

Correlation between Leaf Area Formation and Net Photosynthetic Productivity in Soybean Varieties Under the Agroecological Conditions of Uzbekistan

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Abstract: Net photosynthetic productivity (NPP) is an important physiological indicator that characterizes the efficiency of plant photosynthesis and reflects the amount of dry matter accumulated by a plant per unit of leaf area during a specific period. It is closely associated with the intensity of carbon dioxide assimilation, the formation of organic compounds, and the accumulation of biomass through photosynthetic processes. The application of the highest nutrient rate played a decisive role in maximizing the assimilatory (leaf) area of soybean plants. The high mineral fertilizer rate ($N_{120}P_{90}K_{60}$) markedly increased leaf area, it was associated with a slight reduction in net photosynthetic productivity during the flowering-pod-setting stage. This response may be attributed to the excessive development and density of the stem-leaf canopy, which can increase mutual shading among leaves and consequently reduce the efficiency of light interception and photosynthetic assimilation within the canopy. In contrast, foliar application of Kalifos and SAKO under a moderate $N_{60}P_{45}K_{30}$ fertilization regime resulted in the highest net photosynthetic productivity during the budding flowering stage. Compared with the control, this treatment increased net photosynthetic productivity by 5.47-5.57 g/m² per day in the “Toshkent” cultivar and by 5.17-5.37 g/m² per day in the “Madad” cultivar.

Keywords: net photosynthetic productivity, leaf area, leaf age, light intensity, temperature, water availability, mineral nutrition, surface, evaporation, carbon dioxide, soybean, grain, oxygen, dry matter, biomass.

Introduction

Soybean (*Glycine max* (L.) Merr.) is one of the most important legume crops worldwide and is a major source of high-quality plant protein and vegetable oil. Its productivity is determined by the interaction of genetic characteristics, environmental conditions, and crop management practices. Among the physiological processes controlling soybean productivity, photosynthesis occupies a central position because it provides the carbon skeletons and assimilates required for biomass formation, reproductive development, and seed filling. The amount of radiation intercepted by the crop, the efficiency with which absorbed radiation is converted into biomass, and the subsequent partitioning of assimilates to reproductive organs are therefore fundamental determinants of soybean yield [1].

The term **net photosynthetic productivity** is closely related to several physiological indicators used in crop science. In particular, **Net Photosynthetic Rate (P_n)** describes the net rate of carbon dioxide assimilation by a leaf and is commonly expressed as $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$. **Net Assimilation Rate (NAR)**, in contrast, describes the rate of dry-matter accumulation per unit leaf area over a given period and is generally expressed as $\text{g m}^{-2} \text{ day}^{-1}$.

Photosynthesis contributes to soybean yield through both carbon assimilation and the subsequent allocation of assimilates to sink organs. According to Zhu et al. [1], improving photosynthetic efficiency represents one of the most important opportunities for increasing crop productivity. Crop yield can be viewed as the result of three interconnected processes: interception of solar radiation, conversion of absorbed radiation into biomass, and partitioning of biomass into the harvested product. In soybean, these processes are particularly important because considerable variation exists among genotypes in canopy structure, photosynthetic capacity, radiation-use efficiency, and assimilate partitioning.

Ainsworth and Long emphasized that increasing photosynthetic efficiency alone is not sufficient to ensure a proportional increase in crop yield. Improvements in photosynthesis must be accompanied by efficient transport and utilization of assimilates by reproductive sinks. Their analysis of soybean production indicated several potential targets for improving yield potential, including increased photosynthetic efficiency, optimization of carbon delivery and utilization, improved nitrogen fixation, and modification of reproductive development [2].

The physiological basis of soybean yield formation has been reviewed extensively by Egli and colleagues and, more recently, by Vogel et al.. Crop growth rate during the reproductive period is strongly dependent on canopy photosynthesis and assimilate supply. Increasing canopy photosynthesis during the reproductive period can increase the number of seeds per unit area, demonstrating the importance of maintaining high photosynthetic activity during reproductive development [3].

Genetic variation in photosynthetic activity among soybean genotypes provides an important opportunity for physiological breeding. López et al. evaluated 383 soybean recombinant inbred lines under field conditions and measured photosynthetic rate and intrinsic water-use efficiency during the R4-R5 growth stages. The study demonstrated substantial phenotypic variation in photosynthesis and water-use efficiency. Importantly, photosynthetic rate showed a strong positive genetic association with grain yield, indicating that photosynthetic traits may be useful as selection criteria in soybean breeding programs [4].

The relationship between photosynthetic performance and soybean yield has also been demonstrated through historical comparisons of cultivars. Koester et al. evaluated 24 soybean cultivars released between 1923 and 2007 and found that seed yield increased at a rate of approximately $26.5 \text{ kg ha}^{-1} \text{ year}^{-1}$. These results demonstrate that genetic improvement of soybean yield has been accompanied by physiological improvements in the utilization of solar radiation [5].

Radiation-use efficiency (RUE) is particularly important in understanding the relationship between photosynthesis and biomass accumulation. Purcell et al. [6] demonstrated that soybean biomass production and radiation-use efficiency were affected by plant population density. Increasing plant density generally increases the amount of radiation intercepted by the canopy, particularly during the early and middle stages of development.

Van Roekel and Purcell characterized soybean biomass and nitrogen accumulation, radiation-use efficiency, and yield under a maximum-yield environment. Grain yields among the cultivars ranged from 5290 to 7953 kg ha^{-1} . In the highest-yielding year, biomass accumulation rates ranged from 45.6 to 64.3 $\text{g m}^{-2} \text{ day}^{-1}$, while radiation-use efficiency ranged from 1.46 to 1.89 g MJ^{-1} . These results demonstrate the high biomass accumulation capacity that can be achieved when water, nutrients, radiation, and other environmental factors are favorable [7].

Materials and Methods

The importance of canopy architecture has recently received increasing attention. Zhao et al. demonstrated that leaf shape, planting density, and nitrogen application can modify the distribution of direct and diffuse radiation within soybean canopies and consequently affect yield. These findings indicate that photosynthetic productivity should be evaluated not only at the individual-leaf level but also at the canopy level [8].

