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Effect of fertilizer application on watermelon yield in light sierozem soils: A mathematical modeling approach

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Abstract

This study presents mathematical models developed to predict watermelon (Citrullus lanatus) productivity in response to nitrogen (N), phosphorus (P), and potassium (K) fertilizer application on light sierozem soils in the Turkestan Region of Kazakhstan. Field experiments were conducted using a factorial design to observe growth dynamics, biomass accumulation, and yield performance under varying fertilizer combinations. Regression models were used to describe crop response, with high accuracy indicated by coefficients of determination (R^2) ranging from 0.86 to 0.98. The highest observed yield - 48.6 t/ha - was recorded with N200P150K60, closely matching the model's predicted yield of 47.5 t/ha. The results emphasize the significance of including both the main effects and interactions of N, P, and K factors up to the second degree in predictive modeling. These models offer a practical tool for optimizing fertilization strategies, improving yield forecasting, and supporting precision agriculture practices. The study underscores the value of integrating mathematical modeling with agronomic decision-making to enhance productivity and economic sustainability. Future research should focus on extending these models to various soil and climatic conditions to broaden their applicability.

Keywords: Crop response modeling, Factorial field experiment, Fertilizer efficiency assessment, Plant nutrient management, Sustainable land management.

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1. Introduction

1.1. Importance of Agrochemical Research

Agrochemical research plays a pivotal role in preserving, enhancing, and restoring soil fertility. It underpins the rational and efficient use of agricultural land, promotes ecological sustainability of soil resources, and ensures the precise application of fertilizers to strengthen national food security [1].

1.2. Fertilizer Use and Soil Fertility

Well-managed fertilizer application contributes significantly to agricultural productivity, helping to alleviate pressure on land resources and preventing unnecessary land-use expansion. In addition, fertilizers mitigate the risks of soil degradation and crop failure resulting from nutrient depletion and insufficient nutrient uptake [2].

1.3. Integrated Nutrient Management Approaches

Modern nutrient management increasingly relies on the integration of organic, mineral, and biological inputs [3, 4]. In practice, nutrient needs are estimated through field trials and balance-based calculations of nutrient removal from soils [5, 6]. However, these methods require refinement to account for soil-specific fertility conditions.

1.4. Challenges in Fertilizer Application and Precision Agriculture

Despite the adoption of precision irrigation technologies in many regions, crop yields often remain suboptimal due to imbalanced or inefficient fertilizer use [7]. Addressing this requires accurate determination of fertilizer rates and ratios based on local nutrient uptake standards and the specific needs of different soil types [8-10].

In high-input systems, balanced fertilization is essential for sustaining yields and protecting soil health. Yet, the overuse and mismanagement of agrochemicals have led to declining soil quality and broader ecological concerns [11, 12]. Therefore, regionally adapted fertilizer strategies are needed, particularly for soils affected by degradation or fertility decline.

Recent international studies have demonstrated the effectiveness of mathematical modeling in optimizing fertilizer regimes for watermelon cultivation. For example, Kang, et al. [13] applied the Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model to determine balanced nutrient requirements for Citrullus lanatus in China, providing clear recommendations to improve fruit yield while avoiding nutrient excess or deficiency. Similarly, Bui, et al. [14] used Response Surface Methodology (RSM) to optimize bio-organic fertilizer derived from watermelon rind, which improved Brassica juncea growth and highlighted the potential for sustainable reuse of agro-waste.

These studies emphasize the growing relevance of predictive models in tailoring fertilization strategies to local agroecological conditions, especially in arid and semi-arid climates. In Kazakhstan's southern and southeastern regions, field trials have confirmed the efficiency of balanced fertilization. Regression models derived from these trials have been useful for optimizing nutrient input to meet target yields [15-22]. Nevertheless, many historical recommendations failed to consider nutrient uptake efficiency, soil degradation status, and actual fertility levels [23-26].

1.5. Relevance of the Current Study

Developing accurate and locally calibrated fertilizer recommendations is essential for advancing precision agriculture. Pilot studies have shown that such data-driven approaches can significantly improve agricultural efficiency [27-29]. Field experiments incorporating factorial designs and computer-based data processing enable the development of updated nutrient coefficients tailored to soil and climate specifics [30, 31].

Due to the lack of modern national standards and growing soil degradation, many farmers continue to apply outdated fertilization practices. Both under- and over-application of fertilizers in inappropriate proportions reduce nutrient use efficiency and intensify environmental risks [32].

While traditional nutrient management relies on farmer experience and general application of major macronutrients-nitrogen, phosphorus, and potassium-modern strategies must integrate mathematical modeling that reflects soil fertility, degradation status, and local agroclimatic conditions [33, 34]. Such adaptive fertilizer management supports more efficient input use and reduces dependence on chemical fertilizers.

2. Materials and Methods

2.1. Field Experiment Location and Conditions

The field experiments were carried out on the lands of the "Sarkyrama" peasant farm located in the Otyrar district of the Turkestan region (Figure 1).

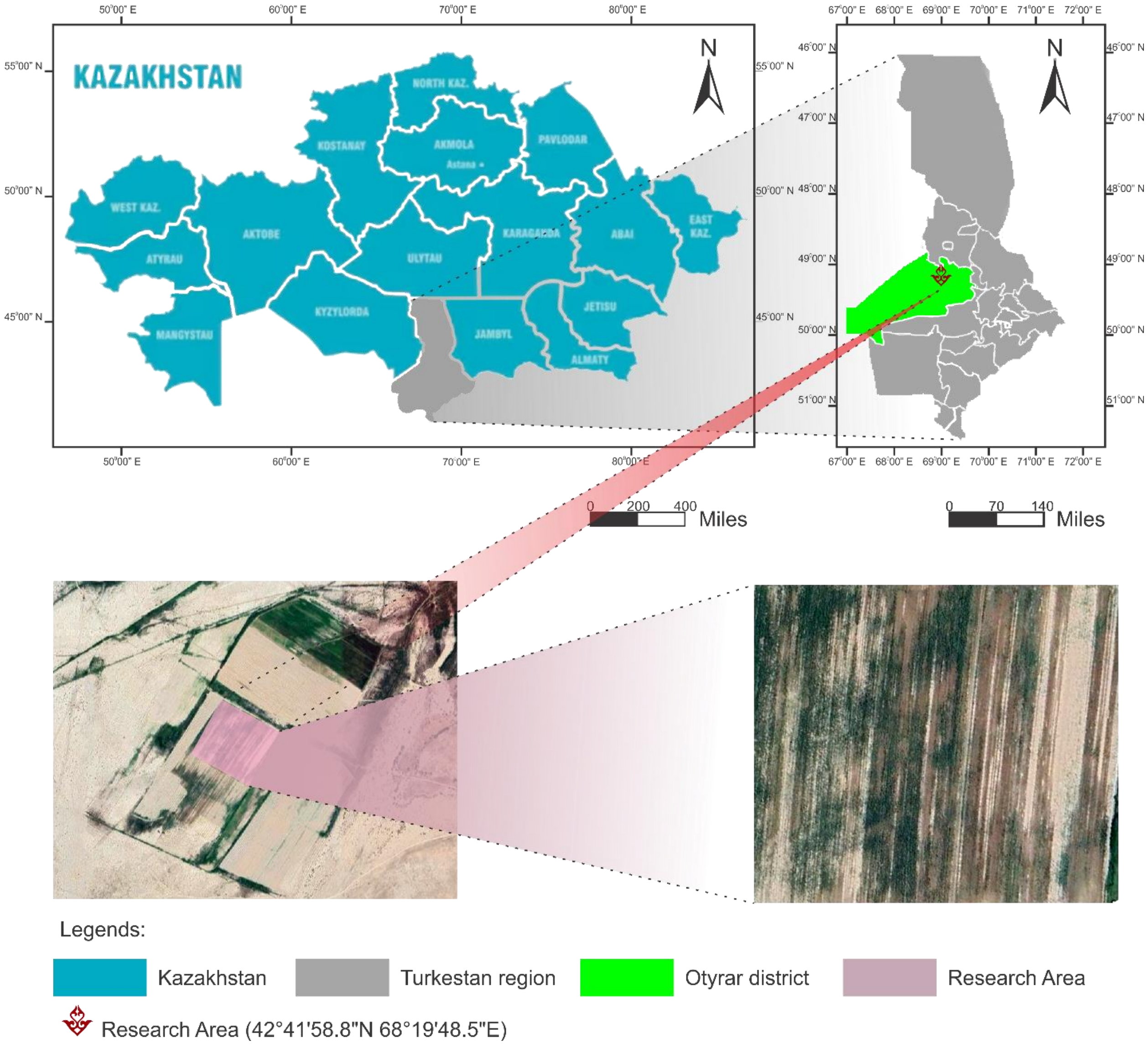

Figure 1.
Map of experimental field location.

2.2. Meteorological Data Analysis

Meteorological observations were obtained from the Arys weather station for the period from October 2023 to October 2024. Table 1 summarizes monthly precipitation and temperature data, including deviations from long-term averages.

