International Journal of Design & Nature and Ecodynamics
Vol. 18, No. 6, December, 2023, pp. 1391-1398
Journal homepage: http://iieta.org/journals/ijdne

Influence of Climate Conditions and Biofertilizers on Soybean Yield in Southeastern Kazakhstan

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https://doi.org/10.18280/ijdne.180612

Received: 16 August 2023
Revised: 15 October 2023
Accepted: 8 November 2023
Available online: 26 December 2023

Keywords:
abiotic factors, biofertilizers, climate influence, nitrogen-fixing microorganisms, plant structure, soybean, soybean yield

ABSTRACT

Soybean (*Glycine max*) serves as a crucial legume crop in Kazakhstan, with an annual production volume approximating 282,185 t. Nevertheless, in southeastern Kazakhstan, notably the Almaty region, minimal research has been conducted to investigate the impact of fluctuating weather conditions and biofertilizer variability on soybean yields. As a response to the dynamic climate, particularly in light of technogenic influences, and evolving biofertilizer formulations, the present study seeks to elucidate the effects of abiotic factors on soybean productivity and symbiotic process activation. Field experiments were conducted to assess the influence of abiotic conditions during critical soybean development stages. Comparisons were made between the years 2020, 2021, and 2022, with the low precipitation in June 2021 and high average daily temperatures during grain filling and bean ripening stages observed to create critical abiotic stress conditions. These conditions were found to significantly influence soybean yields, with 2020 and 2022 yielding superior performance in terms of bean and seed count, seed weight, and the weight of 1,000 seeds. Biofertilizers including BioEcoGum, Biogumus, HanselPlant, Manure, and Tumat were applied to the soil, and their impact on the soil's microbial population and soybean yield parameters was assessed. A marked increase in the number of nodules per plant, the weight of individual nodules, nitrogen-fixing microorganisms, bean count, seed count, and overall seed weight per plant was observed in biofertilizer-treated soil compared to untreated control plots. In conclusion, the study underscores the influence of abiotic stressors on soybean productivity in Kazakhstan's sharply continental climate. The findings suggest that the strategic use of biofertilizers offers a compelling approach to enhance soybean yields under these challenging conditions.

1. INTRODUCTION

Soybean (*Glycine max*) is of considerable importance in global agriculture, prompting extensive research on factors influencing its productivity on a worldwide scale and within diverse regions [1-12].

1.1 Climate

Among these factors, climate change is often regarded as the most critical determinant of crop productivity, prompting comprehensive investigations into its impact on individual plants and agroecosystems [13-18]. Specifically, soybeans exhibit sensitivity to temperature increases during the reproductive stage, especially during pollination and bean formation [19, 20]. A 1°C rise in the growing season temperature correlates with a 3.1% decrease in global soybean yield. Concurrently, insufficient precipitation during the bean formation phase is identified as a significant limiting factor for yield [21-23]. Other critical considerations include soil and climatic conditions of the cultivation region [24, 25], optimal sowing period [25], and tillering technology [26]. Excessive rainfall is deleterious to cultivated plants, negatively impacting yields [27], and diminished solar radiation, in turn, reduces plant photosynthesis and potentially affects yield potential [28].

1.2 Fertilizers

Beyond climatic conditions, the availability of macronutrients, particularly nitrogen, can ensure consistently high crop yields. While mineral fertilizers can provide nitrogen, their application involves additional costs and potential risks, including soil contamination by heavy metals in soybean crops [15]. For instance, field experiments conducted by Egyptian researchers demonstrated that the use of mycorrhizal fungi in combination with potassium humate produced optimal plant productivity, reducing the need for NPK fertilizers by 25% and increasing net income [29]. Thus, microbial inoculants, such as biofertilizers, phytostimulators, and biopesticides, offer an environmentally friendly alternative to synthetic fertilizers and chemical pesticides. The microorganisms contained within these biological fertilizers can stimulate plant growth, enhancing nutrient availability via processes of biological nitrogen fixation and phosphate dissolution in the soil and plant rhizosphere [30-32].

