

GENETIC VARIABILITY AND TRAIT ASSOCIATIONS OF EARLY SEEDLING MORPHOLOGICAL CHARACTERISTICS IN SUNFLOWER (*HELIANTHUS ANNUUS* L.) ACCESSIONS FOR BREEDING SUPERIOR GENOTYPES

Iram Khizar¹, Sobia Niaz², Aiman Akbar³, Rabia Shaheen Niazi⁴, Mahrukh Mumtaz⁵,
Tanzila Aslam⁶, Dr. Zill-E-Huma⁷, Dr. Abid Ejaz⁸, Dr. Mian Jahan Zaib Rasheed⁹

¹Department of Botany, University of Agriculture Faisalabad, Punjab, Pakistan

²Department of Botany, Bahauddin Zakariya University, Multan, Pakistan

³Department of Botany, University of Sargodha, Sargodha, Pakistan

⁴Department of Biological Sciences, Thal University of Bhakkar, Punjab, Pakistan

⁵Department of Botany, University of Sargodha, Sargodha, Pakistan

⁶Department of Chemistry, Government College Women University Faisalabad, Punjab, Pakistan, Senior Scientific Assistant, Pakistan Navy

^{7,8}Department of Botany, University of Sargodha, Sargodha, Punjab, Pakistan

⁹Department of Botany, University of Sargodha, Sargodha, Pakistan

¹Iramkhizar08@gmail.com, ²sobasco786@gmail.com

³aimanakbar315@gmail.com, ⁴rabia.shaheen@tu.edu.pk, ⁵mahrukhy128@gmail.com

⁶tanzilaaslam@gcwuf.edu.pk, ⁷humashah690@gmail.com, ⁸abid155yahoo.com,

⁹jahanzaibrasheedgc@gmail.com

DOI: <https://doi.org/10.5281/zenodo.22007444>

Keywords

Helianthus annuus, genetic variability, seedling vigor, morphological traits, phenotypic correlation, genotypic correlation, breeding.

Article History

Received: 16 May 2026

Accepted: 12 June 2026

Published: 15 August 2026

Copyright @Author

Corresponding Author: *

Sobia Niaz

Abstract

Early seedling vigour is an important factor in crop establishment, resource efficiency, and final productivity in sunflower (*Helianthus annuus* L.). The current study examined the genetic variability and relationships among seedling morphological traits in ten sunflower accessions under controlled conditions in order to identify promising breeding material. Seedlings were grown in a completely randomized factorial design and harvested at three intervals (18, 26, and 32 days following sowing). Morphological traits such as shoot length, root length, leaf length, leaf breadth, number of leaves, number of secondary roots, fresh weight, and dry weight were measured. There was significant variance among accessions, with G-61, A-9, G-1, G-30, and A-6 demonstrating higher performance for numerous growth parameters depending on harvest stage, but accession 017583 consistently shown poor seedling performance. Genotypic and phenotypic correlation analyses revealed considerable positive relationships between leaf characteristics, secondary root growth, biomass accumulation, and seedling vigour, implying that these traits can be increased concurrently via indirect selection. Positive correlations between fresh and dry biomass and leaf development and secondary root production emphasized their significance as dependable indicators of early growth potential. The study demonstrates that

the evaluated sunflower accessions contain significant exploitable genetic variability and identifies key morphological traits that can be used as effective selection criteria for breeding vigorous, high-performing sunflower cultivars with improved establishment and productivity.

INTRODUCTION

Pakistan edible oil has growing importance during the last two decades. It is of concern to meet consumption requirements of growing population, the government has not only doing efforts to increase its domestic production but also spent too much money for edible oil imports (Rana et al., 2022). In Pakistan the main oilseed crops are sunflower, cottonseed, canola and rapeseed. Sunflower (*Helianthus annuus* L.) is a potential oilseed crop in the country. But during its history of four decades, the area and production remained almost stagnant during the first decade and started increasing with a lot of fluctuations during 2nd and 3rd decades of its cultivation. However, due to its potential for contributing towards edible oil, the area had been increasing continuously since 2000-01 to 2007-08 (397 thousand ha.). However, after that there was declining trend in area and production in the coming years (Tan & Kaya, 2019). Sunflower can be grown in all conditions of environment for the production of seeds, it having high phenotypic adaptation and also suitable for crop alternation. Sunflower oil provided high value of vitamins E than other vegetable (Mallick & Kar, 2023).

