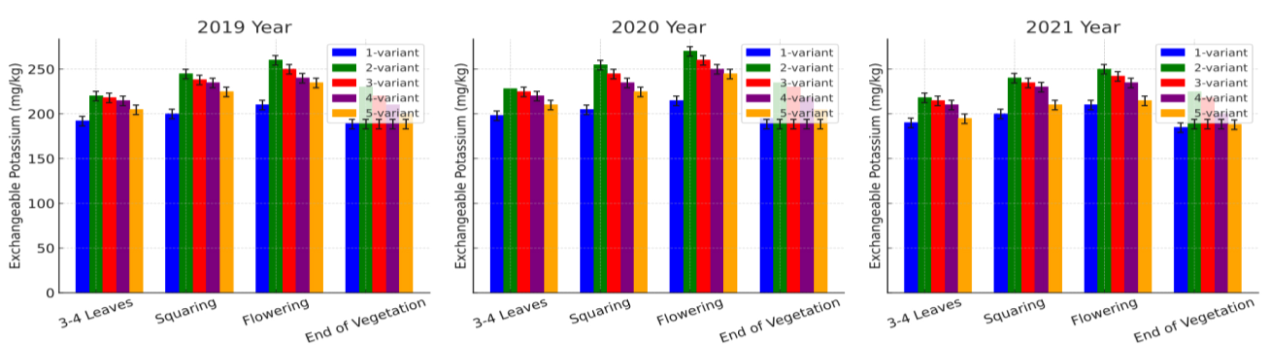

Fig. 3. Seasonal dynamics of exchangeable potassium (K_2O, mg kg^{-1}) in the 0–30 cm layer of meadow-alluvial soil under different fertilizer treatments during 2019–2021. Values represent treatment means based on three replications. Statistical significance was assessed by ANOVA followed by the LSD test at $P \leq 0.05$.

content under combined mineral and organic fertilization is consistent with previous studies reporting improved soil organic matter status under integrated nutrient management systems.[13–15] Similar increases in available phosphorus and potassium following manure application have been documented in irrigated cotton systems, where organic inputs enhance nutrient mineralization and microbial activity.[16–18] This pattern is consistent with the positive changes observed in the present study and is supported by established agronomic mechanisms. Statistical analysis confirmed treatment-related differences in available phosphorus and exchangeable potassium in the topsoil layer ($P \leq 0.05$).

It was found that the highest nutrient content was recorded in the second year (2020), during the cotton flowering phase, in the upper 0-30 cm soil layer in Figs. 1, 2, 3. Thus, the application of mineral and organic fertilizers contributes to an increase in the content of essential nutrients in the soil, which positively affects the growth and yield of cotton.

Table 4. Nitrogen, phosphorus and potassium content in cotton organs at the end of the growing season (mean of 2019–2021).

Treatment	Leaf N (%)	Leaf P (%)	Leaf K (%)	Stem N (%)	Stem P (%)	Stem K (%)	Boll N (%)	Boll P (%)	Boll K (%)
Control	0.97	0.18	1	0.40	0.29	0.80	0.49	0.35	1.96
$N_{150}P_{150}K_{150}$ + 25 t ha^{-1} manure	1.69	0.79	1.87	0.47	0.44	1.81	0.65	0.47	2.14
N200P150K100 + 25 t ha^{-1} manure	2.00	0.81	2.03	0.57	0.54	1.88	0.79	0.67	2.33
$N_{250}P_{175}K_{125}$ + 25 t ha^{-1} manure	1.78	0.80	1.91	0.49	0.44	1.78	0.69	0.56	2.19
25 t ha^{-1} manure	1.25	0.27	1.28	0.42	0.40	1.10	0.54	0.39	2.00

Note: Values represent means of three growing seasons (2019–2021). Differences among fertilizer treatments were assessed using one-way ANOVA at $P \leq 0.05$.

Fertilizer rates affected nitrogen accumulation in cotton organs. In the control treatment, nitrogen content was 0.97% in leaves, 0.40% in stems, and 0.49% in bolls. The highest values were recorded under $N_{200}P_{150}K_{100}$ + 25 t ha^{-1} manure, where nitrogen reached 2.00% in leaves, 0.57% in stems, and 0.79% in bolls. In the manure-only treatment, nitrogen accumulation was higher than in the control, but lower than in the combined mineral–organic treatments.

The values presented in Figs. 1 to 3 are treatment means based on three replications, and statistical significance among treatments was evaluated using ANOVA followed by the LSD test at $P \leq 0.05$.