Recent research further supports the importance of canopy configuration in high-density soybean production. Li et al. [9] reported that optimizing canopy spacing under high planting density could improve canopy photosynthesis and soybean yield. The results suggest that appropriate spatial arrangement of plants can reduce excessive shading and improve the utilization of available radiation. This is particularly important in modern high-yielding soybean systems, where increasing plant population without optimizing canopy architecture may result in diminishing returns in photosynthetic productivity.

Vogel et al. emphasized that crop growth rate during the reproductive period is closely related to canopy photosynthesis and assimilate supply. The R1–R5 period is particularly important for determining the number of seeds per unit area. Consequently, physiological characteristics that maintain high canopy photosynthesis during this period may contribute substantially to final yield.

Source-sink relationships represent another key component of soybean photosynthetic productivity. Photosynthetic leaves function primarily as source organs, whereas developing pods and seeds function as major sink organs. The efficiency of photosynthate transport from source to sink determines how effectively assimilated carbon contributes to final seed yield. Recent reviews indicate that soybean seed yield depends on both photosynthetic carbon fixation and the transport and allocation of photosynthetic products to seeds and nodules [10].

The coordination of carbon and nitrogen metabolism is particularly important in soybean because the crop forms a symbiotic association with nitrogen-fixing bacteria. Sinclair emphasized that carbon and nitrogen accumulation are fundamental processes determining soybean plant and seed growth. Photosynthesis supplies carbon skeletons and energy, while biological nitrogen fixation supplies nitrogen required for protein synthesis and development. Changes in photosynthate supply and demand can therefore influence both photosynthetic activity and nitrogen fixation. This interaction provides an important physiological basis for understanding variation in soybean productivity [11].

Result and Discussion

PLACE OF RESEARCH, SOIL-CLIMATIC CONDITIONS

Natural conditions of the study region and soils of the experimental field

Kashkadarya region is located between the southwestern branches of the Zarafshan mountain range. The Kashkadarya River flows through the valley from northeast to southwest. The valley begins on the southwestern slope of the Hisar mountain range (highest point 4,145 m) and extends 310 km to the Karshi steppe. The valley consists mainly of plains, which descend and widen toward the west and southwest. The Kashkadarya valley occupies terraces 1-5 of the Kashkadarya River. These terraces are covered with Quaternary proluvial and alluvial deposits.

Because the Kashkadarya oasis lies in the south, its climate is dry and relatively hot. The average temperature is +1°C in January and +28-29°C in July; the minimum temperature reaches -25°C to -29°C, and the maximum reaches +46-48°C. Precipitation increases with elevation, from 200 mm on the plains to 450–500 mm on the mountain slopes. Most precipitation falls in winter and spring. The climate of the Kashkadarya basin reflects all the characteristics of a continental dry subtropical climate.

The Table 1. experimental field and analytical soil tests were conducted at the "Saidakbar Saidaxror" farm in Kasbi district, Kashkadarya region. The soil of the experimental site is irrigated light-colored gray soil.[12]

Table 1. Agrochemical properties of the experimental field soil

№	Sampled layer depth	Humus	Total N	Total P	Total K	Mercurial phosphorus mg/kg	Exchangeable potassium (K ₂ O),
	cm	%	%	%	%	P ₂ O ₅	K ₂ O
1	0 – 30	0,820	0,017	0,156	1,48	26,0	216
2	30 – 50	0,676	0,056	0,148	1,31	19,5	186
3	50 – 70	0,260	0,032	0,103	1,18	10,2	165
4	70 – 100	0,105	0,010	0,061	1,01	5,0	80

Light-colored gray soils generally form the lower part of the gray soil belt and are distributed in the middle and lower parts of the plains. The upper limit of the area where light-colored gray soils occur corresponds to an elevation of 300–600 meters above sea

Light-colored gray soils (sierozems) are located on plains. Their humus content (0.81%) is very low, and they are highly carbonated and consist of medium and light loams. They are not sufficiently supplied with mobile phosphorus and exchangeable potassium.

Analysis of weather observed in the study area

The climate of Kashkadarya region is characterized mainly by a hot, long, and dry summer, a short and cold winter, and a relatively humid spring. The weather is variable, with winds blowing from the desert toward the mountains. The region's sum of positive temperatures is +4900–5000 °C, the sum of effective temperatures is +2519–2980 °C, and the frost-free period lasts 213–233 days.

According to the analysis of long-term seasonal weather data for Karshi district, where the research was conducted, annual precipitation is 238.7 mm and the mean annual air temperature is 13.1 °C.

During the 2022–2024 seasons of the research, the mean daily air temperature during the sowing-to-emergence period of the crops was observed to be in the range of 7.4–14.5 °C. In October 2021, the mean daily air temperature was 13.4 °C; in that month the lowest air temperature was 11.4 °C and the highest was 14.9 °C. The mean relative humidity that month was 47%, and the mean wind speed was 8 m/s.

Besides temperature, which is important for agricultural crops, including soybean, precipitation during the season also matters. Precipitation in the October–December period was 38.8 mm in 2021, 65.0 mm in 2022, and 41.0 mm in 2023. The data show that autumn precipitation in 2022 was the highest of the research years, indicating a larger reserve of soil moisture. Conversely, the lowest precipitation for this season was recorded in 2021.

In the spring (January–May) season of the research years, precipitation was 136.9 mm in 2022, 37.5 mm in 2023, and 194.2 mm in 2024. The data show that spring precipitation in 2024 was the highest of the research years, indicating a larger reserve of soil moisture. Conversely, the lowest precipitation for this season was recorded in 2023.

In the March–May period, precipitation in 2023 was 16.7 mm, which differed sharply from 2022 and 2024. Thus, total precipitation over the season was 175.7 mm for the 2022 crop, 102.5 mm for the 2023 season, and 194.2 mm for the 2024 season.[13]

Experimental design and methodology

This research was conducted in 2022–2024 on the fields of the "Sadakbar Saidaxror" farm in Kasbi district, Kashkadarya region, on light-colored gray soils (sierozems). The experiment consisted of 24 variants, arranged in 3 replications in three tiers. Each plot was 7.2 m wide and 33.3 m long, so one variant covered a total area of 240 m², of which 120 m² was the accounting area. The total area of the experiment, including protective zones and paths, was 1.72 hectares.