During the period October 2023 - October 2024, 339 mm of precipitation fell, which is 73.2 mm above the long-term average (183.7 mm). This indicates wetter conditions during the study periods compared to the norm. The highest monthly precipitation was recorded in March (51.7 mm) and May (48 mm). May is especially notable, where precipitation amounted to 48 mm, which is 36 mm above the mean annual norm (12 mm).

Table 1.
Main meteorological indicators during the field experiments (Arys meteorological station).

Month	Precipitation (mm)			Temperature (°C)		
	Actual	Average	Deviation	Actual	Average	Deviation
October 2023	31.00	19.00	+12.00	15.00	10.73	+4.27
November 2023	46.80	31.00	+15.80	9.00	5.97	+3.03
December 2023	38.30	32.00	+6.30	0.80	-5.79	+6.59
January 2024	36.40	34.00	+2.40	1.00	-1.67	+2.67
February 2024	22.20	39.00	–16.80	1.50	-3.17	+4.67
March 2024	51.70	45.00	+6.70	8.40	7.74	+0.66
April 2024	34.80	22.00	+12.80	16.20	14.75	+1.45
May 2024	48.00	12.00	+36.00	21.00	19.74	+1.26
June 2024	0.50	3.00	–2.50	29.20	27.98	+1.22
July 2024	8.20	0.80	+7.40	29.80	27.09	+2.71
August 2024	0.00	1.00	–1.00	27.00	25.10	+1.90
September 2024	0.10	4.00	–3.90	20.00	16.87	+3.13
October 2024	21.00	19.00	+2.00	13.60	11.38	+2.23
Total / Avg	339.00	265.80	+73.20	15.22	12.42	+2.80

Low precipitation was observed in the summer months, which is typical for the climate of this region. June and August had less than 1 mm of precipitation, which is 2.5 mm and 1 mm below normal, respectively. The largest positive deviation was observed in May (36 mm), while the largest negative deviation was recorded in February (-16.8 mm), when precipitation was significantly less than normal. In general, deviations from the norm indicate high precipitation during the off-season and spring, while the summer months remain dry.

The average temperature for the period (Table 1) was 15.22 °C, which is 2.80 °C above the multiyear average (12.42 °C). This indicates a general warming trend during the period. The highest mean monthly temperatures were recorded in June (29.2 °C), July (29.8 °C) and August (27.0 °C), exceeding the multiyear average by 1.2-2.7 °C, which is typical for the region, but the average daily air temperatures were higher than usual for the whole period. The lowest average temperature was observed in December (0.8 °C), which is 6.59 °C above the multiyear average (-5.79 °C), as well as in January and February, where the temperature was close to zero but above the multiyear average. The most significant positive deviations were recorded in December (6.59 °C), indicating an anomalously warm winter for the region. Temperatures for all months under consideration are positive and noticeably higher than a multiyear average, indicating a warming trend. November and October 2023, as well as January and February 2024 were also warmer than usual.

Thus, the fall-spring period turned out to be more humid, which positively affected the growth and development of the watermelon. Moreover, if we take into account the traditional use of flushing irrigation in the winter-early spring period by farms in the region, whose lands are saline to varying degrees, moisture reserves in the pre-sowing period are usually sufficient to obtain friendly plant shoots and full growth and development before the resumption of summer irrigation. The entire accounting period is characterized by higher temperatures, especially in the winter and summer months, in relation to long-term indicators. This contributed to faster growth of agricultural crops in the spring and the formation of high yields of watermelon.

The Shaulder massif, where our experiments are conducted, is a zone with an arid and semi-arid climate, where soil salinization is one of the main agroecological problems. Saline soils here limit the possibilities for agricultural production and require special melioration and management methods [35].

Under conditions of limited natural leaching and high evapotranspiration, different types of salts such as chlorides, sulphates and carbonates accumulate in soils. The type of salinization and its intensity depend on soil composition, hydrological conditions, water table and irrigation patterns. According to early studies conducted in this region, chloride-sulfate and sulfate-chloride soils are the predominant salinity type. These types of salts have a depressing effect on plant growth, leading to lower yields. Salinization of soils in Shaulder massif is caused by several main factors. At close location of groundwater to the surface capillary rise of salts occurs, which leads to their accumulation in the upper layers of soil. High temperature and low air humidity promote active evaporation, due to which salts remain in the surface layers of soil, forming the so-called salt crust. Use of mineralized water for irrigation and insufficient ameliorative treatment lead to secondary salinization.

One effective method for improving saline soils in the region is regular leaching during the fall and early spring, significantly reducing salt levels and enhancing land productivity. While leaching and abundant precipitation contribute to decreasing salt levels in the root zone, they can have both positive and negative effects. Salt migration is influenced by the physicochemical properties of the soil, water composition, and its interaction with the soil profile. Leaching water removes soluble salts such as chlorides and sulfates from the profile, which is effective when soil permeability is good. Leaching can be either surface or deep and requires control of infiltration rate and water quality. Improper leaching or high groundwater levels can lead to the return of salts to the surface, causing secondary salinization.

Autumn-spring precipitation increases water infiltration and salt leaching to lower horizons. However, during dry periods due to capillary rise salts can return to the upper layers, creating a threat of secondary salinization.

2.3. Soil Properties and Pre-treatment Analysis

The experimental site is located on light sierozem soils with variable salinity. The principal agrochemical and physical characteristics of these soils, under watermelon (*Citrullus lanatus*) cultivation at the 'Sarkyrama' farm, are presented based on the results of a detailed soil survey conducted in the spring of 2024 (Tables 2–5). These soils have been under long-term agricultural use and are predominantly allocated for the cultivation of melon crops due to their favorable structure and fertility under irrigation conditions.

Table 2.
Main agrochemical indicators of soil of the plot under watermelon, farm "Sarkyrama", Otyrar district, Turkestan region, spring, 2024.

Soil layer (cm)	Humus (%)	pH	CO_2 (%)	Total N (%)	Total P (%)	Total K (%)	Easily hydrolysable N (mg/kg)	Available P (mg/kg)	Available K (mg/kg)
0–25	0.81	7.87	10.21	0.112	0.152	2.863	75.2	10	290
25–50	0.60	8.33	10.48	0.070	0.145	2.758	103.4	8	200
50–75	0.17	8.50	10.69	0.056	0.120	2.652	56.4	6	180
75–100	0.13	8.58	10.55	0.042	0.085	2.758	150.4	4	170

Table 2 shows that humus content gradually decreases with depth, from 0.81% in the 0–25 cm layer to 0.13% in the 75–100 cm layer, indicating a more fertile upper soil layer. Soil reaction in the profile changes from neutral in the upper layer (pH 7.87) to more alkaline in the lower layers (up to pH 8.58).

The concentration of total nitrogen is higher in the upper layer (0.112%) and decreases with depth (down to 0.042%). The content of total phosphorus and total potassium is also relatively high throughout the soil profile, ranging from 0.085% to 0.152% and 2.652% to 2.863%, respectively.

Analysis of plant-available forms of nitrogen, phosphorus, and potassium shows some atypical patterns for many soils [36]. Easily hydrolysable nitrogen is present in relatively high amounts throughout the one-meter soil depth, with uneven distribution: increasing from 75.2 mg/kg in the top layer to 103.4 mg/kg in the 25–50 cm layer, then decreasing to 56.4 mg/kg in the 50–75 cm layer, and rising again to 150.4 mg/kg in the 75–100 cm layer [37]. This uneven distribution likely results from early spring leaching irrigations, which cause nutrients and salts to migrate downward with water flow. The soil has very low available phosphorus content (4–10 mg/kg), while exchangeable potassium shows moderate availability (170–290 mg/kg).

Table 3.
Sum of absorbed bases and soil texture of the soil under watermelon, farm "Sarkyrama", Otyrar district, Turkestan region, spring, 2024.

Soil layer (cm)	Absorbed bases, mg-eq/100 g				Sand, %		Silt, %			Clay, %	Physical clay (<0.01 mm), %
	Sodium	Potassium	Calcium	Magnesium	1-0.25 mm	0.25-0.05 mm	0.05-0.01 mm	0.01-0.005 mm	0.005-0.001 mm	<0.001 mm	
0-25	1.60	0.46	13.37	5.45	1.08	34.54	31.79	4.89	17.12	10.60	32.60
25-50	1.06	0.58	15.35	3.47	0.80	48.52	18.39	9.81	11.45	11.04	32.29
50-75	1.46	0.26	10.89	5.45	0.55	11.08	52.94	4.48	25.25	5.70	35.43
75-100	1.41	0.23	13.37	10.40	0.59	8.76	61.66	24.50	3.68	0.82	28.99

The data in Table 3 show that calcium and magnesium dominate among the absorbed bases, ranging from 10.89 to 15.35 mg-eq/100 g and 5.45 to 10.40 mg-eq/100 g of soil, respectively. Soil texture analysis shows that the coarse (0.25–1.0 mm) and medium (0.05–0.25 mm) sand fractions in the upper half-meter of soil are 0.8–1.08% and 34.54%, indicating a significant presence of sand particles. These fractions enhance drainage, reduce compaction, and promote air circulation in the rooting zone. Larger silt-sized fractions (0.01–0.05 mm) comprise 31.79%, adding looseness to the soil. Particles in the 0.01–0.001 mm range may contribute to dust formation under strong winds. The soil also contains a moderate amount of clay-sized particles (<0.001 mm), which support water retention and nutrient holding capacity.