1.3 Territory

Regional specificity due to differing soil types and climates influences the impact of various factors on soybean yield. While some regions have seen extensive research into these key factors over recent decades, others remain under-studied, obscuring the understanding of principal factors and patterns that determine soybean yield [7-12]. Our study aims to investigate the influence of abiotic factors on soybeans cultivated in Kazakhstan, where soy represents a critical legume crop with an annual production volume of 237-282 thousand t over the last five years [3, 18]. Despite an area of over 1.5 million ha, the average yield is approximately 2.03 t/ha, nearly three times less than the global average [15, 18]. While the planted acreage of soybean in Kazakhstan has steadily increased since 2000, from 3.5 thousand ha to over 100 thousand ha in 2014-2021 [3, 18], modern methods to enhance soybean yields are underutilized, such as intensifying agricultural methods and increasing cultivation area. The government of Kazakhstan has initiated programs to expand soybean production in southeastern, eastern, and northern regions of Kazakhstan [13]. To further this initiative, it is critical to investigate the influence of various factors on soybean yield in these regions [13-18]. Research conducted at the Kazakh National Agrarian Research University (Almaty, Kazakhstan) from 2015-2018 demonstrated that resource-saving technology for soybean cultivation in a warming climate in southeastern Kazakhstan reduced the risk of drought in high-temperature years and optimized crop growth and development, increasing soybean yield by up to 23.8% [16]. However, these findings are insufficient for further yield enhancement. It is crucial to investigate the influence of weather changes and biofertilizers on soybean yield, particularly in southeastern Kazakhstan, a region with a high level of crop production. Consequently, our study aims to assess the influence of abiotic factors, including weather conditions and biofertilizers, on the activation of the symbiotic process and soybean productivity in southeastern Kazakhstan.

2. MATERIALS AND METHODS

Laboratory and field experiments were carried out during 2020-2022 at the farm of Baltabai 2030 Limited Liability Partnership (LLP) (Baltabai village, Almaty region, Kazakhstan) (latitude 43°30'23.256", longitude N E 77°32'38.76") (Figure 1).

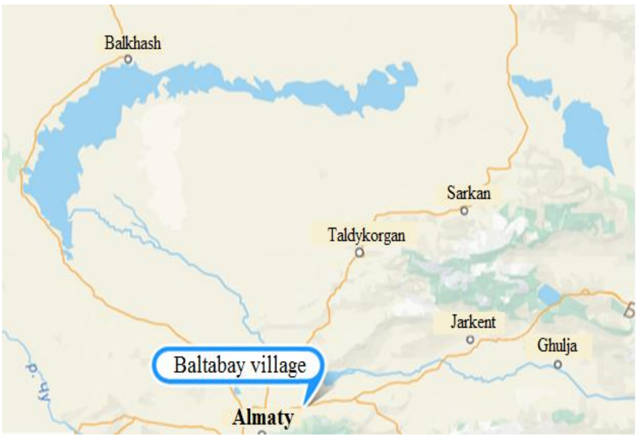

Figure 1. Map of the Almaty region (Google.com)

The climate of the study area is characterized as continental. The area belongs to the foothill desert-steppe zone with absolute elevations of 550-700 m above sea level. The soil of the experimental site is ordinary gray soil. The humus value is 1.3-1.5%, and the total nitrogen content in the upper horizons is 0.10-0.13 [33]. The climatic conditions in the years of the study are presented in Table 1.

The object of the study is soybean, Nazgum variety, midseason ripening, yield up to 4.0 t/ha, the weight of 1,000 seeds 260-280 g, 40-43% protein, and 22-23% oil accumulating in the seeds. The variety is well adapted to mechanized harvesting. The height of the plants is 90-120 cm, and the height of attachment of the lower beans is 12-14 cm. This variety is resistant to the lodging and cracking of beans during overmature stand.

Table 1. Climatic conditions during the study period (Almaty region, Baltabai village, Baltabai 2030 LLP, 2020-2022)

