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Modeling Optimal Fertilizer Application and Evaluating Soil Fertility and Crop Productivity in Saline Soils under Advanced Agrotechnologies

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Abstract

This study is aimed at scientifically substantiating an optimal fertilizer application system to increase wheat yield under saline irrigated soil conditions of the Surkhandarya and Bukhara regions of Uzbekistan. Field experiments were conducted during 2023–2025 on moderately saline soils (EC 4.5–6.8 dS/m), where the effects of different mineral fertilizer treatments (NPK) on crop productivity were evaluated. The results demonstrated that the application of mineral fertilizers significantly increased grain yield compared to the control treatment. The optimal rate ($N_{180}P_{120}K_{90}$ kg/ha) provided the highest agrobiological and economic efficiency in both regions, increasing wheat yield by more than 60% in Surkhandarya and by 65–70% in Bukhara. Increasing fertilizer rates beyond the optimal level did not result in a statistically significant yield improvement. Regression analysis revealed that yield decreased with increasing soil salinity; however, this negative effect was partially mitigated under optimal fertilization regimes. The findings highlight the importance of determining optimal fertilizer application ranges in saline soils to ensure efficient resource use and stable crop productivity.

Keywords: saline soil, wheat yield, mineral fertilizers, optimal fertilizer rate, agrotechnology, soil fertility, Surkhandarya, Bukhara, modeling, irrigated lands.

Citation
Mashhura F. G., & Nodira Kh. H. (2026). Modeling Optimal Fertilizer Application and Evaluating Soil Fertility and Crop Productivity in Saline Soils under Advanced Agrotechnologies. J Open, 02(02), 12–17.

Submitted: March, 2026
Accepted: May, 2026
Published: June, 2026

Vol. 02, **No.** 02, 2026.
10.70728/jopen.be.0226.003

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1 Introduction

Soil salinization is one of the major global ecological and agronomic challenges in modern agriculture, leading to reduced crop yields, degradation of soil fertility, and decreased efficiency of water resource use. This problem is particularly critical in irrigated regions, where salinity alters the physical and chemical properties of soils, thereby limiting plant nutrient uptake and water absorption processes. As a result, the development of scientifically grounded fertilization and irrigation strategies has become an essential task for ensuring stable agricultural productivity in agroecosystems [1].

In recent years, research on improving productivity in saline soils has increasingly focused on advanced agrotechnologies, modeling approaches, and digital monitoring systems. The use of remote sensing, sensor-based technologies, geographic information systems (GIS), and agroecological models has significantly expanded the possibilities for assessing soil conditions and optimizing fertilizer application rates [2]. Furthermore, the integration of fertilization and irrigation regimes enables the maintenance of plant nutrient balance under saline conditions, effective management of water–salt dynamics, and enhancement of crop productivity [3].

Scientific literature highlights that modeling of yield formation processes in saline soils represents a key research direction. Modern crop simulation models serve as effective tools for supporting agro-technological decision-making, allowing the prediction of crop responses to fertilization, irrigation, and other agronomic practices [4]. At the same time, integrated evaluation of water–salt regimes, fertilizer effects, and plant growth processes plays a crucial role in the development of sustainable agricultural systems [5].

Developing an optimal fertilizer application system in saline soils based on advanced agrotechnologies allows not only increasing crop yield, but also reducing soil degradation and ensuring efficient use of resources. Therefore, comprehensive assessment of soil fertility and crop productivity in saline soils, as well as modeling of optimal fertilization agrotechnology, is one of the urgent scientific tasks facing modern agricultural science [6].

The aim of this study is to assess soil fertility and crop productivity in saline soils based on advanced agrotechnologies and modeling methods, as well as to develop a scientifically grounded agrotechnological system for the optimal application of fertilizers. The issue of increasing crop yield and restoring soil fertility in saline soils is one of the widely studied areas in agricultural science. Studies show that the level of salinity directly affects plant nutrition, water uptake, and physiological processes. Therefore, it is necessary to plan and optimize agrotechnical measures on a scientific basis [7].

Recent studies have widely applied modeling and digital technologies to manage crop productivity in saline soils. The use of crop simulation models makes it possible to optimize fertilization and irrigation regimes, predict water–salt dynamics, and assess crop yield in advance [8]. At the same time, well-developed agroecological models are being used as effective decision-making tools for optimizing fertilization strategies [9].

Many scientific studies have identified the integrated system of irrigation and fertilization as one of the key factors in increasing crop productivity in saline soils. By adapting fertilizer application and water regimes, it is possible to improve the physicochemical properties of soil and optimize plant growth conditions [10]. At the same time, simulation-modeling approaches for optimizing irrigation schedules contribute to efficient resource use and increased crop yield [11].