The content of physical clay (<0.01 mm) throughout the profile ranges from 29.0% to 35.4%, indicating high water-holding capacity, strong particle cohesion, and a tendency to form compact layers. These compacted layers can hinder root penetration, especially at depth, and may worsen water stagnation in the presence of significant salinity.

Thus, the soil has a predominantly fine-textured composition with moderate sand and silt fractions. The high clay content contributes to good moisture and nutrient retention but may require management practices to maintain aeration, particularly before planting.

Table 4.
Water extract from light sierozem soil under watermelon cultivation, "Sarkyrama" farm, Otyrar district, Turkestan region, spring 2024.

Soil layer (cm)	Amount of salts (%)	HCO_3^-	CO_3^{2-}	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^+	K^+
		mg-eq/100 g soil							
0-25	0.19	0.32	0.00	0.25	2.18	1.11	0.84	0.65	0.15
25-50	0.21	0.36	0.00	0.14	2.60	1.30	1.12	0.56	0.13
50-75	0.20	0.28	0.00	0.00	2.63	1.11	1.12	0.54	0.14
75-100	0.21	0.32	0.08	0.04	2.74	1.11	1.30	0.54	0.14

Analysis of the water extract Table 4 shows that the salt content varies from 0.19% to 0.21% along the profile, indicating uniform and moderate soil salinization.

Among the cations, calcium and magnesium predominate. Sulfates (SO4) are also present in significant amounts, especially in the lower layers, indicating sulfate-type salinization.

In summary, the soil under the watermelon plot is characterized by a fertile top layer, moderate salinity, and good water retention, creating favorable conditions for watermelon cultivation.

2.4. Experimental Design and Fertilizer Application

Field experiments under watermelon were laid out using an incomplete factorial design representing 1/9 (6×6×6) with 24 treatments in two replications and 4 blocks to even out the variegation of the area Figure 2.

Figure 2.
Layout of field experiments on watermelon (Citrullus lanatus) with fertilizer application on light sierozem soils at the "Sarkyrama" peasant farm, Otyrar District, Turkestan Region (2024). Source: Photograph taken by the authors.

The placement of experimental plots in the field was done according to the configuration and homogeneity of the field, and single doses of fertilizer were coded for ease of handling (Table 5 and 6).

Table 5.
Conditional coding of dose and fertilizer ratios.

# Variants	Conditional codes			Doses (kg dry weight/ha)		
	N	P	K	N	P	K
1	0	0	0	0	0	0
2	0	0	3	0	0	90
3	0	3	0	0	90	0
4	0	3	3	0	90	90
5	1	1	1	40	30	30
6	1	1	4	40	30	120
7	1	4	1	40	120	30
8	1	4	4	40	120	120
9	2	2	2	80	60	60
10	2	2	5	80	60	150
11	2	5	2	80	150	60
12	2	5	5	80	150	150
13	3	0	0	120	0	0
14	3	0	3	120	0	90
15	3	3	0	120	90	0
16	3	3	3	120	90	90
17	4	1	1	160	30	30
18	4	1	4	160	30	120
19	4	4	1	160	120	30
20	4	4	4	160	120	120
21	5	2	2	200	60	60
22	5	2	5	200	60	150
23	5	5	2	200	150	60
24	5	5	5	200	150	150

Table 6.
Scheme of coding of the treatments by blocks.

Repetition 2	Block 4	114	444	300	141	003	555
		030	411	252	225	522	333
	Block 3	414	330	552	303	255	033
		000	111	222	441	144	525
Repetition 1	Block 2	222	525	144	000	303	033
		414	441	255	552	330	111
	Block 1	030	114	411	225	300	444
		555	333	141	522	252	003

Regression analysis, as the main method of statistical treatment for experiments with incomplete factorial designs, allows:

- Assessing the impact of individual factors and their interactions on the indicator under study, helping to identify the most significant factors;
- Building a mathematical model of the relationship between the level of factors and the response indicator, enabling prediction of results under varying conditions;
- Interpolating data for conditions not represented in the original experimental designs;
- Testing statistical significance using coefficients of determination (R^2) and Fisher's criterion;
- Optimizing experimental conditions to determine factor combinations that maximize or minimize the target indicator [38-40].

The block method of plotting multivariate experiments allows us to increase the validity of the experiment by adjusting the data:
1) data on variants in blocks are counted;
2) the average yield per block is determined;
3) the difference (deviation) between the average for blocks and for the experiment as a whole is established. At that, positive value of this indicator indicates higher soil fertility within a block compared to other blocks as a whole, and vice versa. The obtained deviations (corrections) by blocks are added or subtracted to the corresponding actual indicators of variants by blocks. For further analysis and interpretation of the results, the obtained corrected experimental data are used. After adjustment, the data are processed by methods of variance and regression analysis.

The area of each experimental plot was 50 m².

The hybrid Au Producer (Hollar Seeds - USA), an improved variety of the well-known variety Crimson Sweet, was used as a study object of watermelon culture, which was sown on 1.06.2024. The maturity period under normal growing conditions is 75 days. The plant forms fruits weighing up to 14 kg with bright red flesh and has high taste qualities. Au - Producer is resistant to fusarium wilt, false powdery mildew, stem rot, and anthracnose. Resistance to diseases is one of the reasons for the high yield of the variety. It is well preserved and transported.

In the experiments with watermelon, the existing agro-technique of cultivation of crop in the region was used.

In the field experiments, soil sampling was carried out before laying the experiment and in the main phases of plant vegetation basic agrochemical analyses were performed for the content of basic nutrients and salt content in the arable and subsoil horizons. Ammonium nitrate (34 %), amorphous (12-52 %), and potassium sulfate (51 %) were used as fertilizers, which were applied in one step before sowing the crop.

2.5. Biometric and Analytical Methods

Biometric studies and plant sampling were conducted during the main phases of plant growth and development to study the dynamics of crop development and identify correlations with the applied fertilizer doses [41, 42].

Analytical procedures, including the determination of humus content [43] easily hydrolysable nitrogen, total nitrogen, mobile phosphorus (P_2O_5), total phosphorus, exchangeable potassium (K_2O), total potassium, and pH in selected soil samples, were carried out using standard, widely accepted methodologies [44].

Biometric observations related to plant developmental phases were conducted in accordance with the methodology of state variety testing of agricultural crops [41, 45].

Photosynthetic indices of the plants were measured according to the method proposed by Nichiporovich, et al. [46].

2.6. Statistical and Economic Analyses

The economic efficiency of the studied fertilizer treatments was evaluated based on actual technological costs and the cost of applied inputs.

Statistical processing of the obtained data was performed using variance, correlation, and regression analyses with the Excel software application.

In the current context of agricultural development and cropping systems, there is a growing need to forecast crop yields and assess productivity indicators throughout the crop development process. Yield forecasting relies on mathematical modeling and information technologies. The methodological and informational foundation for such assessments should include crop productivity models based on mathematical yield forecasting systems [47].

Numerous approaches exist for estimating crop productivity. These include mathematical and simulation models of varying complexity, built on experimentally derived dependencies between crop growth and meteorological data such as air and soil temperature, humidity, precipitation, vegetative activity levels, sowing dates, nutrient availability in soil, ameliorative conditions, and degrees of degradation [48-59].

It is important to note that, in Kazakhstan, there are currently no integrated, model-based technologies for yield forecasting used in agricultural production.

Traditional field experiments with a limited number of variants do not provide sufficient data to determine the effects and interactions of different types of fertilizers and ameliorants. In contrast, incomplete factorial designs allow identification of regularities in the effects and interactions of fertilizer doses over a wide range using mathematical methods [60-63].

To establish the quantitative dependence of crop yield on fertilizer effects and their combinations, researchers have often used regression models with half and whole degrees to describe pairwise interactions—especially with half degrees [64]. These models are particularly suited to describing mineral fertilizer effects on yield, especially in experiments with many factor levels. In such experiments, these models offer more precision than quadratic models, which may suffice when factor levels are limited and spaced widely [65, 66]. The gain in yield typically results from individual factor effects and pairwise interactions, while higher-order interactions account for no more than 5% of the total effect [67, 68].

Based on these principles, various regression equations were evaluated in the current study to describe yield formation processes in relation to fertilizer application under limiting natural conditions.

To model the relationships between biometric and yield indices of watermelon and fertilizer doses, regression analysis was applied to assess both main effects and interactions.