Soil, water, plant, and grain analyses were carried out in the laboratories of the "Technology of Production and Processing of Agricultural Products" department of Karshi State Technical University.

Before the experiment was set up, soil samples were taken from the plowed and sub-plowed layers of each variant for agrochemical analysis and analyzed in the laboratory. Soil samples were analyzed according to the methods of "Methods of Agrochemical, Agrophysical and Microbiological Research in Irrigated Cotton-Growing Regions". Humus content was determined by the I.V. Tyurin method (GOST 26213). Nitrate nitrogen was determined by the ion-selective method (GOST 13496-10).

Total nitrogen, phosphorus, and potassium were determined in a single sample by the method of I.M. Maltseva and L.P. Gritsenko. Mobile phosphorus was determined in a 1% ammonium carbonate solution by the B.P. Machigin method. Exchangeable potassium was determined on a flame photometer by the P.V. Protasov method. Water-soluble salts and dry residue were determined by the generally accepted method (GOST 26423-85), and pH was measured in aqueous extract with a potentiometer.

The soybean varieties were sown on the main area in April according to the research program. The field research used the local soybean varieties "Toshkent" and "Madad".

In the field experiments, "Toshkent" and "Madad" were grown with three mineral fertilizer rates: control (no fertilizer), N60P45K30, and N120P90K60. For suspension (foliar) feeding there were four variants: control (no fertilizer), urea (standard), Kalifos, and SAKO fertilizers.

Table 2. Phosphorus and potassium fertilizers were applied at 100% of the set annual rate during pre-sowing soil preparation. Nitrogen fertilizer was applied at its set annual rate before the first irrigation, that is, at the beginning of the budding-flowering phase.[14]

Table 2. Weather conditions during the study years based on data from the Qarshi meteorological station (2022–2024)

Months	Years	Ten-day air temperature, °C			Average monthly temperature, °C	Ten-day precipitation amount, mm			Monthly precipitation, mm
		I	II	III		I	II	III	
XI	2021	7,4	6,0	9,7	7,7	10,6	3,4	0,6	14,6
	2022	11,0	9,6	10,9	10,5	24,6	16,4	0,0	41,0
	2023	14,5	14,8	12,5	13,9	5,5	0,0	18,4	24,2
	<i>Long-Term Average</i>	<i>12,4</i>	<i>9,4</i>	<i>7,3</i>	<i>9,7</i>	<i>6,7</i>	<i>8,1</i>	<i>7,1</i>	<i>21,9</i>
XII	2021	10,1	5,2	6,5	7,3	4,2	2,1	4,0	10,3
	2022	0,5	4,5	3,4	2,8	7,6	0,0	0,1	7,7
	2023	8,0	3,5	9,2	7,0	0,0	1,0	5,6	7,5
	<i>Long-Term Average</i>	<i>4,9</i>	<i>5,0</i>	<i>3,9</i>	<i>4,6</i>	<i>9,2</i>	<i>10,9</i>	<i>12,8</i>	<i>32,9</i>
I	2022	5,2	9,0	4,2	6,1	22,0	21,1	0,0	43,1
	2023	5,6	– 10,8	– 1,6	– 2,2	7,3	0,0	0,9	8,2
	2024	9,3	7,1	5,6	7,2	4,7	0,0	37,4	42,1
	<i>Long-Term</i>	<i>3,4</i>	<i>2,8</i>	<i>2,9</i>	<i>3,0</i>	<i>11,5</i>	<i>10,4</i>	<i>10,6</i>	<i>32,5</i>

II	<i>Average</i>								
	2022	6,8	6,9	11,2	8,1	19,5	0,0	0,4	19,9
	2023	8,3	6,2	11,5	8,5	7,3	5,3	0,0	12,6
	2024	8,0	8,2	2,9	6,5	2,5	30,6	12,5	45,6
	<i>Long-Term Average</i>	4,9	4,5	6,6	5,3	16,9	11,1	7,9	35,9
III	2022	12,2	10,8	10,4	11,1	12,5	33,6	2,6	53,7
	2023	17,6	17,1	18,6	17,8	0,0	4,1	0,0	4,1
	2024	7,0	12,7	15,1	11,7	18,2	24,4	17,0	59,6
	<i>Long-Term Average</i>	8,8	10,2	12,5	10,5	15,8	15,8	20,9	52,5
IV	2022	21,7	20,7	23,7	21,8	0,0	5,7	1,0	6,7
	2023	18,8	19,0	23,4	20,4	3,6	0,0	0,0	3,6
	2024	16,3	18,4	20,5	18,4	0,0	10,2	0,0	10,2
	<i>Long-Term Average</i>	14,3	17,7	20,0	17,3	13,1	8,5	11,0	32,6
V	2022	24,4	23,9	24,0	24,1	0,3	0,0	13,2	13,5
	2023	21,5	24,8	27,4	24,7	5,2	3,8	0,0	9,0
	2024	21,7	21,9	23,9	22,5	12,0	24,1	0,6	36,7
	<i>Long-Term Average</i>	21,0	23,4	25,0	23,2	10,7	5,4	3,2	19,3
VI	2022	28,3	28,9	32,0	29,7	0,0	0,0	0,0	0,0
	2023	31,0	32,6	30,2	31,2	0,0	0,1	0,0	0,03
	2024	28,8	30,8	30,7	30,1	0,0	0,0	0,1	0,03
	<i>Long-Term Average</i>	27,0	27,8	30,2	28,6	0,6	0,3	0,8	1,7

The first foliar feeding by suspension was done at the beginning of the pod-setting phase, at 6 kg/ha with urea, 1.5 l/ha with Kalifos, and 1.5 kg/ha with SAKO. The second was done at the beginning of ripening of the first pods, at 10 kg/ha with urea, 2.5 l/ha with Kalifos, and 2.5 kg/ha with SAKO.

