

ROOT SYSTEM ARCHITECTURE AND PHYSIOLOGICAL TRAITS OF SOYBEAN GENOTYPES

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ABSTRACT

Soybean (*Glycine max* L.) is a major legume crop whose growth, productivity, and adaptability are strongly influenced by root architecture, physiological processes, and symbiotic efficiency. This study assessed the genetic variation of soybean varieties (Genetik-1, Sochilmas, Ehtiyoj, Xotira, Nafis) and breeding lines (Gen-8, Gen-9, Gen-19, Gen-26, Gen-40, BK-84, BK-98) across different developmental stages. Root morphological traits, nodule number, transpiration rate, and photosynthetic pigment content were evaluated under field conditions. The results revealed substantial genotypic differences. Among varieties, Ehtiyoj exhibited superior performance with the highest total root length (392.27 ± 90.68 cm) and root projection area (20.77 ± 2.51 cm²), indicating enhanced capacity for soil exploration. Genetik-1 also demonstrated total root length (364.07 ± 91.27 cm), while Sochilmas was distinguished by higher root volume (1.28 ± 0.14 cm³). In contrast, Nafis consistently displayed the lowest root development. Among breeding lines, Gen-8 and Gen-9 recorded the strongest root system development, while Gen-40 exhibited maximum root volume (1.51 ± 0.85 cm³). In terms of nodulation, Gen-26, Gen-8, and Gen-19 maintained high nodule numbers during reproductive stages, while traditional varieties showed limited persistence. Transpiration rate demonstrated that Gen-9, Gen-8, and BK-84 maintained higher water-use activity during vegetative and flowering stages, whereas Genetik-1 and Gen-19 showed reduced rates. Sochilmas, Nafis, Gen-19, and Gen-26 accumulated higher chlorophylls and carotenoids, contributing to superior photosynthetic efficiency. Overall, the findings confirm significant genetic variation among soybean genotypes. Breeding lines, particularly Gen-26, Gen-19, Gen-8, and Gen-9, exhibit enhanced traits for nitrogen fixation, water-use efficiency, and photosynthetic productivity, underscoring their potential in developing climate-resilient soybean cultivars.

KEYWORDS: Soybean, root morphological traits, nodule number, transpiration rate, photosynthetic pigments, leaf area.

1. INTRODUCTION

Soybean (*Glycine max* L.) is a significant leguminous crop characterized by its high oil and protein content, rendering it a dietary staple that enhances human welfare and food security [1–3]. In addition to being nutritionally important, soybeans also have economic significance due to their ability to fix nitrogen, which plays a role in soil fertility [4]. The symbiotic interaction between the plant and bacteria of the genus *Bradyrhizobium* allows efficient nitrogen fixation by plants. Nodule formation is also an important contributing factor to the nitrogen fixation ability of Soybean, and that also has a significant effect on the yield and nutrition of the plant [5,6].

The interaction between physiological processes such as transpiration, photosynthesis, and nodule development determine crop productivity in adverse environmental conditions like drought or extremely high or low temperatures. Plants regulate water balance and allow carbon dioxide uptake for photosynthesis through stomatal openings during transpiration and the pigments chlorophylls convert light energy into chemical energy during photosynthesis and convert carbon dioxide and water into carbohydrates, which directly contribute to biomass accumulation [7]. The accessory pigments carotenoids prevent damage to tissues under intense light exposure during photoprotection. Subsequently, pigment combinations are allowed to achieve maximum photosynthetic activity, securing plant health and later growth for enhanced yield [8]. The considerable genetic variety found in soybean cultivars and breeding lines provides a considerable source for agricultural practices with the aim to enhance sustainability and production. Plant breeders can recognize the most prominent genotypes that efficiently fix nitrogen, improve water management, and increase stress resistance by evaluating the nodule formation, water uptake patterns, and pigment development during the growth phase [9,10]. Hence, we studied the morphological, physiological, and biochemical responses of soybean varieties and breeding lines.