Table 4 summarizes the N, P and K concentrations in cotton leaves, stems and bolls at the end of the growing season. Fertilizer application increased nutrient accumulation in all plant organs compared with the control. The highest values were mostly recorded under $N_{200}P_{150}K_{100}$ + 25 t ha^{-1} manure. For example, leaf N increased from 0.97% in the control to 2.00%, while boll K increased from 1.96% to 2.33%. The differences among treatments were significant at $P \leq 0.05$.

The stronger response of $N_{200}P_{150}K_{100}$ + 25 t ha^{-1} manure can be explained by the joint effect of mineral and organic nutrient sources. Mineral fertilizers supplied readily available N, P, and K during active growth stages, while manure likely supported a more gradual nutrient release in the root zone. This combination may explain why Variant 3 performed better than the manure-only treatment and did not require the highest mineral fertilizer rate.[38]

The synergistic effect under combined mineral-organic fertilization can be explained not only by complementary nutrient release patterns, but also by manure-induced improvements in soil structure and biological activity. Mineral fertilizers provide immediately available nutrients during early growth stages, ensuring rapid vegetative development. In contrast, organic manure promotes the formation of a more stable soil structure, improves aggregation and porosity, and enhances water retention, thereby creating more favorable conditions for root growth and nutrient diffusion in the root zone. At the same time, manure stimulates microbial activity, which accelerates the mineralization of organic compounds and supports the transformation and mobilization of nitrogen, phosphorus, and potassium into more plant-available forms. In this experiment, this combined effect was reflected in higher N, P, and K concentrations in cotton organs and in the higher yield obtained in Variant 3.

Phosphorus accumulation also increased under fertilizer application. In the control treatment, P concentration was 0.18% in leaves, 0.29% in stems, and 0.35% in bolls. Under $N_{200}P_{150}K_{100}$ + 25 t ha^{-1} manure, these values increased to 0.81%, 0.54% and 0.67%, respectively. The manure-only treatment showed lower P values than the combined mineral–organic treatments, indicating that manure alone was not sufficient to meet cotton phosphorus demand under the studied conditions. This response is consistent with the role of phosphorus in cotton reproductive development.[39–41]

Potassium content in the control treatment was 1.00% in leaves, 0.80% in stems, and 1.96% in bolls. The application of $N_{150}P_{150}K_{150}$ + 25 t ha^{-1} manure increased potassium levels to 1.87% in leaves, 1.81% in stems, and 2.14% in bolls. The highest potassium accumulation was observed in the $N_{200}P_{150}K_{100}$ + 25 t ha^{-1} manure treatment, where leaf potassium reached 2.03%, stem potassium 1.88%, and boll potassium 2.33%. In the $N_{250}P_{175}K_{125}$ + 25 t ha^{-1} manure treatment, potassium content was slightly lower, amounting to 1.91% in leaves, 1.78% in stems, and 2.19% in bolls. In the manure-only treatment (25 t ha^{-1}), potassium levels were 1.28% in leaves, 1.10% in stems, and 2.00% in bolls.

Cotton is considered a potassium-demanding crop, as potassium plays a key role in osmotic regulation and maintenance of cell turgor.[42] The increase in potassium content in cotton organs with fertilizer application reflects improved mineral nutrition.

According to the obtained data, the best and most stable results were observed in Variant 3 with