Accurate monitoring and management systems are essential for developing fertilization strategies in saline soils. Precision agriculture technologies, sensor-based systems, and remote sensing methods make it possible to monitor soil conditions in real time and determine fertilizer application rates with high accuracy [12]. Such approaches are effective tools for ensuring the stability of agroecosystems and increasing crop productivity [13].

In this context, the application of advanced agrotechnologies contributes to the stable improvement of crop productivity under saline conditions [14].

In general, the existing scientific literature indicates the need to integrate advanced technologies, modeling approaches, and fertilization strategies to improve soil fertility and crop productivity in saline soils. At the same time, comprehensive studies on optimal fertilizer application and modeling of agrotechnological systems remain insufficiently developed. This study is aimed at filling this gap and improving the scientific foundations of agrotechnological management in saline soils.

2 Research Object and Methods

The research object includes saline soils of different degrees distributed in the irrigated areas of the Surkhandarya and Bukhara regions, as well as the agroecosystems of major agricultural crops grown under these soil conditions. The experimental sites were selected from representative farms differing in hydrogeological and agroclimatic conditions, soil texture, salinity level, and water–salt regime. The study comprehensively examined the fertilization system, water–salt dynamics, and agrotechnological factors affecting crop productivity in saline soils.

Field and laboratory experiments, agrochemical analyses, and modeling methods were used in the study. Soil samples were collected according to generally accepted standard methods, and their salinity level, nutrient content, and physicochemical properties were determined. Crop yield and fertilizer efficiency were evaluated through field experiments.

Based on the obtained data, mathematical and statistical analysis, correlation-regression methods, and agroecological modeling approaches were applied to determine optimal fertilizer rates and predict crop productivity.

In addition, integrated assessment methods based on advanced agrotechnologies and monitoring tools were used to develop an optimal agrotechnological fertilization system for saline soils.

3 Results

As a result of field and laboratory studies conducted on saline irrigated soils in the Surkhandarya and Bukhara regions, the relationship among soil fertility, fertilizer application rates, and crop productivity was comprehensively assessed. The studies were carried out during 2023–2025 on fields with different degrees of salinity, and the physicochemical properties of soils, fertilization treatments, and yield indicators were compared.

In the experimental areas, the level of soil salinity was determined based on electrical conductivity (EC), total salt content, and the composition of major nutrients. Moderately saline soils prevailed in the Surkhandarya region, whereas more strongly saline soils were dominant in the Bukhara region.

The results presented in the Table 1 indicate that with increasing soil salinity, the content of humus and plant-available nutrients in the soil progressively decreases. In Surkhandarya region, agrochemical parameters were relatively higher, suggesting that soil fertility in this area is somewhat better compared to Bukhara region.

In strongly saline conditions, the reduction in mineral nitrogen, available phosphorus, and exchangeable potassium confirms the necessity of optimizing the fertilization system. These findings served as a basis for subsequent agrotechnological experiments and were taken into account in determining the optimal fertilizer application rates.

In the study, different application rates of mineral fertilizers (NPK) were used, and their effects on crop yield were evaluated. The control treatment was conducted under unfertilized conditions, while the remaining treatments were examined at optimal and elevated application rates (Table 2).

The presented data confirm that fertilizer application rates have a significant impact on grain yield in saline soils. Compared to the control treatment, the application of mineral fertilizers increased yield by 30-60% in Surkhandarya region and by 30–65% in Bukhara region.

These results indicate that under saline conditions, plants have a higher demand for nutrients, and fertilization plays a crucial role in stabilizing crop productivity.

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The optimal fertilizer rate ($N_{180}P_{120}K_{90}$) provided the highest agrobiological efficiency in both regions. Although the application of a higher rate ($N_{220}P_{140}K_{100}$) resulted in a slight increase in yield, the identical lettering in the table indicates that this difference is not statistically significant.

This suggests that excessive increases in fertilizer application rates do not lead to substantial additional yield gains under saline soil conditions.

A comparative analysis across regions showed that

Table 1. Main Agrochemical Indicators of Soil in the Study Areas

Region	**Salinity level, EC (dS/m)**	**Humus (%)**	**Mineral N (mg/kg)**	**Available P_2O_5 (mg/kg)**	**Exchangeable K_2O (mg/kg)**
Surkhandarya (moderately saline)	3.2–4.8	1.10 ± 0.05	42 ± 2	28 ± 1.5	310 ± 12
Surkhandarya (strongly saline)	5.1–6.4	0.90 ± 0.04	36 ± 2	24 ± 1.3	295 ± 10
Bukhara (moderately saline)	4.5–6.2	0.80 ± 0.03	38 ± 2	22 ± 1.2	280 ± 11
Bukhara (strongly saline)	6.5–8.1	0.70 ± 0.03	31 ± 1.8	19 ± 1.1	265 ± 9

Table 2. Crop yield by fertilization treatments (centners/ha)

Treatment variant	Fertilizer rate (kg/ha N–P_2O_5–K_2O)	Surkhandarya (centners/ha)	Bukhara (centners/ha)
Control (unfertilized)	0–0–0	22.6 ± 0.8^c	18.9 ± 0.7^c
Low rate	120–80–60	29.4 ± 1.0^b	24.8 ± 0.9^b
Optimal rate	180–120–90	36.2 ± 1.1^a	31.6 ± 1.0^a
High rate	220–140–100	36.8 ± 1.2^a	32.1 ± 1.1^a

yield indicators in Surkhandarya were higher than in Bukhara across all treatments. This can be explained by relatively more favorable agro-climatic conditions and a lower degree of soil salinity in the region (Figure 1).