2. MATERIAL AND METHODS

2.1. Plant Materials and Experimental Design

The field and laboratory experiments were conducted at the Institute of Genetics and Plant Experimental Biology, Academy of Sciences of the Republic of Uzbekistan, in the Laboratory of Genetics of Leguminous and Oilseed Crops and the institute's experimental field station. A total of 12 soybean (*Glycine max* L. Merr.) genotypes were used in this study, consisting of local varieties (Genetik-1, Sochilmas, Ehtiyoj, Xotira, Nafis) and breeding lines (Gen-8, Gen-9, Gen-19, Gen-26, Gen-40, BK-84, BK-98). All accessions were obtained from the germplasm collection of the Laboratory of Genetics of Leguminous and Oilseed Crops, Institute of Genetics and Plant

Experimental Biology. Seeds were carefully selected for uniformity and sown on 12 May 2025 under field conditions. The experimental design consisted of three replications, with a row spacing of $60 \times 5 \times 1$ cm and a plot length of 2 m. Standard agronomic practices were applied during the growing season. Phenological observations were performed at three key growth stages: branching, flowering and pod formation. At each stage, physiological parameters were recorded under field conditions, including root morphological traits, nodule number, transpiration rate, and photosynthetic pigment composition.

2.2. Measurement of root morphological traits of soybean varieties and lines

The roots were carefully washed with water. The whole root system was spread out and analyzed using a scanning system (Expression 4990, Epson, CA) with a blue board as a background. Digital images of the root system were analyzed using Win RHIZO software (Régent Instruments, Québec, Canada). The total root length, the root surface area, the root volume, the projected area, and the root diameter were evaluated.

2.3. Physiological parameter measurement

Photosynthetic pigments such as total chlorophyll, chlorophyll a, chlorophyll b, and carotenoid contents in soybean, were measured by Hiscox and Israelstam [11]. A fresh leaf sample (50 mg) of alfalfa was cut, and dimethylsulfoxide (5 mL) was added to test tubes. The test tubes were incubated at 28°C for 4 h. The absorbance of the extract was taken at 470 nm, 645 nm, and 663 nm using a spectrophotometer against a DMSO blank. The relative water content of leaves in soybean was analyzed using Barrs and Weatherley's method [12].

2.4. Statistical analysis

Analysis of variance (ANOVA) was used to examine the experimental data using the IBM SPSS Statistics 20. Duncan's multiple range test with the least significant difference at the 5% level of significance ($\alpha = 0.05$) was applied.

3. RESULTS

3.1. Root morphological traits

The obtained results demonstrate that soybean varieties and lines exhibit significant genetic variation in root morphological traits, which reflect not only structural characteristics but also physiological adaptability to environmental stresses (Table 1). Among the varieties, Ehtiyaj showed superior performance with the highest total root length (392.27 ± 90.68 cm) and root projection area (20.77 ± 2.51 cm²), indicating its ability to exploit larger soil volumes for water and nutrient acquisition. Genetik-1 also performed well (total root length – 364.07 ± 91.27 cm), highlighting its potential as a strong-rooted variety. Sochilmas was distinguished by its root volume (1.28 ± 0.14 cm³). Xotira maintained intermediate values across traits, while Nafis consistently exhibited the lowest values, suggesting weak root development and limited adaptability under stress.