Field and laboratory experiments. Field and laboratory experiments followed the methodological manual of the All-Russian Institute of Plant Industry. Phenological observations and biometric analyses followed the methodological manual of the State Commission for Variety Testing of Agricultural Crops.

To determine the yield structure, 100-plant samples were taken from the marked plots of each variant and replication before harvest. In the laboratory, based on 10 model plants from each replication, the following were recorded: plant height, number of pods per stem, number of seeds per pod and their weight, and number of seeds per plant and their weight.

Yield was determined in all variants from a 5 m² area at 3 points of each plot, harvested entirely by hand. Yield was recorded to an accuracy of 0.1 kg. Grain samples were taken from the experimental plots to determine moisture, and yield was adjusted to standard grain moisture (14%).

To determine the technological quality of the grain in the laboratory, seed samples of the varieties were selected using an MLN device in accordance with GOST 13586.3-83, and the analyses were conducted according to "Methods and Recommendations for Assessing Grain Quality".[15]

Description of the "Toshkent" soybean variety.

Breeders: R.U. Saitkanova, I.T. Mirzayeva, M.A. Sattarov, X.A. Idrisov and N.G. Otamirzayev.

The soybean cultivar 'Toshkent' was developed at the Scientific Research Institute of Rice Production of Uzbekistan using the individual selection method. The cultivar has a growing season of 120-125 days and reaches a plant height of 155-160 cm. The lowest pods are positioned 14-16 cm above the soil surface. Plants develop 3-5 branches, with approximately 140-150 pods per plant and 2-4 seeds per pod. The weight of 1,000 seeds ranges from 170 to 175 g.

The seed protein content is 40-42%, while the protein content of the vegetative stems is 22-24% and the oil content of the seeds is approximately 24%. The cultivar is characterized by resistance to lodging, pod shattering, and diseases and is suitable for mechanized harvesting.

Under favorable growing conditions, the cultivar can produce a grain yield of 3.0–3.5 t ha⁻¹ and a green biomass yield of 25–30 t ha⁻¹. For use as a main crop, sowing is recommended during the third decade of April (20–30 April) to the first decade of May (1-10 May). The recommended seeding rate is 60 kg ha⁻¹, with seeds sown at a depth of 4-5 cm using a SON 2.8 seeder and a row spacing of 60 cm.

The recommended fertilizer rate is 30 kg N, 120 kg P, and 60 kg K ha⁻¹. Irrigation is generally carried out 3-4 times during the growing season. The cultivar was registered in the State Register of Uzbekistan in 2022.

Description of the "Madad" soybean variety.

Breeders: R.U. Saitkanova, N.I. Sodiqova, A.Q. Abdullayev, M.A. Sattarov and I.T. Mirzayeva.

The soybean cultivar 'Madad' was developed at the Scientific Research Institute of Rice Production of Uzbekistan using the individual selection method. The cultivar has a growing season of 125-130 days and reaches a plant height of 145-150 cm. The lowest pods are positioned 14-16 cm above the soil surface. Plants produce 2-4 branches, with approximately 94-102 pods per plant and 3-4 seeds per pod. The weight of 1,000 seeds ranges from 170 to 175 g.[16]

The seeds contain 43.2% protein and 20.9% oil. The cultivar is characterized by resistance to lodging, pod shattering, and diseases and is suitable for mechanized harvesting.

Under favorable growing conditions, the cultivar can produce a grain yield of 3.3–3.5 t ha⁻¹ and a green biomass yield of 30–35 t ha⁻¹. When grown as a main crop, sowing is recommended from the third decade of April (20-30 April) to the first decade of May (1-10 May). The recommended seeding rate is 60 kg ha⁻¹, with seeds sown at a depth of 4-5 cm. The recommended plant spacing is 60 × 15 cm.

The recommended fertilizer rate is 30 kg N, 120 kg P, and 60 kg K ha⁻¹. Irrigation is generally performed 3-4 times during the growing season. The cultivar was registered in the State Register of Uzbekistan in 2019.

According to the results obtained in the second year of the field experiment, dry matter accumulation in the control treatment varied considerably across the developmental stages of both soybean cultivars. In the 'Toshkent' cultivar, dry matter content was 21.8 g plant⁻¹ at the budding stage, increasing to 54.7 g plant⁻¹ at full flowering and 126.8 g plant⁻¹ at the pod formation stage. In the 'Madad' cultivar, the corresponding values were 21.1, 51.2, and 118.7 g plant⁻¹, respectively.

Foliar application of urea suspension increased dry matter accumulation in both cultivars. In 'Toshkent', dry matter accumulation reached 23.4, 60.5, and 140.1 g plant⁻¹ at the budding, full flowering, and pod formation stages, respectively, while in 'Madad' the corresponding values were 23.0, 56.5, and 131.0 g plant⁻¹.

Application of Kalifos suspension further enhanced dry matter accumulation, reaching 24.3, 61.9, and 143.4 g plant⁻¹ in 'Toshkent' and 24.3, 58.6, and 135.7 g plant⁻¹ in 'Madad' at the respective developmental stages. The SAKO suspension produced the highest values in 'Toshkent', with dry matter accumulation of 24.5 g plant⁻¹ at budding, 62.4 g plant⁻¹ at full flowering, and 144.5 g plant⁻¹ at pod formation. In 'Madad', the corresponding values were 24.3, 58.6, and 135.7 g plant⁻¹, respectively.