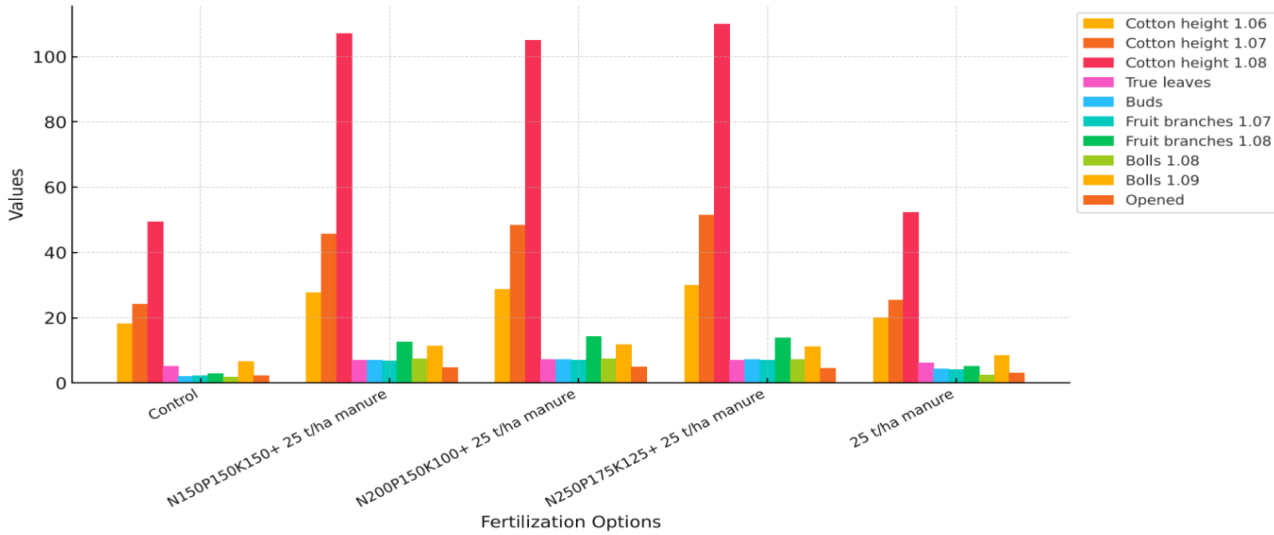

Fig. 4. Effect of fertilizer treatments on cotton growth parameters (number of true leaves, buds and fruiting branches per plant) in 2019.

fertilizer application. In other variants, where the amount of mineral fertilizers was higher than in Variant 3, no improvement was observed, which indicates the "law of diminishing returns". The comparison of Variant 3 and Variant 4 shows that the higher fertilizer dose was not more effective. Although Variant 4 received more mineral fertilizer, it did not provide higher nutrient accumulation or yield. Under furrow irrigation, this may indicate lower fertilizer-use efficiency and a greater risk of nutrient losses, especially in meadow-alluvial soils with possible secondary salinization.[43]

Fertilizer treatments influenced early cotton growth. By June 1, the control plants had 5.2 true leaves, while fertilized treatments had 6.1–7.1 leaves. Bud formation followed the same pattern: the control had 2.1 buds, whereas fertilized variants reached up to 7.1 buds. One of the important indicators in cotton is the formation of fruiting branches, where bolls can develop. By August 1, their number in the unfertilized variant reached 2.8, while in the fertilized variants, it ranged from 5.2 to 14.3. The best results were observed in Variant 3 with the application of $N_{200}P_{150}K_{100}$ + 25 t ha^{-1} manure. It should be noted that the combined application of mineral and organic fertilizers increases the number of buds, which may indicate that the plant is ready for reproductive processes. The integrated use of fertilizers (mineral + organic) stimulates the growth of vegetative mass, improves photosynthesis, and leads to the formation of a greater number of leaves, buds, fruiting branches, and bolls, which can play an important role in cotton yield formation. The application of integrated fertilization enhances the growth of agricultural crops, including cotton, due to improved nutrient uptake.[39]

During the course of the experiments, the amount of accumulated dry matter was calculated. Observations revealed that in the early phase of vegetation, dry matter accumulation occurs more slowly, but then its rate increases. The dry leaf mass in the variant without fertilizers ranged from 14.0 to 14.7 g, while the best results were observed in Variant 3, where it reached up to 28.6 g. A similar pattern was observed in the dry mass of stems and bolls, which influenced the total dry matter accumulation by the end of the vegetation period. For instance, in the variant without fertilizers, the accumulated dry mass was 54.1–57.3 g, whereas in the most optimal variant (Variant 3), it amounted to 124.2 g. This process is explained by the fact that in the early stages of cotton development, metabolic activity is limited due to the insufficient formation of vegetative organs capable of participating in photosynthesis, and thus the rate of dry matter accumulation is very low.[40] When the plants begin to grow intensively (under favorable nutrient conditions), the leaf surface area increases, activating metabolism and photosynthesis, which leads to biomass accumulation. Based on this, it can be noted that the combined application of mineral and organic fertilizers results in the highest increase in dry matter, which contributes to higher cotton yields. The obtained results are consistent with those of other researchers. For example, according to the findings of Fageria et al., the integrated application of fertilizers contributed to dry matter accumulation by enhancing root growth,[39] which in turn improved nutrient availability from the soil and increased metabolic and photosynthetic activity.[42] The effect of fertilizer treatments on cotton growth parameters in 2019 is presented in Fig. 4. The corresponding effect of fertilizer treatments on