Among the lines, Gen-8 and Gen-9 exhibited the strongest root system development, with superior total root length (456.13 ± 35.04 cm and 422.23 ± 82.83 cm), root surface area (69.80 ± 4.75 cm² and 69.03 ± 13.01 cm²), and root projection area (22.27 ± 1.57 cm² and 21.93 ± 4.06 cm²). These traits indicate enhanced efficiency in soil exploration and resource uptake. Gen-40 had the highest root volume (1.51 ± 0.85 cm³), demonstrating strong biomass formation. BK-84 showed moderate values but performed well in root surface area (59.53 ± 22.16 cm²) and root projection area (18.91 ± 7.04 cm²). In contrast, Gen-19 and Gen-26 displayed the lowest performance across traits (total root length – 44.80 ± 5.40 cm and 72.97 ± 17.99 cm; root surface area – 12.27 ± 1.63 cm² and 26.00 ± 3.67 cm²). However, both recorded the highest root diameters (1.14 ± 0.03 mm and 1.18 ± 0.31 mm), which may represent an adaptive strategy under water deficit or mechanical stress through thicker root formation. BK-98 exhibited intermediate performance with a relatively high root diameter (0.98 ± 0.14 mm).

Table 1. Root morphological traits of soybean varieties and lines.

Varieties and lines	Root morphological traits				
	TRL (cm)	RSA (cm ²)	RPA (cm ²)	RV (cm ³)	RD (mm)
Genetik-1	$364.07 \pm 91.27d$	$49.20 \pm 8.58cd$	$13.53 \pm 5.00bcd$	$0.66 \pm 0.18ab$	$0.62 \pm 0.28ab$
Sochilmas	$210.87 \pm 77.55c$	$57.23 \pm 6.96cde$	$18.17 \pm 2.15cde$	$1.28 \pm 0.14bc$	$0.91 \pm 0.20abcde$
Ehtiyaj	$392.27 \pm 90.68d$	$65.50 \pm 7.83de$	$20.77 \pm 2.51e$	$0.90 \pm 0.24abc$	$0.54 \pm 0.11a$
Xotira	$256.50 \pm 7.26c$	$58.90 \pm 5.03de$	$17.93 \pm 1.34cde$	$1.10 \pm 0.03abc$	$0.72 \pm 0.04abcd$
Nafis	$203.03 \pm 75.59bc$	$40.41 \pm 3.29bc$	$12.67 \pm 1.06bc$	$0.77 \pm 0.18abc$	$0.80 \pm 0.24abcde$
Gen-8	$456.13 \pm 35.04d$	$69.80 \pm 4.75e$	$22.27 \pm 1.57e$	$0.86 \pm 0.18abc$	$0.50 \pm 0.07a$
Gen-9	$422.23 \pm 82.83d$	$69.03 \pm 13.01e$	$21.93 \pm 4.06e$	$0.90 \pm 0.19abc$	$0.52 \pm 0.04a$
Gen-19	$44.80 \pm 5.40a$	$12.27 \pm 1.63a$	$4.43 \pm 0.35a$	$0.39 \pm 0.01a$	$1.14 \pm 0.03de$
Gen-26	$72.97 \pm 17.99a$	$26.00 \pm 3.67ab$	$8.26 \pm 1.17ab$	$0.77 \pm 0.23abc$	$1.18 \pm 0.31e$
Gen-40	$186.10 \pm 39.35bc$	$56.33 \pm 11.16cde$	$17.90 \pm 3.51cde$	$1.51 \pm 0.85c$	$1.02 \pm 0.41cde$
BK-84	$267.73 \pm 15.80c$	$59.53 \pm 22.16de$	$18.91 \pm 7.04de$	$1.17 \pm 0.85bc$	$0.72 \pm 0.30abc$
BK-98	$106.83 \pm 8.96ab$	$32.50 \pm 1.85b$	$10.17 \pm 0.64b$	$0.83 \pm 0.17abc$	$0.98 \pm 0.14bcde$