Table 3. dry matter accumulation increased progressively from budding to pod formation in both cultivars, with the most pronounced accumulation occurring during the transition from full flowering to pod formation. Foliar application of urea, Kalifos, and SAKO generally enhanced dry matter accumulation relative to the control, with the strongest response observed in the 'Toshkent' cultivar under SAKO treatment.[17]

Table 3. Formation of dry mass and leaf area in soybean varieties under different fertilizer rates and suspension treatments

№	Fertilizer rate	Suspension type	Variety	Dry mass, g/plant			Leaf area, cm ² /plant		
				Budding	Full flowering	Pod formation	Budding	Full flowering	Pod formation
1	Control (unfertilized)	Control	Toshkent	21.8	54.7	126.8	286.3	925.2	1929.1
2		(unfertilized)	Madad	21.1	51.2	118.7	280.4	913.8	1921.9
3		Carbamide	Toshkent	23.4	60.5	140.1	297.4	962.0	1980.0
4		(standard)	Madad	23.0	56.5	131.0	295.5	957.7	1978.5
5		Kalifos	Toshkent	24.3	61.9	143.4	305.8	994.6	2030.7
6			Madad	24.3	58.6	135.7	302.0	987.8	2020.2
7		SAKO	Toshkent	24.5	62.4	144.5	308.5	1003.3	2031.2
8			Madad	24.3	58.6	135.7	304.3	993.5	2023.3
9	N60P45K30	Control	Toshkent	22.9	56.1	130.0	293.4	956.5	1975.9
10		(unfertilized)	Madad	22.7	53.1	123.1	293.4	937.4	1971.8
11		Carbamide	Toshkent	24.1	60.9	141.2	301.8	987.1	2012.8
12		(standard)	Madad	23.8	57.7	133.6	301.3	971.2	1990.5
13		Kalifos	Toshkent	25.6	65.5	151.7	328.3	1077.9	2107.9
14			Madad	24.7	59.9	138.9	308.8	1006.9	2052.9
15		SAKO	Toshkent	25.3	64.5	149.5	316.0	1061.2	2080.1
16			Madad	24.8	59.9	138.9	314.5	1016.7	2066.8
17	N120P90K60	Control	Toshkent	22.5	55.4	128.4	290.9	946.2	2107.5
18		(unfertilized)	Madad	22.5	52.5	121.6	290.3	942.0	2073.8
19		Carbamide	Toshkent	23.8	60.7	140.7	301.6	986.6	2141.5
20		(standard)	Madad	23.6	57.4	133.1	300.7	974.0	2122.5
21		Kalifos	Toshkent	25.4	65.2	151.2	322.4	1081.4	2244.0
22			Madad	24.7	59.9	138.9	309.2	1021.5	2205.1
23		SAKO	Toshkent	25.2	64.0	148.4	315.1	1051.3	2220.7
24			Madad	24.7	59.5	137.8	308.7	1015.5	2181.8

Dry matter accumulation in soybean plants is influenced by a range of genetic, environmental, and agronomic factors, as documented in the scientific literature. In the present study, the conventional mineral fertilizer background of N₆₀P₄₅K₃₀, without additional foliar feeding,

resulted in progressive dry matter accumulation throughout the growing season. In the 'Tashkent' cultivar, dry matter accumulation was 22.9 g plant⁻¹ at the budding stage, increasing to 56.1 g plant⁻¹ at full flowering and 130.0 g plant⁻¹ at the pod formation stage. In the 'Madad' cultivar, the corresponding values were 22.7, 53.1, and 123.1 g plant⁻¹, respectively.

Foliar application of urea suspension increased dry matter accumulation in both cultivars. In 'Tashkent', the values reached 24.1, 60.9, and 141.2 g plant⁻¹ at the budding, full flowering, and pod formation stages, respectively, whereas 'Madad' recorded 23.8, 57.7, and 133.6 g plant⁻¹ at the same stages.

The application of Kalifos suspension resulted in a more pronounced increase in dry matter accumulation. In 'Tashkent', dry matter accumulation reached 25.6 g plant⁻¹ at budding, 65.5 g plant⁻¹ at full flowering, and 151.7 g plant⁻¹ at pod formation. In 'Madad', the corresponding values were 24.7, 59.9, and 138.9 g plant⁻¹, respectively.

Foliar application of SAKO also increased dry matter accumulation. The 'Tashkent' cultivar accumulated 25.3, 64.5, and 149.5 g plant⁻¹ at the budding, full flowering, and pod formation stages, respectively, while 'Madad' accumulated 24.8, 59.9, and 138.9 g plant⁻¹.

Overall, dry matter accumulation increased progressively with plant development, reaching its maximum at the pod formation stage in both cultivars. Among the foliar treatments, Kalifos produced the greatest increase in dry matter accumulation, particularly in the 'Tashkent' cultivar, whereas SAKO also demonstrated a substantial positive effect compared with the unfed control. [18]

These results indicate that foliar application of nutrient-containing preparations can enhance biomass accumulation in soybean, although the magnitude of the response depends on cultivar and developmental stage.

Under the background of the conventional mineral fertilizer rate of N120P90K60 applied to soybean varieties, the dry mass index formed during the growing season was as follows: in the variant with no additional foliar feeding, 22.5 g/plant at the budding stage, 55.4 g/plant by full flowering and 128.4 g/plant at the pod formation stage in the "Toshkent" variety, and 22.5 g/plant at the budding stage, 52.5 g/plant by full flowering and 121.6 g/plant at the pod formation stage in the "Madad" variety; with Carbamide suspension, 23.8 g/plant at the budding stage, 60.7 g/plant by full flowering and 140.7 g/plant at the pod formation stage in the "Toshkent" variety, and 23.6 g/plant at the budding stage, 57.4 g/plant by full flowering and 133.1 g/plant at the pod formation stage in the "Madad" variety; with Kalifos suspension, 25.4 g/plant at the budding stage, 65.2 g/plant by full flowering and 151.2 g/plant at the pod formation stage in the "Toshkent" variety, and 24.7 g/plant at the budding stage, 59.9 g/plant by full flowering and 138.9 g/plant at the pod formation stage in the "Madad" variety; with SAKO suspension, 25.2 g/plant at the budding stage, 64.0 g/plant by full flowering and 148.4 g/plant at the pod formation stage in the "Toshkent" variety, and 24.7 g/plant at the budding stage, 59.5 g/plant by full flowering and 137.8 g/plant at the pod formation stage in the "Madad" variety.