The regression equation was compiled using Excel software, with non-significant coefficients ($P<0.05$) removed stepwise. The consistency between theoretical and actual data was verified using the coefficient of determination (R^2).

A polynomial regression model including square root terms was used to describe the factor influence:

$$Y = a_0 + a_1N + a_2P + a_3K + a_4\sqrt{N} + a_5\sqrt{P} + a_6\sqrt{K} + a_7\sqrt{(NP)} + a_8\sqrt{(NK)} + a_9\sqrt{(PK)} \qquad (1)$$

Where:

Y – dependent variable (yield);

a_0 – intercept (baseline yield with no fertilizer);

$a_1, a_2, a_3...a_9$ – regression coefficients indicating the strength and direction of effects;

N, P, K – doses of nitrogen, phosphorus, and potassium fertilizers (kg/ha).

This modeling approach reflects prior research in Kazakhstan and globally on yield modeling using nutrient input interactions. The model allows determining the optimal fertilizer combinations under resource-limited and degraded soil conditions.

3. Results

3.1 Impact of Fertilizers on Biomass Accumulation

Table 7 presents the results of biometric observations, specifically the dynamics of raw aboveground biomass accumulation in watermelon plants at flowering and ripening stages, under various nitrogen (N), phosphorus (P), and potassium (K) fertilizer doses and ratios. The data indicate that treatments with higher doses of nitrogen and phosphorus (e.g., variants 17–24) resulted in the greatest biomass accumulation in both growth phases. Potassium also had a positive effect, though its influence was less pronounced compared to nitrogen and phosphorus.

Table 7.
Dynamics of raw aboveground biomass accumulation depending on fertilizer application, g/plant.

# Variants	Fertilizer Doses	Blooming	Maturation
1	N0P0K0	632	6046
2	N0P0K90	659	6505
3	N0P90K0	725	7863
4	N0P90K90	841	8339
5	N40P30K30	777	8117
6	N40P40K120	861	8116
7	N40P120K30	933	8828
8	N40P120K120	988	8614
9	N80P60K60	938	9610
10	N80P60K150	1020	9105
11	N80P150K60	1017	10153
12	N80P150K150	1024	8616
13	N120P0K0	894	7867
14	N120P0K90	872	7338
15	N120P90K0	1038	10429
16	N120P90K90	1095	9954
17	N160P30K30	1028	10517
18	N160P30K120	1140	8359
19	N160P120K30	1177	10864
20	N160P120K120	1266	9688
21	N200P60K60	1230	10849
22	N200P60K150	1338	9395
23	N200P150K60	1340	11757
24	N200P150K150	1350	10804
LSD 05		115	1156

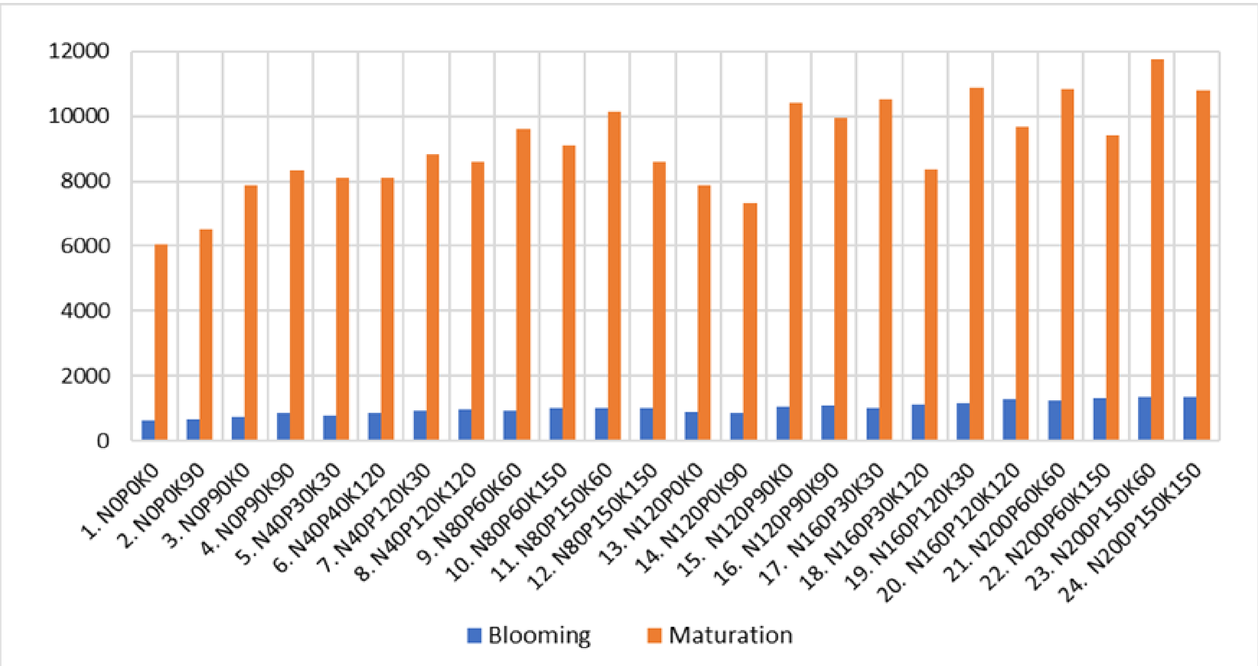

Figure 3.
Biomass accumulation dynamics by fertilizer dose and ratio.

As shown in Table 7 and Figure 3 significant increases in biomass were recorded with combined N and P application. The positive effect of potassium was evident at moderate levels, while excessive doses had diminishing returns. Similar trends have been observed in subtropical regions of China and India, where optimal N and P fertilization significantly influenced watermelon biomass and leaf area index [13, 69].

The regression equations to predict watermelon biomass accumulation as a function of N, P, and K doses by the flowering and ripening phases are shown below (Figure 4). Both equations have high coefficients of determination (R^2), indicating that the models explain most of the variation in biomass:

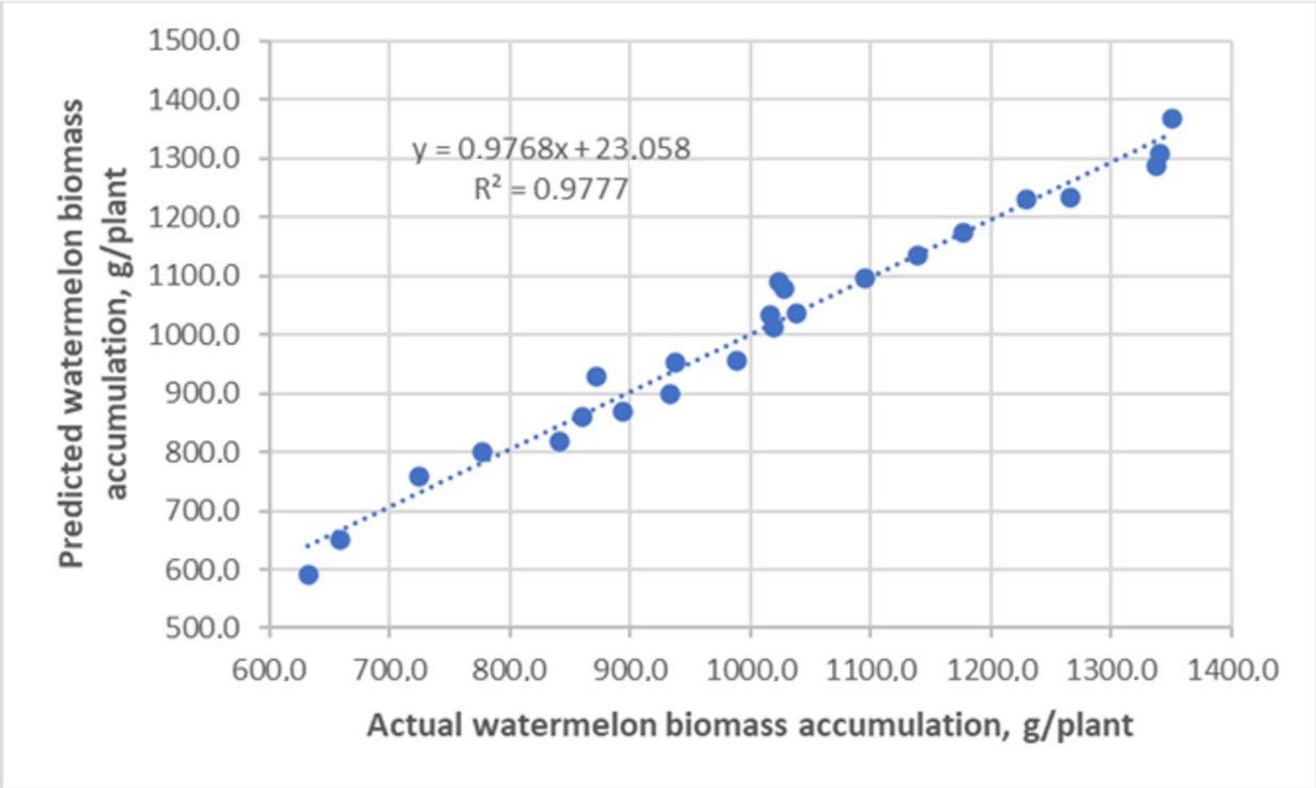

Figure 4.
Biomass accumulation model during flowering phase.