Major sunflower growing countries in the world are China, Turkey, Ukraine, United States, South Africa, France, Hungary, Romania, Argentina, Bulgaria Europe, Canada, Serbia, Russia and India (Bekele et al., 2019). Genetic variations supplied chance for the plant breeders to produce new and modified cultivars with suitable traits, which comprise both farmer-preferred characters and the traits preferred by breeders (photosensitivity, pest and disease resistance, etc.). From the very start of the agriculture to fulfill the sustenance food requirements, natural genetic variations have been oppressed between crop species and now it

is focusing on the better food for increasing populations. The global food production chain is becoming more sustainable due to accessibility and easy approach to genetic resources (Salgotra and Chauhan, 2023).

The growth of plant has very important role in the biosphere functioning (Gómez-Fernández and Milla, 2022). Its experiment is an expounding, holistic and integrative tactic to inferring plant shape and function. It uses primary simple data in the structure of areas, weight, volumes and contents of plant mechanisms to evaluate procedures among the whole plant. Now it is more widely used in the various fields such as breeding of plant, plant ecology and physiology of plant (Poorter et al., 2023). Sunflower is an important crop for edible oils and there is limited information available on the level of genetic variability and inheritance of seedling morphological traits of sunflower genotypes available. Assessing these characteristics at the early growth stage can give a good indication of the genotype performance and help in selecting the best breeding materials. Hence, the current study was carried out to evaluate the genetic variability of sunflower genotypes for seedling morphological traits and determine the important genetic parameters and potential sunflower lines with better traits. The results of this research will help in the development of effective strategies for selecting breeding lines and will benefit sunflower breeding programs for better seedling vigor and yield.

Germplasm collection

Ten sunflower (*Helianthus annuus* L.) accessions (Table 3.1) were collected from Oilseed Research Group of the Department of Plant Breeding and Genetics in University of Agriculture, Faisalabad.

Table 1: Names of Sunflower accessions used in research

Sr.No.	Names of accessions
1)	G-61
2)	A-2
3)	G-16
4)	G-1
5)	A-12
6)	G-13
7)	A-9
8)	A-6
9)	G-30
10)	017583

Experimental design

Sowing of sunflower seeds was done in wire house which is under department of Plant Breeding and Genetics, University of Agriculture, Faisalabad. It was arranged in CRD through factorial structured treatments. Seeds were sown in sand filled polythene bags of size 6.3cm length and 3.7cm width. Three sets per accession per replication of polythene bags were prepared. Each bag contained two seeds of one genotype per replication per set. Seedlings were observed and watered on daily basis. Three different harvests were cut.

H1= First harvest was done after 18 days of sowing and data were recorded.

H2= Second harvest was done after 26 days of sowing and data were recorded.

H3= Third harvest was taken after 32 days of sowing and data were recorded

Data recording

Data was recorded for various traits:

Shoot length (cm)

Shoot lengths of seedlings per accession per replication per harvest were recorded in cm with measuring scale.



(Fig. 1): A view of seedling's shoot length after harvest 1



(Fig. 2): A view of seedling's shoot length after harvest 2



(Fig. 3): A view of seedling's shoot length after

harvest 3

Root length (cm)

Root lengths of seedlings per accession per replication per harvest were recorded in cm with measuring scale



(Fig. 4): A view of seedling's root length after harvest 1



(Fig. 5): A view of seedling's root length after harvest 2



(Fig 6): A view of seedling's root length after harvest 3

Leaf length (cm)

Leaf lengths of seedlings per accession per replication per harvest were recorded and measured in cm with measuring scale.



(Fig. 7): A view of leaf length after harvest 1



(Fig. 8): A view of leaf length after harvest 2



(Fig. 9): A view of leaf length after harvest 3

Leaf width (cm)



Leaf width of seedlings per accession per replication per harvest were recorded which was measured in cm with measuring scale.