Month	Air Temperature, °C				Precipitation, mm			
	2020	2021	2022	Average Long-Term Value	2020	2021	2022	Average Long-Term Value
January	-4.0	-6.5	-1.2	-10.8	14.7	18.1	18.5	19.8
February	0.9	0.8	-2.8	-8.5	48.8	64.5	34.0	21.9
March	5.2	3.7	4.2	0.7	54.7	89.2	102.1	48.8
April	12.8	11.0	15.2	10.4	112.5	35.6	42.0	56.5
May	17.4	17.9	17.6	16.4	53.3	45.3	89.2	61.6
June	20.8	24.2	22.3	21.2	30.0	12.6	42.0	53.9
July	23.3	28.0	24.5	24.1	16.6	18.8	14.6	26.6
August	22.9	27.0	20.7	22.1	34.0	7.7	17.0	21.3
September	15.3	17.3	19.3	16.5	19.3	12.8	3.9	15.7
October	8.2	6.4	7.6	8.1	12.5	67.0	23.2	28.3
November	-1.1	-0.1	0.3	-0.5	30.8	34.1	29.7	38.9
December	-7.4	-0.2	1.3	-7.6	12.0	18.3	14.0	29.1

Table 2. Characteristics of biofertilizers used in the study

No.	Name	Country of Manufacture	Product Characterization	Microorganisms and Components Used in Biofertilization
1	HANSEPLANT-ALMATY (Koppert Biological Systems)	Netherlands	Complex nutrition with a balanced combination of microorganisms, leaf dressing, and natural, liquid, concentrated NPK fertilizers. It is used in the form of several separate preparations, which are introduced sequentially when growing crops	SeedSpor S: Mycorrhiza, *Trichoderma asperellum*, *Bacillus subtilis*, *Bacillus megaterium*, *Bacillus* sp., seaweed, oils, microelements; Fe+Zn; Smart Start P: triple superphosphate, superphosphate, (N)3.8%, (P_2O_5) 33%, (K_2O) 0.1%, (S) 2.3% (Ca) 18%; HanseBiosulfur: 100% natural, micron, liquid fertilizer based on hydrophilic S; Prairie Pride A: mineral liquid fertilizer for additional fertilizing, (N) 1%, (P_2O_5) 3%, (K_2O) 3%; Prairie Pride B: a concentrated complex, NPK mineral fertilizer with sulfur, (N) 10%, (P_2O_5) 40%, (K_2O) 6%; (S) 4%; Re-Ject: leaf fertilizer that protects the surface of the treated plant from excessive evaporation, contains Pongamia seed oil (Pongamia glabra)
2	BioEcoGum	Kazakhstan	A dark brown liquid suspension obtained from vermicompost processed by compost worms in special nurseries of various organic raw materials, by enriching it with nutrients in a form accessible to plants	Contains the following macronutrients (g/l): N: 5, P_2O_5: 10, K_2O: 10, Ca: 7, Mg: 2, and microelements (g/l): Mn: 30, Mo: 30, Zn: 25, Se: 3
3	Tumat	Uzbekistan	Tumat organic humic fertilizer is obtained from leonardite and sapropel, with the addition of bone meal and oilcake (Kazakh patent No. 35883 C05F 11/02)	It contains humic acids, fulvic acids, organic acids, some necessary macroelements (NPK), and microelements (Zn, Fe, Cu, Mn, Ni, Cr, Si) in a form accessible to plants
4	Manure		Includes ungulate feces and straw	Contains nutritional elements including nitrogen (N), phosphorus (P), and potassium (K) and trace elements, such as iron (Fe), zinc (Zn), and others

Table 3. Experimental conditions for determining the effect of fertilizers on soybean yield

Variant	Conditions of the Experiment
1	Control variant (without the use of biologization means);
2	Manure (30t/ha);
3	Biogumus (2 t/ha);
4	Treatment with the Hanseplant-Almaty complex program (Koppert B.V., the Netherlands) including seed treatment before sowing (SeedSpor S, 2.0 ml/1 kg of seeds); application of starting fertilizer during sowing (Smart Start P, 150 kg/ha); first leaf dressing in the 2-4 leaf phase (HanseBiosulfur, 5.0 l/ha); and second leaf dressing in the 6 leaf phase (Prairie Pride A, 3.0 l/ha + Prairie Pride B, 7.5 kg/ha + Re-Ject, 1.0 l/ha);
5	Treatment with BioEcoGum fertilizer (Kazakh Research Institute of Soil Science and Agrochemistry named after U.U.Uspanov, Kazakhstan) including seed treatment before sowing, 0.25 l/100 kg; the first leaf dressing in the 2-4 leaf phase, 5 l/ha; and the second leaf dressing in the 6 leaf phase, 5 l/ha;
6	Treatment with Tumat fertilizer (Kazakh Research Institute of Soil Science and Agrochemistry named after U.U.Uspanov, Kazakhstan) including seed treatment before sowing, 30 ml/100 kg; first leaf dressing in the 2-4 leaf phase, 1 l/ha; and second leaf dressing in the 6 leaf phase, 1 l/ha.