At the flowering stage (g/plant):

$$Y = 592 + 2.313N + 17.689\sqrt{P} + 0.649K; \quad R^2 = 0.978 \quad (2)$$

At the ripening stage (g/plant) (Figure 5):

$$Y = 6305.5 + 12.906N + 202.13\sqrt{P} - 21.06K + 197.16\sqrt{K}; \quad R^2 = 0.907 \quad (3)$$

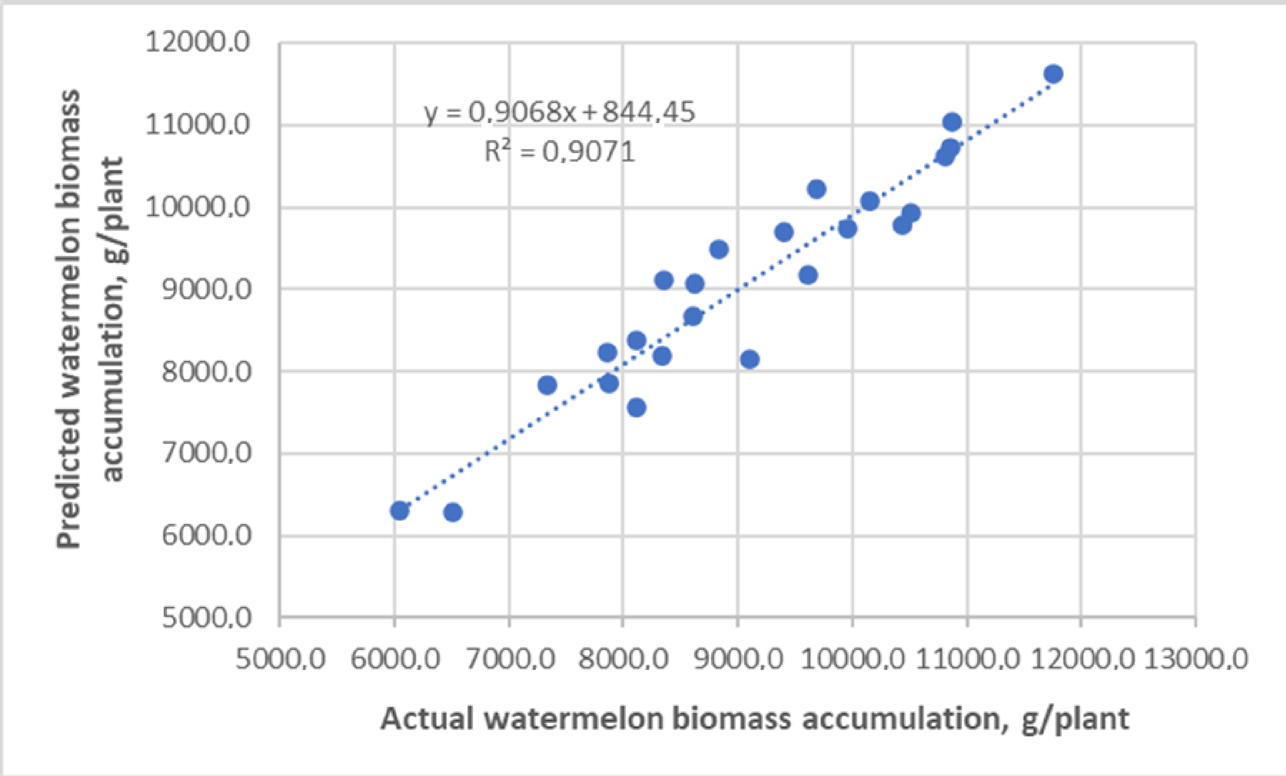

Figure 5.
Dynamics of accumulation of raw aboveground biomass in the ripening phase.

As Equation 2 shows, the increase in aboveground biomass of watermelon in the flowering phase for every 100 kg increase in nitrogen fertilizer dose is greater than that from an equivalent dose of phosphorus fertilizer, amounting to 231 and 177 kg, respectively. The effect of phosphorus increases at low doses but then stabilizes. The contribution of potassium in the flowering phase is much lower than that of nitrogen and phosphorus. Biomass is more sensitive to phosphorus and nitrogen than to potassium during flowering.

Equation 3 confirms that phosphorus remains influential during the ripening stage, while excessive potassium negatively affects biomass, supporting findings by Hazarika, et al. [70]. Thus, both nitrogen and phosphorus are important during ripening, with phosphorus having an even more pronounced effect than during flowering. Potassium shows a dual effect: small doses are beneficial, but large doses reduce biomass accumulation.

In summary, nitrogen and phosphorus make the greatest contribution to the formation of watermelon biomass, with phosphorus being most influential during the ripening phase. Potassium contributes positively in small doses but reduces biomass accumulation when applied excessively.

Table 8.
Yield indicators of watermelon depending on fertilizers, farm "Sarkyrama", Otyrar district, Turkestan region, 2024.

# Variants	Fertilizer doses	Gross yield, t/ha	Marketable yield, t/ha	Marketability, %	Average fruit weight, kg
1	N0P0K0	30.6	26.7	87.3	6.5
2	N0P0K90	30.9	28.6	92.7	6.9
3	N0P90K0	36.1	30.7	85.0	6.2
4	N0P90K90	38.5	34.5	89.8	6.2
5	N40P30K30	40.7	37.0	90.9	7.0
6	N40P40K120	38.8	35.6	91.9	7.1
7	N40P120K30	41.8	37.5	89.7	7.0
8	N40P120K120	39.0	34.0	87.1	6.2
9	N80P60K60	46.9	41.6	88.6	7.4
10	N80P60K150	39.3	36.4	92.7	7.0
11	N80P150K60	45.3	40.4	89.1	6.7
12	N80P150K150	36.5	32.7	89.5	6.1
13	N120P0K0	33.8	30.5	90.2	6.3
14	N120P0K90	34.7	31.0	89.4	5.8
15	N120P90K0	47.6	43.4	91.1	7.1
16	N120P90K90	45.7	41.0	89.8	6.9
17	N160P30K30	46.6	44.1	94.7	7.4

18	N160P30K120	37.7	34.7	92.0	6.6
19	N160P120K30	47.8	43.5	91.2	7.2
20	N160P120K120	41.0	36.1	88.2	6.7
21	N200P60K60	45.5	41.6	91.6	7.3
22	N200P60K150	39.4	34.9	88.7	6.9
23	N200P150K60	48.6	45.6	93.8	7.2
24	N200P150K150	43.3	37.0	85.5	6.6
LSD 05		3.43	3.06	2.66	0.65

3.2. Impact of Fertilizers on Yield

Table 8 illustrates watermelon yield indicators across the fertilizer variants. Optimal gross and marketable yields were observed in treatments with higher NPK levels, particularly variant 23 (N200P150K60), which recorded the highest gross (48.6 t/ha) and marketable yield (45.6 t/ha), with 93.8% marketability and 7.2 kg average fruit weight. Variants with zero or low doses (e.g., var. 1 N0P0K0 and var. 3 N0P90K0) showed significantly lower yields but sometimes higher marketability. The highest marketability (94.7%) was observed in var. 17 (N160P30K30), indicating that moderate fertilizer doses promote high-quality yield. High fertilizer doses (e.g., var. 24 N200P150K150) did not always result in high marketability, potentially reducing fruit quality despite relatively high gross yield.

Variants with higher nitrogen and phosphorus doses (e.g., var. 9 and 17) produced fruits with higher average weight, up to 7.4 kg, likely due to improved plant nutrition. Higher potassium doses did not consistently increase fruit weight, indicating a lesser role compared to N and P [69].

In summary, variant N200P150K60 was most effective for achieving maximum yield and marketability. Moderate doses, such as N160P30K30, ensured high fruit quality. These findings align with Hazarika, et al. [70] who showed that nitrogen and phosphorus primarily determine yield and fruit size, while excessive potassium negatively affects fruit set.

These results demonstrate that achieving quality watermelon crops requires applying optimal fertilizer doses, avoiding both deficiency and excess.

The variation in watermelon yield indices is well described by multiple regression equations, offering potential integration into advanced learning systems [68]. These equations describe the influence of nitrogen (N), phosphorus (P), and potassium (K) on gross yield (Figure 7), marketable yield (Figure 8), marketability (Figure 9), and average fruit weight (Figures 6, 10; Table 9). Coefficients of determination (R^2) indicate the extent to which each model explains variability in the respective indices.