In addition, according to the analysis of the leaf area formed by phase during the growing season of the soybean plant in the experiment, the leaf area index was as follows: with no mineral fertilizer or suspension applied, 286.3 cm²/plant at the budding stage, 925.2 cm²/plant by full flowering and 1929.1 cm²/plant at the pod formation stage in the "Toshkent" variety, and 280.4 cm²/plant at the budding stage, 913.8 cm²/plant by full flowering and 1921.9 cm²/plant at the pod formation stage in the "Madad" variety; with Carbamide suspension, 297.4 cm²/plant at the budding stage, 962.0 cm²/plant by full flowering and 1980.0 cm²/plant at the pod formation stage in the "Toshkent" variety, and 295.5 cm²/plant at the budding stage, 957.7 cm²/plant by full flowering and 1978.5 cm²/plant at the pod formation stage in the "Madad" variety; with Kalifos suspension, 305.8 cm²/plant at the budding stage, 994.6 cm²/plant by full flowering and 2030.7 cm²/plant at the pod formation stage in the "Toshkent" variety, and 302.0 cm²/plant at the budding stage, 987.8 cm²/plant by full flowering and 2020.0 cm²/plant at the pod formation stage in the "Madad" variety; with SAKO suspension, 308.5 cm²/plant at the budding stage, 1003.3 cm²/plant by full flowering and 2031.2

cm²/plant at the pod formation stage in the “Toshkent” variety, and 304.3 cm²/plant at the budding stage, 993.5 cm²/plant by full flowering and 2023.3 cm²/plant at the pod formation stage in the “Madad” variety. Given that research results, under the background of the conventional mineral fertilizer rate of N60P45K30 applied to soybean varieties, the leaf area index formed was as follows: in the variant with no additional foliar feeding, 293.4 cm²/plant at the budding stage, 956.5 cm²/plant by full flowering and 1975.9 cm²/plant at the pod formation stage in the “Toshkent” variety, and 293.4 cm²/plant at the budding stage, 937.4 cm²/plant by full flowering and 1971.8 cm²/plant at the pod formation stage in the “Madad” variety; with Carbamide suspension, 301.8 cm²/plant at the budding stage, 987.1 cm²/plant by full flowering and 2012.8 cm²/plant at the pod formation stage in the “Toshkent” variety, and 301.3 cm²/plant at the budding stage, 971.2 cm²/plant by full flowering and 1990.5 cm²/plant at the pod formation stage in the “Madad” variety; with Kalifos suspension, 328.3 cm²/plant at the budding stage, 1077.9 cm²/plant by full flowering and 2107.9 cm²/plant at the pod formation stage in the “Toshkent” variety, and 308.8 cm²/plant at the budding stage, 1006.9 cm²/plant by full flowering and 2052.9 cm²/plant at the pod formation stage in the “Madad” variety; with SAKO suspension, 316.0 cm²/plant at the budding stage, 1061.2 cm²/plant by full flowering and 2080.1 cm²/plant at the pod formation stage in the “Toshkent” variety, and 314.5 cm²/plant at the budding stage, 1016.7 cm²/plant by full flowering and 2066.8 cm²/plant at the pod formation stage in the “Madad” variety.[19]

Under the background of the conventional mineral fertilizer rate of N120P90K60 applied to soybean varieties, the leaf area index formed was as follows: in the variant with no additional foliar feeding, 290.9 cm²/plant at the budding stage, 946.2 cm²/plant by full flowering and 2107.5 cm²/plant at the pod formation stage in the “Toshkent” variety, and 290.3 cm²/plant at the budding stage, 942.0 cm²/plant by full flowering and 2073.8 cm²/plant at the pod formation stage in the “Madad” variety; with Carbamide suspension, 301.6 cm²/plant at the budding stage, 986.6 cm²/plant by full flowering and 2141.5 cm²/plant at the pod formation stage in the “Toshkent” variety, and 300.7 cm²/plant at the budding stage, 974.0 cm²/plant by full flowering and 2122.5 cm²/plant at the pod formation stage in the “Madad” variety; with Kalifos suspension, 322.4 cm²/plant at the budding stage, 1081.4 cm²/plant by full flowering and 2244.0 cm²/plant at the pod formation stage in the “Toshkent” variety, and 309.2 cm²/plant at the budding stage, 1021.5 cm²/plant by full flowering and 2205.1 cm²/plant at the pod formation stage in the “Madad” variety; with SAKO suspension, 315.1 cm²/plant at the budding stage, 1051.3 cm²/plant by full flowering and 2220.7 cm²/plant at the pod formation stage in the “Toshkent” variety, and 308.7 cm²/plant at the budding stage, 1015.5 cm²/plant by full flowering and 2181.8 cm²/plant at the pod formation stage in the “Madad” variety.

When the effect of conventional fertilization and additional foliar feeding on the net photosynthetic productivity index of soybean varieties was studied, the results of the second year of our research (2023) showed that, over the 20-day budding–flowering period, with no fertilizer or suspension, dry mass was 32.9 g/plant, leaf area 12115.3 m² and net photosynthetic productivity 27.19 g/m² per day in the “Toshkent” variety, and 30.1 g/plant, 11941.5 m² and 25.23 g/m² per day, respectively, in the “Madad” variety; with Carbamide suspension, dry mass was 37.1 g/plant, leaf area 12594.5 m² and net photosynthetic productivity 29.42 g/m² per day in the “Toshkent” variety, and 33.5 g/plant, 12531.8 m² and 26.72 g/m² per day, respectively, in the “Madad” variety; with Kalifos suspension, dry mass was 37.6 g/plant, leaf area 13004.0 m² and net photosynthetic productivity 28.90 g/m² per day in the “Toshkent” variety, and 34.3 g/plant, 12898.4 m² and 26.56 g/m² per day, respectively, in the “Madad” variety; with SAKO suspension, dry mass was 37.9 g/plant, leaf area 13118.4 m² and net photosynthetic productivity 28.87 g/m² per day in the “Toshkent” variety, and 34.3 g/plant, 12978.6 m² and 26.40 g/m² per day, respectively, in the “Madad” variety (Table 3.7). According to the analysis, in the variant with the conventional mineral fertilizer rate of N60P45K30 and no additional foliar feeding, dry mass was 33.2 g/plant, leaf area 12498.8 m² and net photosynthetic productivity 26.57 g/m² per day in the “Toshkent” variety, and 30.4 g/plant, 12308.1 m² and 24.73 g/m² per day, respectively, in the “Madad” variety; with Carbamide suspension, dry mass was 36.8 g/plant, leaf area 12889.2 m² and net photosynthetic productivity 28.56 g/m² per day in

the “Toshkent” variety, and 33.9 g/plant, 12724.6 m² and 26.64 g/m² per day, respectively, in the “Madad” variety; with Kalifos suspension, dry mass was 39.9 g/plant, leaf area 14062.7 m² and net photosynthetic productivity 28.37 g/m² per day in the “Toshkent” variety, and 35.3 g/plant, 13156.8 m² and 26.80 g/m² per day, respectively, in the “Madad” variety; with SAKO suspension, dry mass was 39.2 g/plant, leaf area 13772.0 m² and net photosynthetic productivity 28.47 g/m² per day in the “Toshkent” variety, and 35.1 g/plant, 13312.0 m² and 26.35 g/m² per day, respectively, in the “Madad” variety.