Sowing was carried out at the optimal sowing time for this zone in 3 stages. The sowing of soybeans was carried out with a double-line precision seeding drill (50 × 20 cm). The seeding rate is 600 thousand germinating seeds/ha. The depth of sowing seeds is 4-6 cm. The following agrotechnical measures were carried out: in autumn, mouldboard plowing was carried out to a depth of 21-23 cm; in spring, pre-sowing soil preparation was carried out to a depth of 8 to 10 cm (1-2 times). The growing season of soybean cultivation in the Almaty region is 138-143 days, from late April or early May to the end of September.

The characteristics of the studied biofertilizers and the experiment design to determine the effect of various fertilizers on soybean yield are presented in Tables 2 and 3. These biofertilizers are used according to the manufacturer's recommendations to increase plant productivity. The choice of biofertilizers was made based on their availability in Kazakhstan. Some of them are imported to Kazakhstan, and others are developments of Kazakh research institutes. The application scheme was drawn up considering the recommendations of fertilizer manufacturers.

The activity of the symbiotic apparatus of soybean roots was carried out by randomized selection of a soil monolith with roots and aboveground biomass of plants from an area of 0.1 m^2. Recording the number and weight of nodules by counting and weighing [34].

Determination of the number of nitrogen-fixing microorganisms on agarized nutrient media by the Koch method, by sowing soil suspensions from 1:103, 1:104, and 1:105 dilutions on Ashby agarized medium [32].

Recording the harvest from each plot and simultaneous determination of its humidity, with recalculation to the standard humidity of 14%.

All heavy metals content was determined by flame atomic absorption spectroscopy (AAS) with a hollow cathode lamp and an air-acetylene flame (AnalytikJena AG, novAA 350, Jena, Germany). The wavelengths (nm) used for the determination of the analyses were the following: Cu: 324.8 nm, Zn: 232.0 nm, Pb: 283.3 nm, Fe: 243.8 nm, Ni: 232.0 nm, Zn: 213.9 nm, Co: 240.7 nm, and Cd: 228.8nm. The gas flow was 50 $dm^3 \cdot h^{-1}$ and the aspiration rate was 5 $cm^3 \cdot min^{-1}$. Single-element hollow cathode lamps (HAMAMATSU PHOTONICS K.K., Hamamatsu, Japan) of all heavy metals were used as light sources. These heavy metals were chosen for analysis because they may affect soybean yield.

We weighed 1-2 g of homogenized dried sample and put the weighted sample into a 50 ml quartz crucible. Then we placed the sample into a cool muffle furnace and raised the temperature of the oven to 500-550℃ for a few hours. After that, the ash was dissolved in 25 mL 1% nitric acid and diluted to the volume of a 25 ml volumetric flask [35].

All calibration curves for AAS were prepared using Mn, Cu, Co, Ni, Cd, Fe, Zn, and Pb atomic absorption stock standard solutions (1.0 $g \cdot L^{-1}$) by making successive dilutions. Then, we prepared a working calibration solution from 0.1 mg/mL to 2.0 mg/mL. For the preparation of all the solutions, ultrapure water obtained from a MilliQ system (from Merck Millipore) was used. All chemical reagents used were of standard analytical grade, including nitric acid (65%) and hydrogen peroxide (30%) (Merck).

Statistical methods were used to process data and establish correlations [32, 36-40], which can be used to quantify factors influencing the spread and development of plant diseases [32], their physiological indicators [36], the composition of mycotoxins in plants and plant yield parameters [37], as well as for quantifying the impact of changes in climatic indices on the observed yield, including the reverse exclusion of stepwise regression [38] and analysis of the main components [39]. This method, however, does not consider the main mechanisms of the impact of climate change on yields, which are important to understand to control climate change [40].