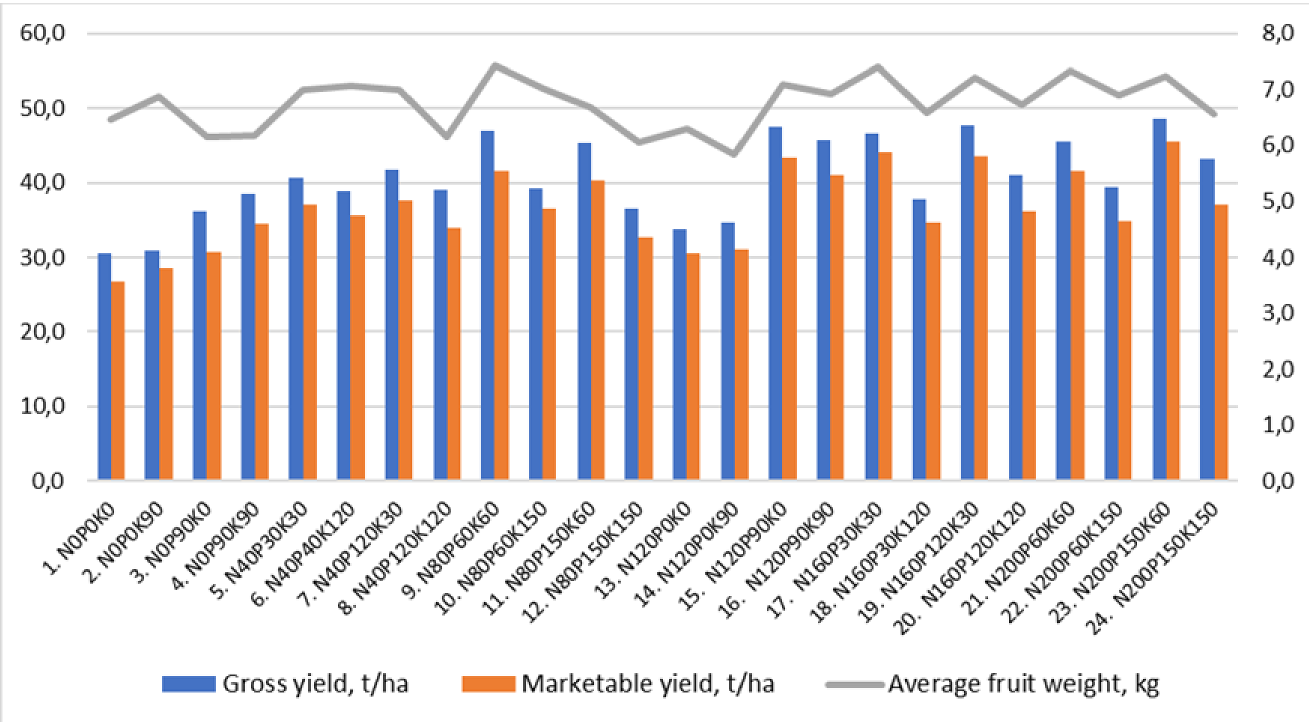

Figure 6.
Yield indicators of watermelon depending on fertilizers, farm "Sarkyrama", Otyrar district, Turkestan region, 2024.

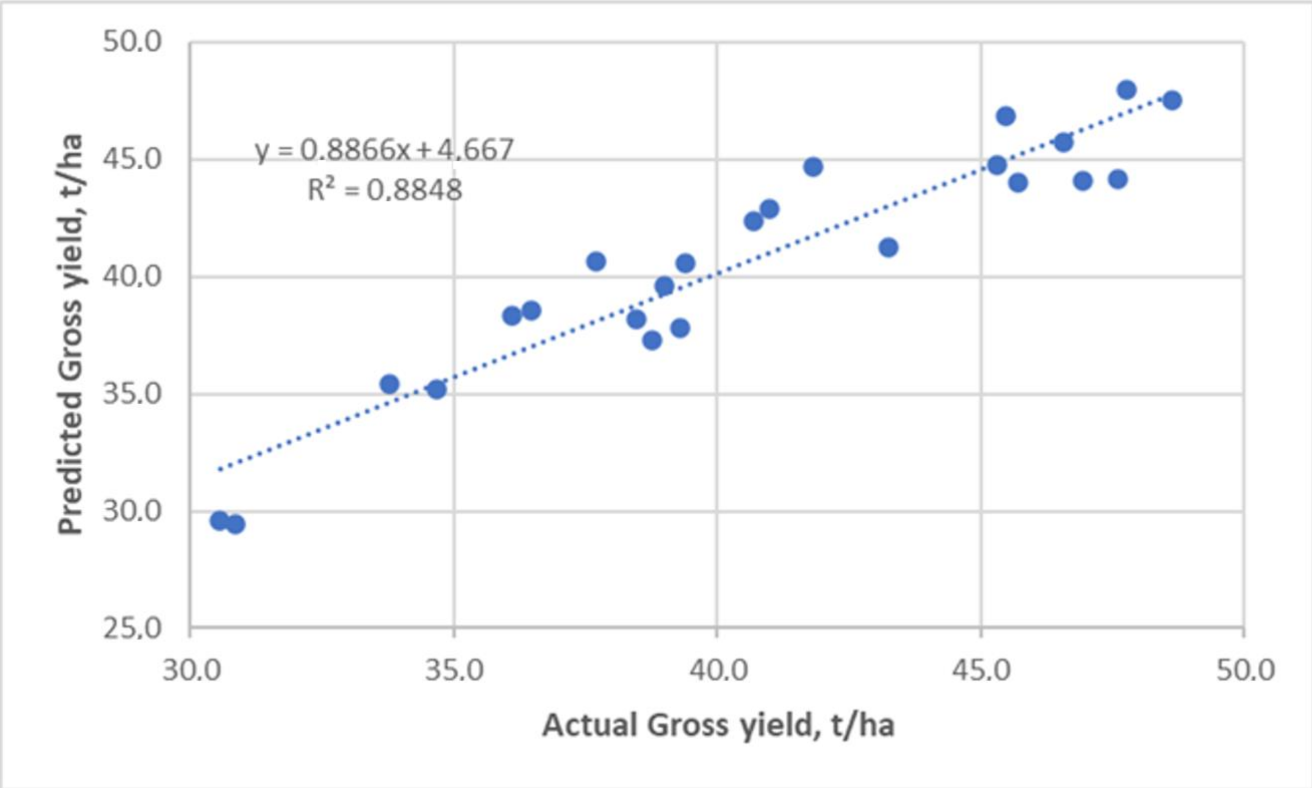

Figure 7.
The impact of (NPK) fertilizers on gross yield of watermelons.

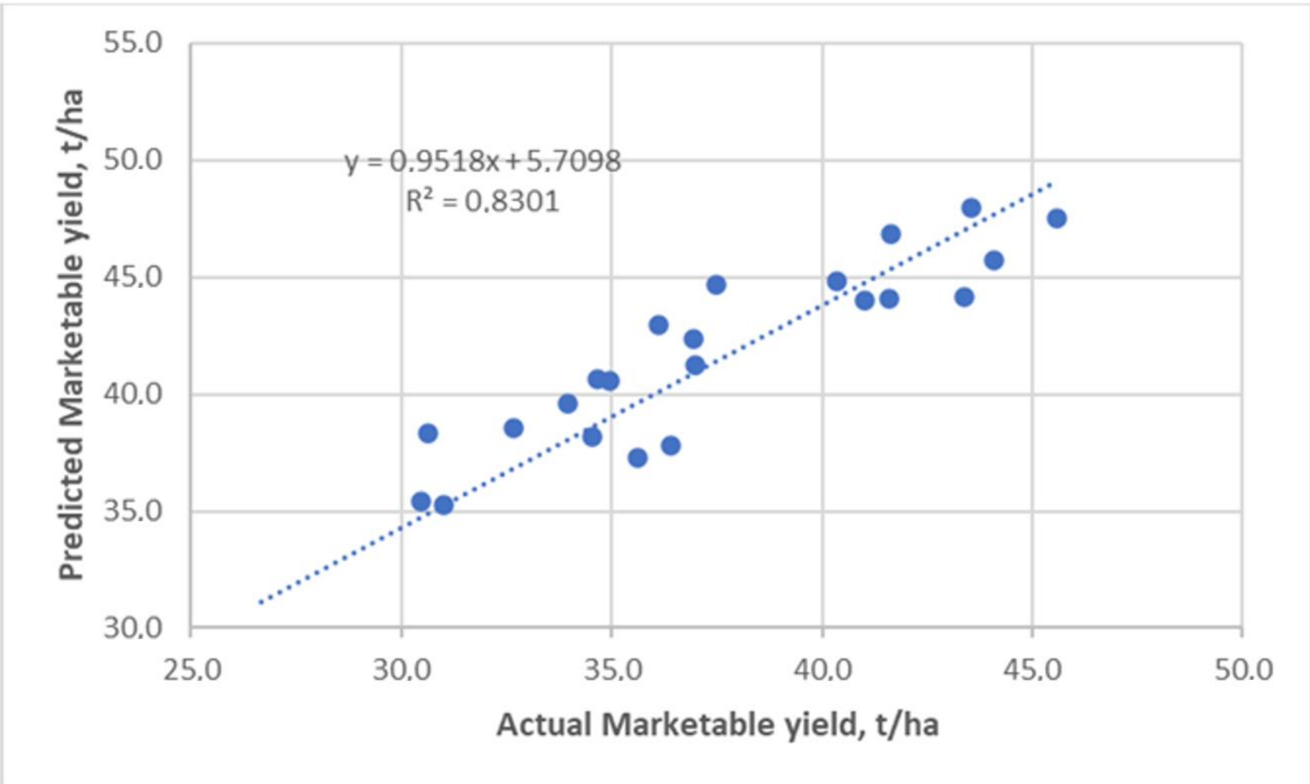

Figure 8.
The Impact of (NPK) Fertilizers on Marketable Yield of Watermelons.