3.2. Nodule number

The evaluation of nodule formation across soybean varieties (Genetik-1, Sochilmas, Ehtiyoj, Xotira, Nafis) and breeding lines (Gen-8, Gen-9, Gen-19, Gen-26, Gen-40, BK-84, BK-98) at different growth stages revealed substantial genetic variation (Table 2). At the flowering stage, the highest nodule numbers were observed in Gen-8 (8.00 ± 1.00) and Gen-26 (8.33 ± 1.53), indicating strong symbiotic efficiency. Breeding lines such as Gen-9 and Gen-19 also showed comparatively high nodule number, while traditional varieties like Genetik-1 (3.00 ± 1.00) and Ehtiyoj (2.67 ± 2.08) exhibited the lowest values. During the pod development stage, a shift in nodule number was recorded. Gen-26 (11.67 ± 3.06) maintained its superiority, followed by Gen-8 (9.33 ± 6.51) and Gen-19 (8.33 ± 3.06). These results highlight the sustained nodulation ability of certain breeding lines, which is essential for nitrogen fixation during reproductive development. In contrast, traditional varieties such as Genetik-1, Ehtiyoj, and Xotira showed lower nodule numbers (4.33–4.67), indicating limited nodulation persistence at later stages.

Table 2. Nodule number of soybean varieties and lines at different growth stages.

Varieties and lines	Stages	Nodule number
Genetik-1	Flowering stage	3.00 ± 1.00 abc
Sochilmas		-
Ehtiyoj		2.67 ± 2.08 ab
Xotira		5.67 ± 1.53 abcd
Nafis		4.00 ± 1.00 abcd
Gen-8		8.00 ± 1.00 d
Gen-9		7.33 ± 2.52 cd
Gen-19		7.00 ± 5.29 bcd
Gen-26		8.33 ± 1.53 d
Gen-40		7.00 ± 4.36 bcd
BK-84		4.00 ± 1.00 abcd
BK-98		-
Genetik-1	Pod development stage	4.33 ± 2.31 a
Sochilmas		-
Ehtiyoj		4.33 ± 1.15 a
Xotira		4.67 ± 2.08 a
Nafis		5.33 ± 2.08 a
Gen-8		9.33 ± 6.51 ab
Gen-9		6.33 ± 1.15 ab
Gen-19		8.33 ± 3.06 ab
Gen-26		11.67 ± 3.06 b
Gen-40		6.33 ± 2.52 ab
BK-84		5.33 ± 3.21 a
BK-98		5.00 ± 2.65 a

3.3. Physiological properties

The analysis of transpiration rates across soybean varieties and breeding lines at different developmental stages demonstrated. At the budding stage, the highest transpiration rate was observed in BK-84 (220.30 ± 67.26) and Gen-8 (218.10 ± 76.08), followed by BK-98 (175.95 ± 66.70) and Gen-19 (177.67 ± 48.73). Soybean varieties such as Genetik-1 (141.50 ± 26.10), Sochilmas (134.11 ± 28.05), and Ehtiyoj (138.94 ± 11.78) exhibited comparatively lower values. At the flowering stage, Gen-9 (276.40 ± 43.03) displayed the highest transpiration rate, followed by Genetik-1 (256.83 ± 22.19) and BK-84 (256.76 ± 33.55), while Xotira (130.70 ± 12.49) and Gen-26 (173.60 ± 42.30) showed the lowest values. This indicates that breeding lines, particularly Gen-9, maintained superior water loss activity during reproductive initiation.

At the pod development stage, transpiration decreased across all genotypes, reflecting a physiological adjustment to conserve water during seed filling. The highest rates were recorded in BK-98 (125.65 ± 0.99), Nafis (119.38 ± 17.33), and Gen-40 (119.83 ± 17.02), whereas Genetik-1 (88.63 ± 8.00), Gen-19 (85.43 ± 9.72), and Gen-9 (93.15 ± 3.59) exhibited the lowest values.

Table 3. Transpiration rate of soybean varieties and lines at different growth stages.