Statistical data processing was conducted using the Integrated Development Environment (IDE) for the R programming language. Since our study had three or more samples, the significance of the variables was determined using a nonparametric one-factor Kraskel-Walliss analysis of variance using the P value. The critical significance level is <0.05 [24, 27]. We built boxplots of the effect of the year factor on the structure of soybean yield and the influence of the factor of the chemical elements type on their composition in soybean seeds.

3. RESULTS

The amount of precipitation in the autumn period of 2020 contributed to a low accumulation of moisture in the soil. The deviation from the average annual values in the autumn months of 2020 was -4.7 mm; -34.7 mm; and -22.2 mm. The average daily temperature in June 2021 and 2022 exceeded the average annual value of this parameter by +1.9℃ and +3.1℃, respectively.

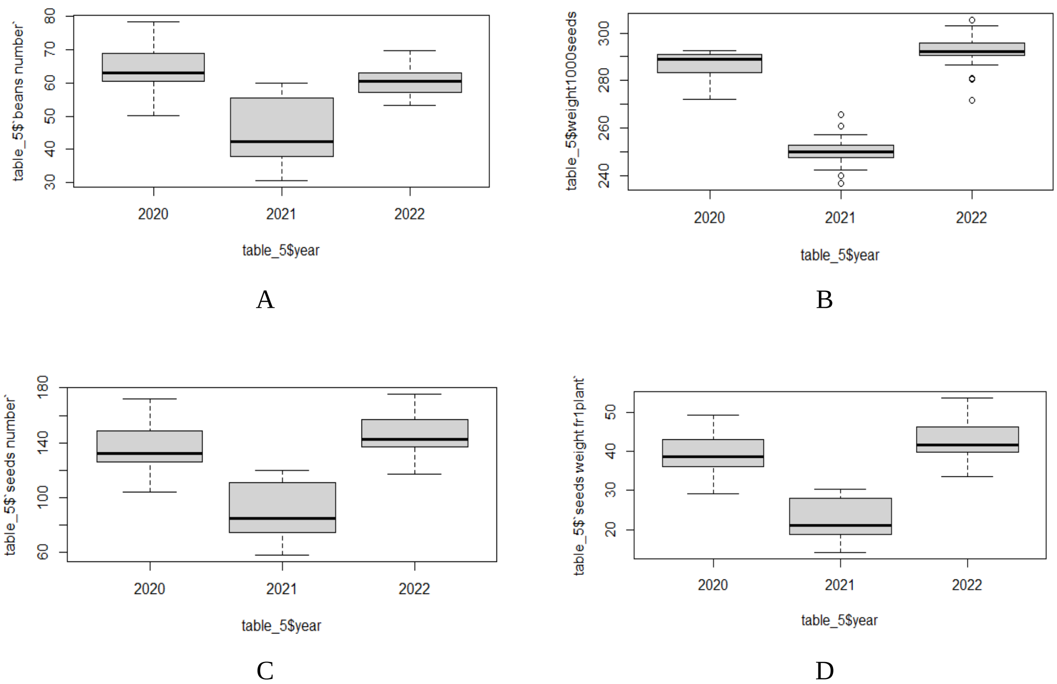

Figure 2. Boxplot effect of the year factor on the structure of soybean yield (2020-2022)

Note: A: the influence of the year factor on the number of beans, pcs; B: the influence of the year factor on the number of seeds, pcs; C: the influence of the year factor on the weight of seeds from 1 plant, g; D: the weight of 1,000 seeds, g.

Table 4. The effect of biofertilization on the number of nodules, their weight, and the number of nitrogen-fixing microorganisms in the soil (2020-2022)

	Preparation	BioEcoGum	Biogumus	HansePlant	Manure	Tumat	Control	P-Value
Roots_Number per 1 Plant	Before treatment	35.4	36.3	32.6	35.5	41.5	37.5	0.483
	After 15 days	52.1	62.5	58.2	58.1	68.7	37.8	<0.001***
Weight of 1 Tuber_g	Before treatment	0.6	0.7	0.6	0.7	0.5	0.5	0.12
	After 15 days	1.1	1.1	1.0	0.9	1.0	0.7	<0.001***
CFU per g of Soil		12.2×10^6	12.7×10^6	15.1×10^6	9.2×10^6	12.6×10^6	8.1×10^6	<0.001***

Note: *** indicate the level of significance.