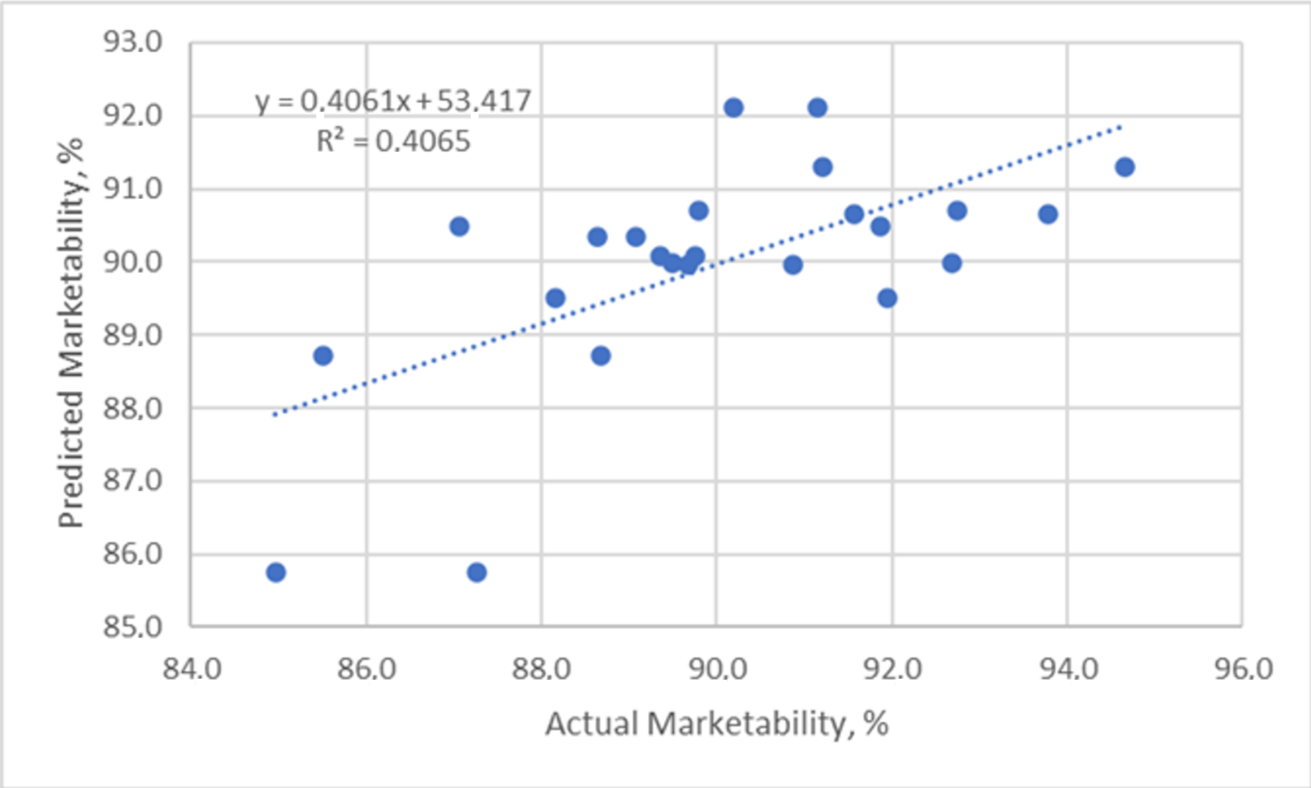

Figure 9.
The Impact of (NPK) Fertilizers on Marketability of Watermelons.

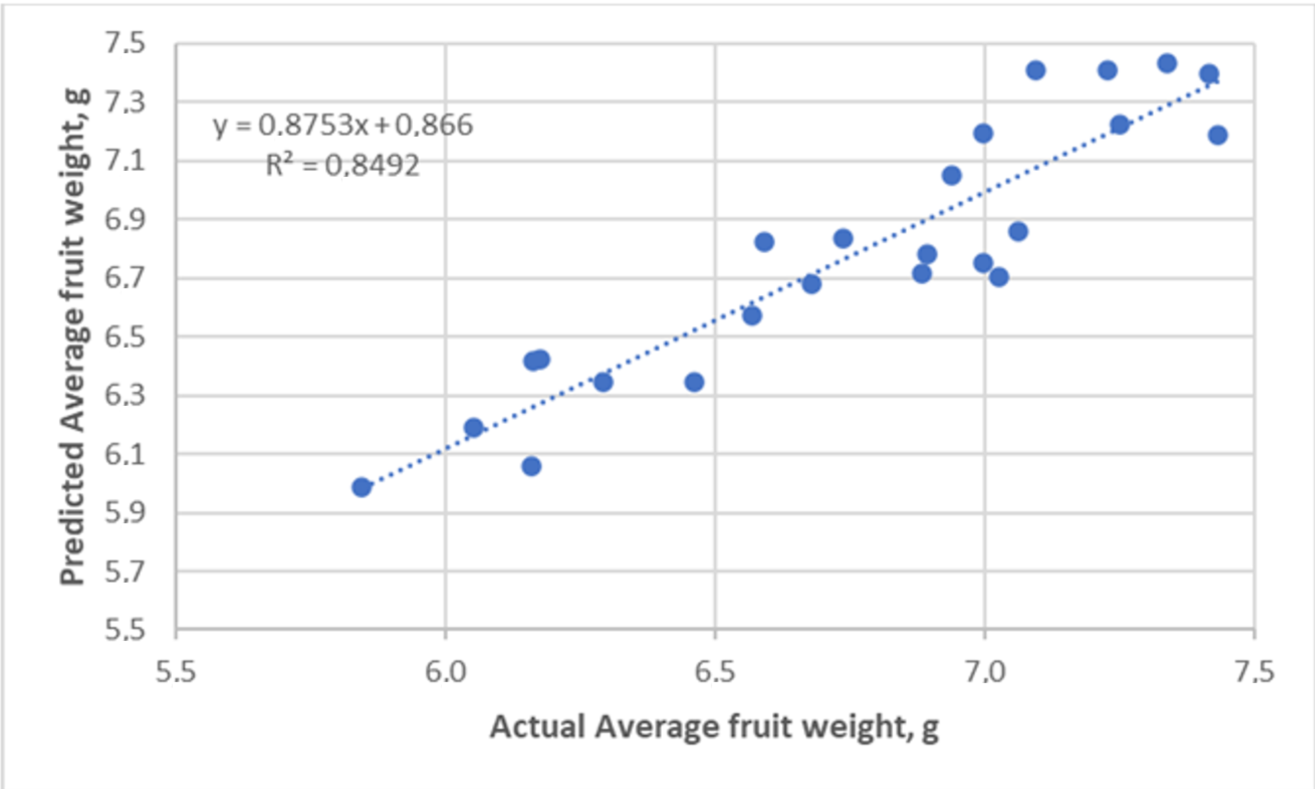

Figure 10.
The Impact of (NPK) Fertilizers on the Average Weight of Watermelons.

Gross yield (t/ha):

$$Y = 29.604 + 0.5285\sqrt{N} - 0.073P + 1.6153\sqrt{P} - 0.131K + 1.2257\sqrt{K}; \quad R^2 = 0.885 \quad (4)$$

Equation 4 shows that nitrogen increases gross yield, especially at low doses. In contrast, direct increases in phosphorus and potassium may reduce gross yield. Small doses of P and K positively influence yield, but their effects diminish or become harmful at higher levels.

Equation 5 describes the marketable yield of watermelon, indicating that low doses of all three nutrients positively influence outcomes, whereas high P and K levels reduce marketable yield.

Marketable yield (t/ha):

$$Y = 26.09 + 0.5243\sqrt{N} - 0.114P + 1.5358\sqrt{P} - 0.111K + 1.4179\sqrt{K} + 0.0599\sqrt{(NP)} - 0.058\sqrt{(NK)}; \quad R^2 = 0.911 \quad (5)$$

Nitrogen and phosphorus interactions promote marketable yield at moderate doses. High doses of nitrogen and potassium may reduce yields due to nutrient uptake competition.

Equation 6 shows that moderate doses of nitrogen and potassium improve marketability by enhancing fruit quality. However, excessive simultaneous application may lead to imbalanced nutrient uptake, decreasing marketability.