Table 4. Over the 20-day budding–flowering period, in the variant with the conventional mineral fertilizer rate of N120P90K60 and no additional foliar feeding, dry mass was 32.9 g/plant, leaf area 12370.4 m² and net photosynthetic productivity 26.59 g/m² per day in the “Toshkent” variety, and 30.0 g/plant, 12322.9 m² and 24.33 g/m² per day, respectively, in the “Madad” variety; with Carbamide suspension, dry mass was 36.9 g/plant, leaf area 12882.7 m² and net photosynthetic productivity 28.67 g/m² per day in the “Toshkent” variety, and 33.8 g/plant, 12747.3 m² and 26.55 g/m² per day, respectively, in the “Madad” variety; with Kalifos suspension, dry mass was 39.8 g/plant, leaf area 14037.5 m² and net photosynthetic productivity 28.38 g/m² per day in the “Toshkent” variety, and 35.3 g/plant, 13307.7 m² and 26.49 g/m² per day, respectively, in the “Madad” variety; with SAKO suspension, dry mass was 38.8 g/plant, leaf area 13663.1 m² and net photosynthetic productivity 28.41 g/m² per day in the “Toshkent” variety, and 34.8 g/plant, 13241.4 m² and 26.28 g/m² per day, respectively, in the “Madad” variety.[20]

Table 4. Net photosynthetic productivity of soybean varieties under different fertilizer rates and suspension treatments, g/m² per day

№	Fertilizer rate	Suspension type	Variety	Budding–flowering period			Flowering–podding period		
				V2 – V1	(L1+L2) /2*20	g/m ² per day	V3 – V2	(L2+L3) /2*40	g/m ² per day
1	Control (unfertilized)	Control	Toshkent	32.9	12115.3	27.19	72.1	57086.5	12.63
2		(unfertilized)	Madad	30.1	11941.5	25.23	67.5	56713.9	11.90
3		Carbamide	Toshkent	37.1	12594.2	29.42	79.7	58840.7	13.54
4		(standard)	Madad	33.5	12531.8	26.72	74.5	58724.3	12.69
5		Kalifos	Toshkent	37.6	13004.0	28.90	81.5	60506.5	13.48
6			Madad	34.3	12898.4	26.56	77.2	60160.6	12.83
7		SAKO	Toshkent	37.9	13118.4	28.87	82.2	60690.6	13.54
8			Madad	34.3	12978.6	26.40	77.2	60335.4	12.79
9	N60P45K30	Control	Toshkent	33.2	12498.8	26.57	73.9	58647.9	12.60
10		(unfertilized)	Madad	30.4	12308.1	24.73	70.0	58185.5	12.03
11		Carbamide	Toshkent	36.8	12889.2	28.56	80.3	59997.1	13.38
12		(standard)	Madad	33.9	12724.6	26.64	76.0	59234.4	12.83
13		Kalifos	Toshkent	39.9	14062.7	28.37	86.3	63717.6	13.54
14			Madad	35.3	13156.8	26.80	79.0	61196.1	12.90
15		SAKO	Toshkent	39.2	13772.0	28.47	85.0	62824.7	13.53
16			Madad	35.1	13312.0	26.35	79.0	61669.0	12.80
17	N120P90K60	Control	Toshkent	32.9	12370.4	26.59	73.0	61073.0	11.95
18		(unfertilized)	Madad	30.0	12322.9	24.33	69.2	60315.5	11.47
19		Carbamide	Toshkent	36.9	12882.7	28.67	80.0	62561.7	12.78
20		(standard)	Madad	33.8	12747.3	26.55	75.7	61931.4	12.22

21	Kalifos	Toshkent	39.8	14037.5	28.38	85.9	66507.2	12.92
22		Madad	35.3	13307.7	26.49	79.0	64531.7	12.24
23	SAKO	Toshkent	38.8	13663.1	28.41	84.4	65438.9	12.89
24		Madad	34.8	13241.4	26.28	78.4	63944.7	12.26

In addition, over the 40-day budding–flowering period, with no fertilizer or suspension, dry mass was 72.1 g/plant, leaf area 57086.5 m² and net photosynthetic productivity 12.63 g/m² per day in the “Toshkent” variety, and 67.5 g/plant, 56713.9 m² and 11.90 g/m² per day, respectively, in the “Madad” variety; with Carbamide suspension, dry mass was 79.7 g/plant, leaf area 58840.7 m² and net photosynthetic productivity 13.54 g/m² per day in the “Toshkent” variety, and 74.5 g/plant, 58724.3 m² and 12.69 g/m² per day, respectively, in the “Madad” variety; with Kalifos suspension, dry mass was 81.5 g/plant, leaf area 60506.5 m² and net photosynthetic productivity 13.48 g/m² per day in the “Toshkent” variety, and 77.2 g/plant, 60160.6 m² and 12.83 g/m² per day, respectively, in the “Madad” variety; with SAKO suspension, dry mass was 88.2 g/plant, leaf area 60690.6 m² and net photosynthetic productivity 13.54 g/m² per day in the “Toshkent” variety, and 77.2 g/plant, 60335.4 m² and 12.79 g/m² per day, respectively, in the “Madad” variety (Table 3.6.2).