Varieties and lines	Growth stages of soybean		
	Budding stage	Flowering stage	Pod development stage
Genetik-1			
Sochilmas	141.50±26.10abc	256.83±22.19cd	88.63±8.00a
Ehtiyoy	134.11±28.05a	190.62±8.99b	92.50±2.28b
Xotira	138.94±11.78ab	224.26±24.89bcd	105.72±12.38abc
Nafis	147.29±17.12abc	130.70±12.49a	96.18±3.69ab
Gen-8	150.66±2.64abc	187.45±37.14b	119.38±17.33bc
Gen-9	218.10±76.08bc	192.10±32.28b	99.27±28.88ab
Gen-19	154.55±27.42abc	276.40±43.03d	93.15±3.59a
Gen-26	177.67±48.73abc	210.52±53.28bc	85.43±9.72a
Gen-40	132.99±7.28a	173.60±42.30ab	105.28±6.78abc
BK-84	137.90±19.75a	201.11±24.01bc	119.83±17.02bc
BK-98	220.30±67.26c	256.76±33.55cd	105.61±15.19abc
	175.95±66.70abc	189.52±4.66a	125.65±0.99c

The analysis of relative water content in soybean varieties and breeding lines at different developmental stages demonstrated (Table 4). At the budding stage, the highest relative water content in soybean was observed in Gen-40 (82.07±6.41d) and Gen-19 (77.77±8.27). Soybean varieties such as Genetik-1 and Ehtiyoy (72.83±6.47) exhibited comparatively highest values compared to other varieties. At the flowering stage, Gen-26 (72.65±7.25) displayed the highest relative water content in soybean, followed by Xotira (71.36±1.47) and Gen-19 (71.25±7.67), while BK-84 (57.59±3.60) and BK-98 (62.25±3.63) showed the lowest values. At the pod development stage, relative water content in soybean varieties and lines was analyzed. The highest rates were recorded in Gen-26 (89.15±8.75), Gen-19 (87.58±2.62), and Genetik-1 (84.62±4.09), whereas Sochilmas (66.18±5.16), BK-84 (68.74±4.48), and Xotira (69.34±6.73) exhibited the lowest values.

Table 4. Relative water content of leaves in soybean varieties and lines at different growth stages.

Varieties and lines	Growth stages of soybean		
	Budding stage	Flowering stage	Pod development stage
Genetik-1			
Sochilmas	75.93±6.06bcd	66.48±1.02abc	84.62±4.09cde
Ehtiyoy	68.44±3.87abc	68.58±2.54bc	66.18±5.16a
Xotira	71.14±6.15abc	67.72±5.47bc	80.76±8.08bcde
Nafis	72.83±6.47abcd	71.36±1.47bc	69.34±6.73ab
Gen-8	62.16±4.47a	62.44±1.24ab	73.59±6.13abc
Gen-9	64.63±2.25a	65.33±6.59abc	76.15±7.55abcde
Gen-19	70.90±5.03abc	64.49±7.58abc	75.32±5.33abcd
Gen-26	77.77±8.27cd	71.25±7.67bc	87.58±2.62de
Gen-40	70.25±5.31abc	72.65±7.25d	89.15±8.75e
BK-84	82.07±6.41d	63.03±6.22abc	71.97±6.40abc
BK-98	66.18±5.07ab	57.59±3.60a	68.74±4.48ab
	72.31±4.30abcd	62.25±3.63ab	75.69±12.79abcd

The analysis of leaf area in soybean varieties and breeding lines at different growth stages revealed considerable genetic variation (Table5). At the budding stage, the highest leaf area was recorded in Gen-8 (39.89±5.34), while BK-98 (28.38±1.52) and Xotira (28.44±2.40) and exhibited the lowest values. At the flowering stage, Ehtiyoy (57.50±3.86) and Gen-19 (56.83±5.71) displayed the highest leaf area in soybean, followed by Nafis (54.40±5.09) and Xotira (51.07±2.62), while Gen-9 (33.73±2.91) showed the lowest values. At the pod development stage, leaf area in soybean varieties and lines was analyzed. The highest rates were recorded in Nafis (96.33±14.45), Gen-8 (93.37±4.21), and BK-98 (84.90±4.20), whereas Genetik-1 (12.60±3.59) exhibited the lowest values.