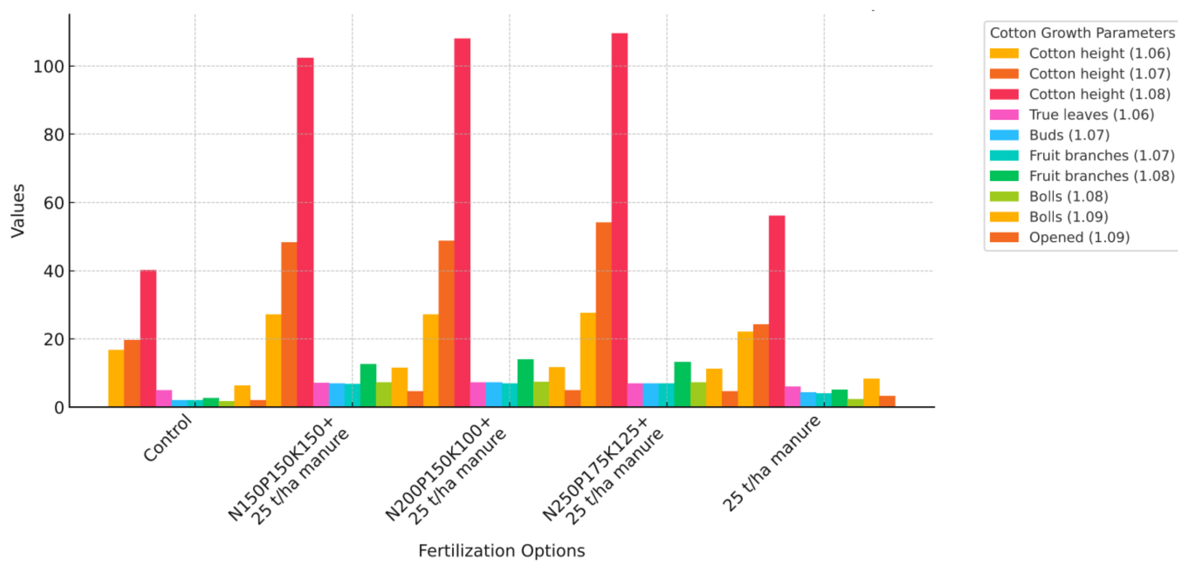

Fig. 5. Effect of fertilizer treatments on cotton growth parameters (number of true leaves, buds and fruiting branches per plant) in 2021.

Table 5. Effect of fertilizer treatments on cotton yield (2019–2021).

Treatment	2019	2020	2021	Mean ± SE
Control	19.3	18.9	17.8	18.7± 0.45 c
$N_{150}P_{150}K_{150}$ + 25 t ha^{-1} manure	32.4	33.8	32.6	32.9± 0.44 b
$N_{200}P_{150}K_{100}$ + 25 t ha^{-1} manure	34.2	36.1	34.0	34.8± 0.67 a
$N_{250}P_{175}K_{125}$ + 25 t ha^{-1} manure	30.1	32.2	31.1	31.1± 0.61 b
25 t ha^{-1} manure	24.5	25.2	23.7	24.5± 0.43 d

Note: Values are means ± SE averaged over three growing seasons (2019–2021). The overall effect of fertilizer treatment on cotton yield was significant according to one-way ANOVA ($P < 0.001$). Means followed by different letters are significantly different at $P \leq 0.05$ according to the LSD test.

Table 6. Partial factor productivity (PFP) and agronomic efficiency (AE) of mineral nutrients in cotton under different fertilizer treatments.

Treatment	PFP-N	AE-N	PFP-P	AE-P	PFP-K
$N_{150}P_{150}K_{150}$ + 25 t ha^{-1} manure	21.9	9.47	21.9	9.47	21.9
$N_{200}P_{150}K_{100}$ + 25 t ha^{-1} manure	17.4	8.05	23.2	10.7	34.8
$N_{250}P_{175}K_{125}$ + 25 t ha^{-1} manure	12.4	4.96	17.8	7.09	24.9

Note: PFP - partial factor productivity (yield per unit of applied nutrient).
AE - agronomic efficiency [(Yield_treatment - Yield_control) / nutrient rate].

cotton growth parameters in 2021 is shown in Fig. 5.

One-way ANOVA showed a significant effect of fertilizer treatment on cotton yield ($P < 0.001$). The highest mean yield was recorded in Variant 3 ($N_{200}P_{150}K_{100}$ + 25 t ha^{-1} manure), reaching 34.8 ± 0.67 c ha^{-1} Table 5. According to the LSD test at $P \leq 0.05$, this value was significantly higher than those of Variant 2 (32.9 ± 0.44 c ha^{-1}), Variant 4 (31.1 ± 0.61 c ha^{-1}), the manure-only treatment (24.5 ± 0.43 c ha^{-1}), and the control (18.7 ± 0.45 c ha^{-1}). The annual and mean seed cotton yield values for all fertilizer treatments are summarized in Table 5.

To further evaluate fertilizer-use efficiency, partial factor productivity (PFP) and agronomic efficiency (AE) were calculated for the mineral fertilizer treatments. These results are presented in Table 6.