Table 5. Effect of fertilizers on soybean plant productivity (average values for 2020-2022)

Preparation	Beans Number	Seeds Number	Seeds Weight from 1 Plant, g	Weight of 1,000 Seeds, g	The Yield of Soybean Oilseeds, t/ha
Hans Plant	66.6	147.3	41.9	281.6	4.3
Biogumus	52.8	114.0	31.9	275.7	3.4
BioEcoGum	62.4	139.6	39.3	279.3	4.0
Manure	51.9	113.9	32.6	278.0	3.4
Tumat	57.6	125.8	35.3	276.8	3.7
Control	47.8	100.3	27.4	267.2	2.6
P value	<0.001***	<0.01	0.002	0.113	<0.01

Note: *** indicate the level of significance.

A significant influence of the year factor on the structural indicators of soybean yield was established (P<0.001). Low precipitation in June 2021 (12.6 mm) and higher average daily air temperature during the period of grain filling and ripening (27-28.2°C) compared to the same period in 2020 and 2022 (30-42 mm and 23.9-24.5°C) also created critical abiotic conditions that affected the yield of soybean samples. In 2021, the number and weight of seeds per plant decreased significantly compared to other years, but in 2022 these indicators increased and returned to the level of 2020. The average number of beans per 1 plant in 2020 was 64.2, in 2021 44.6, and in 2022 60.8. The number of seeds in 2020 was 136.2, in 2021 was 88.8, and in 2022 was 145.6. The indicators of the weight of seeds per plant amounted to 39.4 g in 2020, 22.2 g in 2021, and 42.6 g in 2022. The weight of 1,000 seeds equaled 287.2 g in 2020, 250.1 g in 2021, and 292.0 g in 2022 (Figure 2).

Studies have shown that the use of biological fertilizers like BioEcoGum, Biogumus, HanselPlant, Manure, and Tumat statistically significantly (P<0.0001) increased the number of nodules per 1 plant (52.1-68.7) and the weight of 1 nodule (0.9-1.1 g) compared with the control variant (37.5 nodules; 0.7 g) (Table 4). The statistical significance of the influence of the type of biofertilizers on the number of nitrogen-fixing microorganisms in the soil has been established (P<0.001, Table 4). The least amount of microorganisms was observed in the control variant, without treatment (8.1×10^6 CFU in 1 g of soil). In the Manure variant, it was 9.2×10^6, in the BioEcoGum, Biogumus, and Tumat variants, their number was at the level of $12.2\text{-}12.7\times10^6$ CFU in 1 g of soil, and in the HansePlant variant, it was the highest 15.1×10^6 (Table 4).

The analysis of structural indicators showed that the use of biofertilizers significantly increased the yield of soybean oilseeds by increasing the number of beans, seeds, the weight of seeds per plant, and the weight of 1,000 seeds (Table 5). The best yield values were observed in the Hans Plant and BioEcoGum variants (4.3 and 4.0 t/ha, respectively). They were slightly lower in the Tumat (3.7 t/ha), Biogumus, and Manure variants (3.4 t/ha). The lowest yield was observed in the version without fertilizers (the control variant; 2.6 t/ha) (Table 5).

We noticed no influence of weather factors and bio-fertilizers on the quantitative composition of chemical elements in soybean seeds. In the seeds of this culture, we found Cd (0.06 mg/kg), Co (0.69), Cu (14.3), Fe (43.12), Mn (16.80), Ni (0.77), Pb (0.35), and Zn (38.44) (Figure 3).

Thus, weather had an impact on soybean yields: during the period of bean ripening. The weight of seed oil in normal moisture conditions in 2020 and 2022 was noticeably higher than in the dry year 2021. The use of biological fertilizers, including vermicompost, microorganisms, nitrogen-phosphorus-potassium, and organic fertilizers, significantly increased the number of nitrogen-fixing nodules by 1 and the number of nitrogen-fixing microorganisms and crop yield compared to the control option.