Table 5. Leaf area of soybean varieties and lines at different growth stages.

Varieties and lines	Growth stages of soybean		
	Budding stage	Flowering stage	Pod development stage
Genetik-1			
Sochilmas	32.03±4.37a	35.70±2.65ab	12.60±3.59a
Ehtiyoj	34.53±1.82ab	41.90±4.37bc	67.67±5.04cde
Xotira	28.88±1.9a	57.50±3.86e	56.77±8.50bc
Nafis	28.44±2.40a	51.07±2.62de	78.43±6.35ef
Gen-8	31.91±5.11a	54.40±5.09de	96.33±14.45g
Gen-9	39.89±5.34b	39.07±4.44ab	93.37±4.21g
Gen-19	28.97±0.96a	33.73±2.91a	76.60±2.62ef
Gen-26	31.90±3.78a	56.83±5.71e	51.90±5.91b
Gen-40	31.09±0.88a	39.87±2.82ab	70.87±3.54de
BK-84	29.20±2.50a	49.27±1.88cd	62.33±6.72bcd
BK-98	29.97±4.01a	34.93±6.69ab	57.10±3.10bc
	28.38±1.52a	47.13±1.69cd	84.90±4.20fg

The analysis of photosynthetic pigments in soybean varieties and breeding lines at different growth stages revealed considerable genetic variation (Table 6). At the flowering stage, the highest chlorophyll a (Chl a) content was recorded in Sochilmas (2.24 ± 0.17), Xotira (2.14 ± 0.06), and Nafis (2.13 ± 0.28), while Genetik-1 (1.74 ± 0.19) and BK-84 (1.77 ± 0.12) exhibited the lowest values. A similar trend was observed for chlorophyll b (Chl b), with Sochilmas (0.95 ± 0.15) showing the maximum accumulation. Total chlorophyll (TChl) was highest in Sochilmas (3.19 ± 0.32) and Nafis (2.99 ± 0.48), whereas Genetik-1 (2.34 ± 0.28) and BK-84 (2.37 ± 0.16) maintained lower levels. Carotenoids also peaked in Sochilmas (2.60 ± 0.41) and Nafis (2.46 ± 0.57), suggesting their superior photosynthetic efficiency.

During the pod development stage, pigment content exhibited a shift. Sochilmas, Xotira, Nafis, Gen-9, Gen-19, and Gen-26 showed consistently higher pigment levels across Chl a, Chl b, TChl, and carotenoids, with Sochilmas (Chl a: 2.14 ± 0.22 ; TChl: 3.01 ± 0.45 ; Car: 2.37 ± 0.53) and Gen-19 (Chl a: 2.17 ± 0.14 ; TChl: 3.05 ± 0.27 ; Car: 2.33 ± 0.29) outperforming others. In contrast, Genetik-1 exhibited the lowest pigment concentrations across all parameters (Chl a: 0.46 ± 0.06 ; Chl b: 0.16 ± 0.03 ; TChl: 0.62 ± 0.09 ; Car: 0.50 ± 0.07), reflecting reduced photosynthetic potential at this stage.

Table 6. Photosynthetic pigments in soybean varieties and lines at different growth stages.