According to the analysis, over the 40-day period, in the variant with the conventional mineral fertilizer rate of N60P45K30 and no additional foliar feeding, dry mass was 73.9 g/plant, leaf area 58647.9 m² and net photosynthetic productivity 12.60 g/m² per day in the “Toshkent” variety, and 70.0 g/plant, 58185.5 m² and 12.03 g/m² per day, respectively, in the “Madad” variety; with Carbamide suspension, dry mass was 80.3 g/plant, leaf area 59997.1 m² and net photosynthetic productivity 13.38 g/m² per day in the “Toshkent” variety, and 76.0 g/plant, 59234.4 m² and 12.83 g/m² per day, respectively, in the “Madad” variety; with Kalifos suspension, dry mass was 86.3 g/plant, leaf area 63717.6 m² and net photosynthetic productivity 13.54 g/m² per day in the “Toshkent” variety, and 79.0 g/plant, 61196.1 m² and 12.90 g/m² per day, respectively, in the “Madad” variety; with SAKO suspension, dry mass was 85.0 g/plant, leaf area 62824.7 m² and net photosynthetic productivity 13.54 g/m² per day in the “Toshkent” variety, and 79.0 g/plant, 61669.0 m² and 12.80 g/m² per day, respectively, in the “Madad” variety.

In given that research results, over the 40-day period, in the variant with the conventional mineral fertilizer rate of N120P90K60 and no additional foliar feeding, dry mass was 73.0 g/plant, leaf area 61073.0 m² and net photosynthetic productivity 11.95 g/m² per day in the “Toshkent” variety, and 69.2 g/plant, 60315.5 m² and 11.47 g/m² per day, respectively, in the “Madad” variety; with Carbamide suspension, dry mass was 80.0 g/plant, leaf area 62561.7 m² and net photosynthetic productivity 12.78 g/m² per day in the “Toshkent” variety, and 75.7 g/plant, 61931.4 m² and 12.22 g/m² per day, respectively, in the “Madad” variety; with Kalifos suspension, dry mass was 85.9 g/plant, leaf area 66507.2 m² and net photosynthetic productivity 12.92 g/m² per day in the “Toshkent” variety, and 79.0 g/plant, 64531.7 m² and 12.24 g/m² per day, respectively, in the “Madad” variety; with SAKO suspension, dry mass was 84.4 g/plant, leaf area 65438.9 m² and net photosynthetic productivity 12.89 g/m² per day in the “Toshkent” variety, and 78.4 g/plant, 63944.7 m² and 12.26 g/m² per day, respectively, in the “Madad” variety.

According to the three-year research results, the average net photosynthetic productivity was as follows: with no mineral fertilizer or suspension applied, 22.1 g/m² per day in the “Toshkent” variety and 20.4 g/m² per day in the “Madad” variety; with Carbamide suspension, 23.4 g/m² per day in the “Toshkent” variety and 21.6 g/m² per day in the “Madad” variety; with Kalifos suspension, 22.9 g/m² per day in the “Toshkent” variety and 21.4 g/m² per day in the “Madad” variety; with SAKO suspension, 22.9 g/m² per day in the “Toshkent” variety and 21.3 g/m² per day in the “Madad” variety.

The research results, under the background of the conventional mineral fertilizer rate of N60P45K30 applied to soybean varieties, the average net photosynthetic productivity was as follows: in the variant with no additional foliar feeding, 21.5 g/m² per day in the “Toshkent” variety and 20.1

g/m² per day in the “Madad” variety; with Carbamide suspension, 22.8 g/m² per day in the “Toshkent” variety and 21.4 g/m² per day in the “Madad” variety; with Kalifos suspension, 22.6 g/m² per day in the “Toshkent” variety and 21.4 g/m² per day in the “Madad” variety; with SAKO suspension, 22.6 g/m² per day in the “Toshkent” variety and 21.3 g/m² per day in the “Madad” variety.

According to the scientific research results, under the background of the conventional mineral fertilizer rate of N120P90K60 applied to soybean varieties, the average net photosynthetic productivity was as follows: in the variant with no additional foliar feeding, 20.2 g/m² per day in the “Toshkent” variety and 18.9 g/m² per day in the “Madad” variety; with Carbamide suspension, 21.6 g/m² per day in the “Toshkent” variety and 20.3 g/m² per day in the “Madad” variety; with Kalifos suspension, 21.4 g/m² per day in the “Toshkent” variety and 20.2 g/m² per day in the “Madad” variety; with SAKO suspension, 21.4 g/m² per day in the “Toshkent” variety and 20.0 g/m² per day in the “Madad” variety.

It was obtained, the highest net photosynthetic productivity was recorded under the background of the conventional mineral fertilizer rate of N60P45K30 applied to soybean varieties with additional foliar suspension: with Carbamide suspension, 22.8 g/m² per day in the “Toshkent” variety and 21.4 g/m² per day in the “Madad” variety; with Kalifos suspension, 22.6 g/m² per day in the “Toshkent” variety and 21.4 g/m² per day in the “Madad” variety; and with SAKO suspension, 22.6 g/m² per day in the “Toshkent” variety and 21.3 g/m² per day in the “Madad” variety.

Conclusions

1. The combined application of the maximum N₁₂₀P₉₀K₆₀ fertilizer rate with Kalifos suspension resulted in a substantial increase in leaf area compared with the control, reaching 314.9 cm² plant⁻¹ in the “Toshkent” cultivar and 283.2 cm² plant⁻¹ in the “Madad” cultivar.
2. Although the high mineral fertilizer rate (N₁₂₀P₉₀K₆₀) markedly increased leaf area, it was associated with a slight reduction in net photosynthetic productivity during the flowering–pod-setting stage. This response may be attributed to the excessive development and density of the stem–leaf canopy, which can increase mutual shading among leaves and consequently reduce the efficiency of light interception and photosynthetic assimilation within the canopy. In contrast, foliar application of Kalifos and SAKO under a moderate N₆₀P₄₅K₃₀ fertilization regime resulted in the highest net photosynthetic productivity during the budding flowering stage. Compared with the control, this treatment increased net photosynthetic productivity by 5.47-5.57 g/m² per day in the “Toshkent” cultivar and by 5.17-5.37 g/m² per day in the “Madad” cultivar.

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