The nutrient efficiency indices followed the yield pattern. PFP-N decreased as nitrogen rate increased, and AE-N was lower in Variant 4 than in Variant 2. Variant 3 did not have the highest PFP-N, but it showed a better balance between yield and efficiency for phosphorus and potassium, which corresponds to its highest cotton yield.

The yield results show that Variant 3 provided the most favorable balance between fertilizer input and crop response. Variant 4 received a higher mineral fertilizer rate, but its yield was lower than that of Variant 3. This indicates that cotton productivity was determined not by the maximum fertilizer dose, but by the balance between N, P, K and manure under the studied soil and irrigation conditions. Similar responses have been reported in irrigated cotton systems, where excessive nitrogen reduced nutrient-use efficiency and yield stability.[14,20] Excess fertilizer input under furrow irrigation may also increase the risk of nutrient losses and localized salt accumulation in the root zone of meadow-alluvial soils.[43] The manure-only treatment produced a higher yield than the control, but it did not reach the level of the combined mineral–organic treatments.[44]

Conclusion

The three-year field experiment showed that mineral–organic fertilization improved soil nutrient availability, nutrient accumulation in cotton organs, and seed cotton yield in old-irrigated meadow-alluvial soil of the Shavat district. Among the tested treatments, $N_{200}P_{150}K_{100}$ + 25 t ha^{-1} manure gave the highest mean yield, 34.8 c ha^{-1}, and the most favorable nutrient response. Increasing the mineral fertilizer rate to $N_{250}P_{175}K_{125}$ did not increase yield, indicating that the highest input was not the most efficient option under the studied conditions. The results suggest that balanced mineral fertilization combined with manure is more suitable for cotton production in these soils than applying the maximum fertilizer dose.

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Authors' declaration

- Conflicts of Interest: None.
- We hereby confirm that all the Figures and Tables in the manuscript are ours. Furthermore, any Figures and images, that are not ours, have been included with the necessary permission for republication, which is attached to the manuscript.
- No animal studies are present in the manuscript.
- No human studies are present in the manuscript.
- Ethical Clearance: The project was approved by the local ethical committee at University of Uzbekistan.

Authors' contributions statement

D.G.T. and R. K. N. designed the study and developed the experimental plan. R. K. N. conducted the field experiments, collected soil samples and plant organ samples for laboratory analysis. D.G.T performed data interpretation, statistical analysis, and supervised the research process. Both authors contributed to writing the manuscript, reviewed the results, and approved the final version for publication.

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التأثيرات التآزرية للتسميد العضوي والمعدني المتكامل على ديناميكيات مغذيات التربة وإنتاجية القطن في الترب المروية من نوع المروج الرسوبية في المناطق القاحلة بأوزبكستان

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الخلاصة

أُجريت تجربة حقلية خلال الفترة 2019–2021 في منطقة شافات التابعة لإقليم خوارزم، أوزبكستان، بهدف تحديد تأثير الأسمدة المعدنية المدمجة مع سماد المزرعة (السماد البلدي) على توافر العناصر الغذائية وإنتاجية القطن في الترب الطميية المروية القديمة (المروجية–الغرينية). تم اختبار خمس معاملات تسميد تحت الري بالأخاديد باستخدام تصميم القطاعات العشوائية الكاملة مع ثلاث مكررات. تم تقييم حالة العناصر الغذائية في التربة، وتراكم العناصر في أعضاء نبات القطن، ومعايير النمو، وإنتاجية القطن الزهر. أعطت المعاملة N200P150K100 + 25 طن هكتار$^{-1}$ من السماد أعلى استجابة زراعية. في هذه المعاملة، احتوت طبقة التربة 0–30 سم على مستويات أعلى من النيتروجين النتراتي، والفوسفور المتاح، والبوتاسيوم المتبادل خلال مراحل النمو الرئيسية، كما تراكمت كميات أكبر من N وP وK في الأوراق والسيقان واللوز. بلغ متوسط أعلى إنتاجية 34.8 قنطار هكتار$^{-1}$، وهو ما تجاوز معاملة الشاهد غير المسمدة بنسبة 86.1%. لم تؤدِ زيادة إضافية في معدلات الأسمدة المعدنية إلى تحسين الإنتاجية. في ظل الظروف المدروسة، كان النظام المتوازن بين الأسمدة المعدنية والعضوية أكثر فعالية من أعلى معدل للتسميد المعدني.

الكلمات المفتاحية: إنتاج القطن، السماد البلدي، إقليم خوارزم، التربة الطميية المروية القديمة، امتصاص العناصر الغذائية.