Varieties and lines	Stages	Photosynthetic pigments			
		Chla	Chlb	TChl	Carotinoid
Genetik-1		1.74±0.19a	0.61±0.09bc	2.34±0.28a	1.96±0.26ab
Sochilmas		2.24±0.17c	0.95±0.15d	3.19±0.32c	2.60±0.41c
Ehtiyoj	flowering stage	1.95±0.11abc	0.68±0.04abc	2.63±0.15ab	2.08±0.16abc
Xotira		2.14±0.06c	0.83±0.06cd	2.97±0.12bc	2.38±0.14bc
Nafis		2.13±0.28c	0.87±0.20cd	2.99±0.48bc	2.46±0.57bc
Gen-8		1.85±0.22abc	0.68±0.12abc	2.52±0.34ab	1.93±0.31ab
Gen-9		2.04±0.15bc	0.78±0.09bcd	2.82±0.24abc	2.10±0.26abc

Gen-19		1.93±0.13abc	0.69±0.04abc	2.62±0.17ab	2.03±0.20ab
Gen-26		1.95±0.03abc	0.76±0.02abc	2.71±0.02ab	2.18±0.08abc
Gen-40		2.05±0.06abc	0.74±0.03abc	2.79±0.09abc	2.00±0.10ab
BK-84		1.77±0.12ab	0.60±0.05a	2.37±0.16a	1.81±0.15a
BK-98		1.90±0.17abc	0.69±0.08abc	2.59±0.26ab	1.96±0.26ab
Genetik-1		0.46±0.06a	0.16±0.03a	0.62±0.09a	0.50±0.07a
Sochilmas		2.14±0.22de	0.88±0.23d	3.01±0.45e	2.37±0.53d
Ehtiyoj		1.29±0.10c	0.44±0.05bc	1.39±0.71bc	1.26±0.07bc
Xotira		2.15±0.10e	0.83±0.09d	2.97±0.19e	2.37±0.25d
Nafis		1.42±0.14c	0.49±0.07c	1.91±0.21c	1.41±0.15c
Gen-8	pod	1.84±0.23d	0.71±0.14d	2.55±0.37de	2.18±0.37d
Gen-9	develop	2.03±0.07de	0.74±0.04d	2.77±0.11e	2.19±0.14d
Gen-19	ment	2.17±0.14e	0.89±0.12d	3.05±0.27e	2.33±0.29d
Gen-26	stage	2.08±0.13de	0.78±0.10d	2.86±0.23e	2.27±0.24d
Gen-40		1.35±0.09c	0.48±0.06bc	1.83±0.14c	1.29±0.04bc
BK-84		0.89±0.23b	0.32±0.08ab	1.21±0.31ab	0.92±0.23ab
BK-98		1.51±0.31c	0.52±0.12c	2.03±0.44cd	1.50±0.33c

4. DISCUSSION

As we know, today, as a result of the growing world population, ensuring food security remains one of the urgent issues. In this regard, the creation of varieties of agricultural crops with high protein content and nutritional value, which are important in ensuring food security, is of great importance. The role of soybean in this is incomparable. Because of the high content of high-quality protein in soybean grain, it is grown on very large areas in many developed countries in order to eliminate the problem of protein deficiency. Many scientists have conducted numerous studies on the physiological and biochemical properties, molecular and genetic analysis, and genetic and breeding potential of soybean collection varieties [13–15].

In the present study, the soybean varieties and breeding lines displayed significant genotypic variations with special reference to physiological and chemical parameters, including root morphological traits, nodulation, transpiration rates, and photosynthetic pigment accumulation. These variations in soybean genotypes show the adaptability of the germplasm to environmental stresses. The outcomes of the study validate earlier research showing that root system architecture plays a critical role in growth, development, and productivity of crops [16–23]. The larger roots also observed in genotypes Gen-19 and Gen-26 would suggest structural adaptations to access deeper soil moisture reserves that have a crucial role during drought conditions [24].

Amongst the studied traits, genetic variations were also observed in nodule formation. During the flower development stage, breeding lines, i.e., Gen-8 and Gen-26, showed higher nodulation, while Gen-26 also showed an increase in the number of nodules during pod growth. These results support the findings that improved symbiotic nitrogen fixation contributes to higher yield and improved soil fertility [25–29]. These findings apply to sustainable soybean production in regions where chemical nitrogen fertilizers are either environmentally and economically limiting. Chowdhary et al. [30]. reported that the minimal transpiration rate was in tolerant genotypes of soybean. These results have special importance for sustainable soybean production in regions where chemical nitrogen fertilizers are either environmentally undesirable or economically limiting.