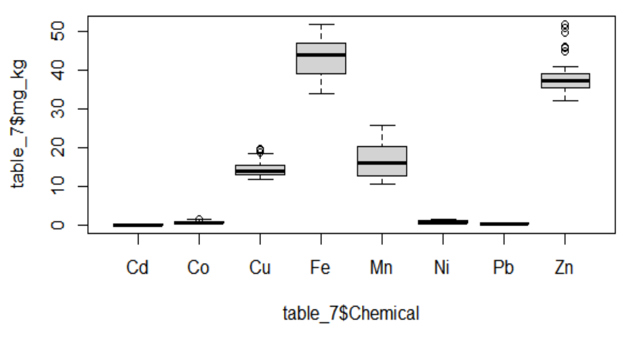

Figure 3. Boxplot of the influence of the factor of the chemical elements type on their composition in soybean seeds (average values for 2020-2022)

4. DISCUSSION

The results obtained here on the example of the study of the influence of various factors on soybean yield in the southeastern part of the territory of Kazakhstan confirmed the patterns previously identified by many studies in various regions of the world conducted in the last 5 years, including analyzing data on the dependence of soybean yield on climatic conditions for several decades [7-12]. The analysis of published works has shown that the influence of such factors as changes in temperature and precipitation on soybean yield may vary depending on the soybean variety, region, and combination of factors. Thus, an increase in the average annual temperature can lead to both an increase and a decrease in yield, depending on how much the average annual temperature in a particular region corresponds to the optimal values for soybean growth. In general, an analysis of the results of published works [7-12], as well as this study, shows that the decrease in humidity combined with an increased temperature leads to a decrease in yield, which is especially typical for regions with a dry hot climate, where average annual temperatures may be close to the upper limits of the optimum for soybean cultivation. Besides that, a comparison of the results obtained in different regions shows the importance of analyzing the influence of a combination of factors, in particular, considering the specifics of the soybean growing region, the results of this work are of the greatest practical importance for agriculture in Kazakhstan, but can also be used to identify general patterns of the influence of climatic factors on crop yields [7, 10].

The results obtained by us the results of this work, as well as the results of some previous studies, show that the use of biofertilizers can be especially effective considering the annual fluctuations in climatic conditions in the studied region. When they are used, the soil is enriched with beneficial microorganisms, which improve its structure and contribute to more efficient absorption of nutrients by plants. In addition, biofertilizers can increase soybean yields by activating its immune system and improving its ability to fight pests and diseases, which makes the crop more resistant to adverse climates [41, 42]. The effectiveness of biofertilizers in increasing soybean yields has been confirmed by many studies [41-43].

At the same time, it is important to note that biofertilizers can not only perform the function of supplying cultivated plants with macronutrients but also reduce the negative effect of lack of moisture [30, 33, 44, 45].

5. CONCLUSION

In this study, we assessed the influence of abiotic factors (weather, species, and biofertilizers) on the activation of the symbiotic process and soybean productivity in southeastern Kazakhstan. The low amount of precipitation in June 2021 and the high average daily air temperature during the filling and ripening of grain compared to the same period in 2020 and 2022 created critical abiotic conditions that affected the yield of soybean samples. In dry 2021, such indicators as the number of beans, number of seeds, weight, and weight of 1,000 seeds significantly decreased compared to the data of 2020 and 2022.

The least number of microorganisms was observed in the control variant, without treatment, equaling 8.1×10^6 CFU/g of soil. In the Manure variant, it was 9.2×10^6, in the BioEcoGum, Biogumus, and Tumat variants, it was at the level of 12.2-12.7×10^6, and in HansePlant we observed the highest number (15.1×10^6 CFU/g of soil). The use of biological fertilizers like BioEcoGum, Biogumus, HanselPlant, Manure, and Tumat statistically significantly increased the number of nodules per 1 plant, the weight of 1 nodule, the number of nitrogen-fixing microorganisms, the number of beans, the number of seeds and the weight of soybean seeds per plant in 1 g of soil compared with the control variant. We did not observe any influence of weather conditions on the content of chemical elements.

It should be noted that for some regions, the identification of such patterns is based on the analysis of data for several decades, whereas for the region studied in our work, such data samples have not been published. Therefore, the results of this work can be used to build a further strategy for the analysis of the climate effect on soybean yield in Kazakhstan.

ACKNOWLEDGMENTS

The paper has been prepared within the framework of program-targeted financing of the Ministry of Agriculture of the Republic of Kazakhstan for 2021-2023 under the scientific and technical program "Development of technologies for organic agriculture for growing crops, taking into account the specifics of regions, digitalization and export" (Individual registration number (IRN) BR10764907).

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