Overall, the results demonstrate that maintaining an optimal range of fertilization in saline soils ensures the highest biological and economic efficiency. The obtained findings have important scientific and practical significance for improving agrotechnological management in saline soils, substantiating optimal fertilizer application rates, and forecasting crop productivity.

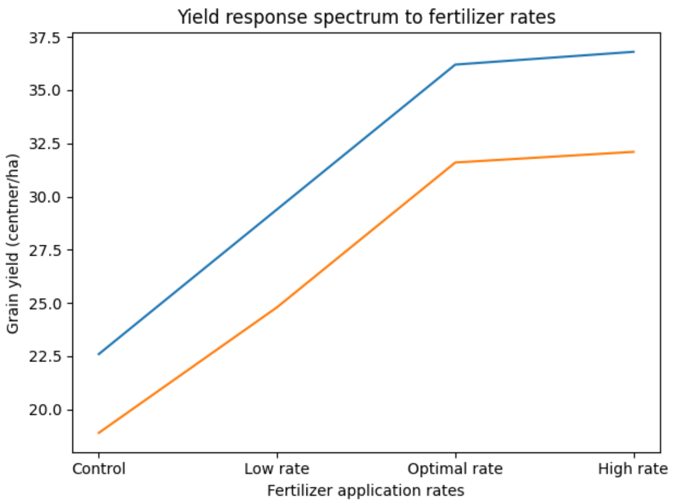

Figure 1. Spectral graph showing changes in yield with increasing fertilizer rates

The yield response spectrum demonstrated a parabolic-type reaction of grain yield to increasing fertilizer rates. In both Surkhandarya and Bukhara regions, the rate of yield increase sharply slowed after the optimal level ($N_{180}P_{120}K_{90}$), and the higher application rate did not provide a statistically significant advantage.

These findings confirm the existence of an optimal fertilization range in saline soils and indicate that excessive fertilizer application is agronomically and economically inefficient.

4 Conclusion

The results of the study conducted under moderately saline irrigated soil conditions of the Surkhandarya and Bukhara regions demonstrated that optimizing the fertilization system based on advanced agrotechnologies is a key factor in increasing crop productivity. As soil salinity increases, the ability of plants to absorb nutrients decreases, leading to reduced yields; however, the application of scientifically justified fertilizer rates can significantly mitigate these negative effects.

According to the field experiment results, the fertilization rate of $N_{180}P_{120}K_{90}$ kg/ha ensured the highest agrobiological and economic efficiency under saline soil conditions. Under this treatment, grain yield increased by more than 60% in Surkhandarya and by 65-70% in Bukhara compared to the control. Further increases in fertilizer rates did not result in a significant yield improvement, highlighting the necessity of maintaining an optimal fertilization range in saline soils.

Mathematical-statistical and regression analyses confirmed the existence of a stable functional relationship between soil salinity, fertilizer application rates, and crop yield. Although an increase in salinity led to a decline in yield, the application of optimal fertilization and appropriate agrotechnical measures improved plant nutrition conditions and contributed to yield stabilization.

It was established that the use of fertilizers in optimal amounts within an integrated agrotechnological approach enhances resource-use efficiency, preserves soil fertility, and ensures the stability of agroecosystems.

Thus, for the sustainable increase of crop productivity in saline soils, it is essential to apply scientifically substantiated optimal fertilization systems, regulate the water–salt regime, and employ modeling approaches. The obtained results provide an important scientific and practical basis for optimizing agricultural production in saline soils, improving fertilizer use efficiency, and forecasting crop yields.

Author Contributions: All authors contributed equally to the conceptualization, methodology, investigation, formal analysis, writing, review, and editing of the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding and was funded by the authors.

Institutional Review Board Statement: This research did not include any experiments involving human participants or animals, so Institutional Review Board (IRB) approval was not necessary.

Informed Consent Statement: This study did not involve human subjects; therefore, informed consent was not required.

Data Availability Statement: All data is shared in this manuscript.

Acknowledgments: The authors sincerely thank the editorial team and anonymous reviewers for their valuable comments and suggestions, which helped improve the quality of this manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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