In the context of other physiological parameters, photosynthetic pigment content also showed important genotypic differences that correlated with the ability to capture light and tolerate stress. Gen-19, Gen-26, Sochilmas and Nafis were capable of higher active component content in chlorophyll (chlorophyll a, b) and carotenoid contents at anthesis to pod filling stages of the crop that can help them maintain photosynthetic efficiency [31]. However, Genetik-1 consistently had the lowest pigment content, which agrees with its lower general physiological performance in other traits. The high pigment concentration displayed in Gen-26 further supports the overall better performance by associating improved photosynthesis with positive nodulation and drought water-use efficiency. Altogether, the results indicate that such breeding lines as Gen-26, Gen-19, or the new one Gen-8 may represent a collection of useful physiological traits with improved nodulation, transpiration dynamics, and photosynthetic pigment composition. Together, these characteristics contribute to improving N₂ fixation, water use efficiency, and large photosynthesis capacity, which make this cultivar a light-type variety with better adaptability and yield stability. Incorporation of these genotypes into breeding programs may have the potential to enhance soybean adaptation, and increase yield under diverse field conditions [32,33].

The differences between the traditional varieties and improved breeding lines observed in our study also emphasize that germplasm should be selected thoughtfully when pursuing particular breeding goals. Traditional genotypes, although representing genetic stocks, might need to cross with traits of advanced breeding lines for enhanced physiological adaptability. We therefore underline the importance of physiological and biochemical trait-based selection in soybean breeding programs for the adaptation to climate change and growing food demand in the world.

In summary, the results highlight that a combination of genotypic variation in root traits, nodulation, transpiration dynamics, and pigment kinetics contributes to adaptation. The discovery of elite breeding lines like Gen-8 and Gen-9 indicates the potential value of focused breeding schemes to dissect superior physiological and morphological traits for improved fixation, yield stability, and resilience under climate variation. Breeding programs can make valuable contributions to the development of climate-resilient soybean cultivars by adopting the selection for such integrated traits.

5. CONCLUSION

The study revealed differences in root morphology, nodulation, transpiration, and photosynthetic pigment content among soybean cultivars and breeding lines. Varieties such as Ehtiyoj and Genetik-1 exhibited strong root traits, while breeding lines like Gen-8, Gen-9, and Gen-26 combined superior nodulation and transpiration efficiency with enhanced pigment accumulation. Overall, the findings demonstrate that soybean breeding lines, particularly Gen-26, Gen-8, and Gen-19, outperform traditional varieties in terms of nodulation. The results demonstrate that breeding lines such as Gen-9, Gen-8, and BK-84 showed enhanced transpiration rate during flowering and pod development phases, while certain traditional varieties (Genetik-1, Sochilmas, Xotira) and lines (Gen-19, Gen-26) exhibited relatively lower rates, indicating diverse water-use strategies. These findings underline the importance of genotypic variation in transpiration dynamics, which is critical for developing soybean cultivars with improved adaptability to environmental stress. Overall, the results indicate that varieties such as Sochilmas, Xotira, Nafis and breeding lines like Gen-9, Gen-19, Gen-26 possess superior pigment accumulation capacity, which could contribute to enhanced photosynthetic performance.

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7. AUTHOR CONTRIBUTIONS

Conceptualization, D.J. and J.J.; methodology, I.K. and N.S.; software, C.J.; formal analysis, D.J.; writing original draft preparation, D.J.; writing, reviewing and editing, D.J. and C.J. All authors having substantial contributions in research, read and agreed to the published version of the manuscript.

8. DATA AVAILABILITY

No datasets were generated or analysed during the current study.

9. DECLARATIONS

Conflict of interests

The authors declare no competing interests.

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