Marketability (%):

$$Y = 85.76 + 0.58\sqrt{N} + 0.52\sqrt{K} - 0.067\sqrt{(NK)}; \quad R^2 = 0.638 \quad (6)$$

Fruit weight, a key yield determinant, is influenced by genetic and agro-environmental factors. The availability of macro- and micronutrients directly affects watermelon development.

Average fruit weight (kg):

$$Y = 6.346 - 0.019P + 0.1498\sqrt{P} - 0.008K + 0.1147\sqrt{K} + 0.013\sqrt{(NP)} - 0.007\sqrt{(NK)}; \quad R^2 = 0.921 \quad (7)$$

Equation 7 shows that moderate doses of phosphorus and potassium increase fruit weight, while high doses may reduce it. Interactions between nitrogen and phosphorus are beneficial, while excessive nitrogen and potassium may decrease weight.

Thus, fruit weight is a complex result of varietal traits and environmental conditions, which can be optimized through balanced nutrient management.

3.3. Economic Efficiency of Fertilizer Use

Table 9 present economic indicators of watermelon production at different fertilizer levels. These include total costs, gross income, net income, production cost per unit, and profitability, providing a comprehensive view of fertilizer efficiency.

Table 9.
Economic indicators of watermelon production under different fertilizer treatments, “Sarkyrama” farm, Otyrar District, Turkestan Region, 2024.

Variant No.	Fertilizer doses	Total Costs (thousand KZT/ha)	Gross Income (thousand KZT/ha)	Net Income (thousand KZT/ha)	Cost Price (KZT/kg)	Profitability (%)
1	N0P0K0	433	1333	900	14	208
2	N0P0K90	531	1432	901	17	170
3	N0P90K0	522	1533	1010	14	194
4	N0P90K90	631	1726	1095	16	174
5	N40P30K30	565	1848	1283	14	227
6	N40P40K120	650	1780	1130	17	174
7	N40P120K30	629	1875	1246	15	198
8	N40P120K120	682	2079	1397	20	205
9	N80P60K60	675	2079	1404	14	208
10	N80P60K150	729	1821	1092	19	150
11	N80P150K60	725	2018	1293	16	178
12	N80P150K150	772	1633	861	21	112
13	N120P0K0	524	1524	999	16	191
14	N120P0K90	625	1549	924	18	148
15	N120P90K0	659	2169	1510	14	229
16	N120P90K90	744	2051	1307	16	176
17	N160P30K30	671	2204	1533	14	229
18	N160P30K120	718	1733	1015	19	141
19	N160P120K30	736	2177	1441	15	196
20	N160P120K120	794	1807	1012	19	127
21	N200P60K60	740	2082	1341	16	181
22	N200P60K150	803	1747	944	20	118
23	N200P150K60	816	2280	1464	17	179
24	N200P150K150	883	1850	967	20	110

Profitability declines with high potassium doses due to increased costs without proportional yield gains. Although potassium supports fruit quality and stress tolerance, excessive application raises costs and may interfere with calcium and magnesium uptake [71] potentially reducing productivity. This highlights the need for balanced fertilization.

Costs peaked in variant 24 (N200P150K150) at 883,000 KZT/ha, while the lowest was in variant 1 (N0P0K0) at 433,000 KZT/ha. Variant 23 (N200P150K60) achieved the highest gross income (2,280,000 KZT/ha).

The most profitable treatments were N120P90K0 and N160P30K30, yielding a profitability of 229% and the highest net income per hectare. These combinations optimized the balance between inputs and returns, confirming that moderate N and P with limited K ensure high profitability. These findings underscore the value of precision fertilization for maximizing both economic and agronomic outcomes.

4. Discussion

The findings of this study reinforce and expand upon existing research regarding the role of macronutrients in watermelon cultivation under semi-arid conditions. The significant influence of nitrogen and phosphorus on both biomass accumulation and fruit yield is consistent with earlier works on cucurbit crops, particularly melon, under similar soil and climate conditions in southern Kazakhstan [17, 18]. Our findings align with Amirov, et al. [18] who observed that balanced NPK fertilization significantly increased photosynthetic activity and biomass in melon, confirming the leading role of nitrogen and phosphorus in vegetative growth.

The nonlinear effects of potassium observed in this study-positive at moderate doses and negative at higher concentrations-reflect findings by Amirov, et al. [17] and da Silva, et al. [72] who documented nutrient antagonism in melon cultivation under saline irrigated sierozem soils. These results are also supported by international studies that report high potassium levels may reduce calcium and magnesium uptake, leading to physiological disorders and reduced fruit quality [72].

Similar conclusions were made by Wen, et al. [73] who applied the QUEFTS model to estimate nutrient requirements for melon and observed that nitrogen and phosphorus exert dominant influence on yield formation, especially when managed in balanced proportions. Their model-based analysis showed that excessive phosphorus had diminishing returns, which aligns with the quadratic response patterns observed in our study.

Likewise, Rolbiecki, et al. [74] demonstrated the effectiveness of nitrogen fertigation for increasing watermelon yields under light-textured soils in Poland. Their results correspond with our findings, especially regarding the efficacy of nitrogen application at low to moderate doses. Torun, et al. [75] also observed that nitrogen and potassium fertilization affected yield and nutrient uptake in grafted watermelon under the Çukurova region conditions, further validating the trends identified in this study.

From a modeling perspective, our use of polynomial regression equations with square root transformations mirrors techniques applied in related research on onion and potato crops under similar soil textures [19, 21]. In particular, the application of fractional power terms allowed for better representation of yield response curves and interaction effects among NPK nutrients. This aligns with global trends in modeling nutrient responses using flexible nonlinear terms to reflect diminishing returns and threshold effects in fertilizer use.

Importantly, this study introduces one of the first calibrated predictive models for watermelon grown on light sierozem soils in Kazakhstan. While previous regional studies focused on melon or onion [17, 19] our results demonstrate the transferability and scalability of regression-based fertilization modeling for watermelon, providing a scientifically grounded tool for precision nutrient management.

The incomplete factorial design used here also echoes the approach employed by Amirov, et al. [19] enabling a broader exploration of nutrient interactions without inflating treatment numbers. Combined with block adjustment, this increased the statistical robustness of our results and improved the extrapolation of findings to similar agro-ecological zones. Such methodological rigor enhances the practical relevance of the study for both research and advisory purposes.

Economically, our conclusions support the optimization-not maximization-of fertilizer inputs. Variants such as N200P150K60 and N160P30K30 yielded the highest profitability and productivity, validating similar conclusions in melon production systems where moderate N and P doses ensured the best return on investment [17, 19]. Moreover, our findings corroborate broader regional studies highlighting the inefficiency of high potassium application in saline-prone soils [20]. This echoes international principles of nutrient stewardship, emphasizing the 4Rs-right source, right rate, right time, and right place-for sustainable fertilization.

This study contributes to precision agriculture by delivering locally validated, model-based fertilization strategies tailored to light sierozem soils. Unlike previous studies, it establishes quantitative relationships between fertilizer dose and agronomic and economic outcomes for watermelon, thereby addressing a knowledge gap in Kazakhstan's irrigated crop systems. Future research should focus on integrating these empirical models into real-time agro-technological platforms, incorporating weather, soil diagnostics, and crop development monitoring to enable adaptive and economically efficient nutrient management.

5. Conclusion

This study provides clear evidence on the agronomic and economic efficiency of different NPK fertilizer combinations in watermelon production on light sierozem soils under the agro-ecological conditions of southern Kazakhstan.

Among all treatments, variant 23 (N200P150K60) demonstrated the highest conditional net income (1464,0 thousand tenge/ha), confirming its effectiveness in maximizing economic returns through balanced high-dose fertilization. In contrast, variant 12 (N80P150K150) resulted in the lowest net income (861,0 thousand tenge/ha) and the highest production cost (21 tenge/kg), highlighting the economic inefficiency of excessive potassium application when not matched by yield gain.

Minimum production costs (14 tenge/kg) were observed in the control variant (N0P0K0) and in variant 5 (N40P30K30), owing to their low input levels. However, these treatments did not achieve optimal yields or economic returns.

Maximum profitability (229%) was recorded in variants 15 (N120P90K0) and 17 (N160P30K30), which achieved a strong balance between yield, fruit quality, and input cost. The lowest profitability (110%) occurred in variant 24 (N200P150K150), where the marginal cost of additional fertilizers outweighed the economic benefit.

Overall, the most agronomically and economically optimal fertilizer regimes were found in variants 23, 15, and 17. These treatments achieved the best results in terms of gross yield, marketable yield, net income, and profitability, demonstrating that moderate to high nitrogen and phosphorus levels, with controlled potassium input, provide the best outcomes.

The study underscores that economically viable fertilization strategies are those that achieve high productivity while avoiding unnecessary input costs. Precision in fertilization-especially avoiding excessive potassium-can ensure sustainable and profitable watermelon cultivation under irrigation on light sierozem soils.

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