(Fig. 10): A view of leaf width after harvest 1 (Fig. 11): A view of leaf width after harvest 2



(Fig. 12): A view of leaf width after harvest 3

Number of leaves

Number of leaves of selected per accession per replication per harvest were counted.

Number of secondary roots



Number of secondary roots of seedlings per accession per replication per harvest were counted.

(Fig. 13): A view of No. secondary roots after harvest 1

(Fig. 14): A view of No. secondary roots after harvest 2



(Fig. 15): A view of No. secondary roots after harvest 3

Biometrical approaches

Table 2: Analysis of variance

Source of variance	Degree of freedom	Sum of square	Mean square	Expected mean square
Accessions	$(g-1)$	SSQ_g	$SSQ_g/(g-1)$	MS_g/MS_E
Treatment	$(t-1)$	SSQ_t	$SSQ_t/(t-1)$	MS_t/MS_E
Accessions × Treatment	$(g-1)(t-1)$	$SSQ_{g \times t}$	$SSQ_{g \times t}/((g-1)(t-1))$	$MS_{g \times t}/MS_E$
Error	$gt(r-1)$	SSQ_E	$SSQ_E/(g^*t^*(r-1))$	~~~~~
Total	$gtr-1$	SSQ_{Total}		

g = Genotypes

δ^2g = Genotypic variance

δ^2e = Phenotypic variance

The significant data were further subjected to least significance difference test (LSD) for individual comparisons of genotypic means and the total variation was splitted into its phenotypic and genotypic components.

Genotypic variance (VG) = (MS1-MS2) / r

Phenotypic variance (VP) = VE + VG

Environmental variance (VE) = MS2

Correlation Analysis

Genotypic and phenotypic correlations among the observed traits were calculated.

Results

Analysis of variance for *Helianthus annuus* L. accessions for various characters under three harvests

Analysis of variance for shoot length indicated significant differences among accessions and harvests and there was significant interaction between accessions and harvests (Accessions $\times$ Harvest). Shoot length was highest in accession G-61 followed by A-2 and A-9; accession G-13 had the lowest shoot length followed by A-12, G-1, A-6, and 017583 in Harvest 1. Shoot length in Harvest 2 ranged from the longest for accession A-12, to G-1, G-16, A-2, G-61, and finally, A-9, with accession 017583 having the shortest shoot length followed by A-6 and G-30. For shoot length, accession G-1 recorded the largest shoot length which was followed by A-6, A-9, and G-61, while accession G-30 had the smallest shoot length followed by G-13 and 017583.

Table 3: Analysis of variance of *Helianthus annuus* L. accessions for shoot length under various harvests

SOV	DF	SS	MSS	Fcal
Accessions (A)	9	339.95	37.772	3.98**
Harvests (H)	2	462.35	231.177	24.37**
H $\times$ A	18	487.87	27.104	2.86**
Error	60	569.09	9.485	
Total	89	1859.26		

SOV= Sources of variations, DF= Degrees of freedom, SS= Sum of square and MSS= Mean sum of square, F_{cal}= F calculated, *=Significant, **= Highly significant

Root length

Any differences among accessions, harvests, and Accessions $\times$ Harvests for root length were significant by the analysis of variance. In Harvest 1, the root length of accession A-9 was the highest, followed by G-13 and A-12 while the lowest root length was recorded for accession G-61 followed by G-30 and G-16. In harvest 2,

accession A-9 again yielded the longest root, followed by A-2, G-61 and G-16 with the lowest root length being G-1, followed by 017583 and A-12. For the root length, accession G-1 showed the highest root length in Harvest 3, followed by accession G-16 and A-2; while accession 017583 had the lowest root length, followed by accession G-13 and G-30.

Table 4: Analysis of variance of *Helianthus annuus* L. accessions for Root length under various harvests

SOV	DF	SS	MSS	Fcal
Accessions (A)	9	339.95	37.772	3.98**
Harvests (H)	2	462.35	231.177	24.37**
H $\times$ A	18	487.87	27.104	2.86**
Error	60	569.09	9.485	

Total	89	1859.26		
-------	----	---------	--	--

SOV= Sources of variations, DF= Degrees of freedom, SS= Sum of square and MSS= Mean sum of square, F_{cal}= F calculated, *=Significant, **= Highly significant

Leaf length

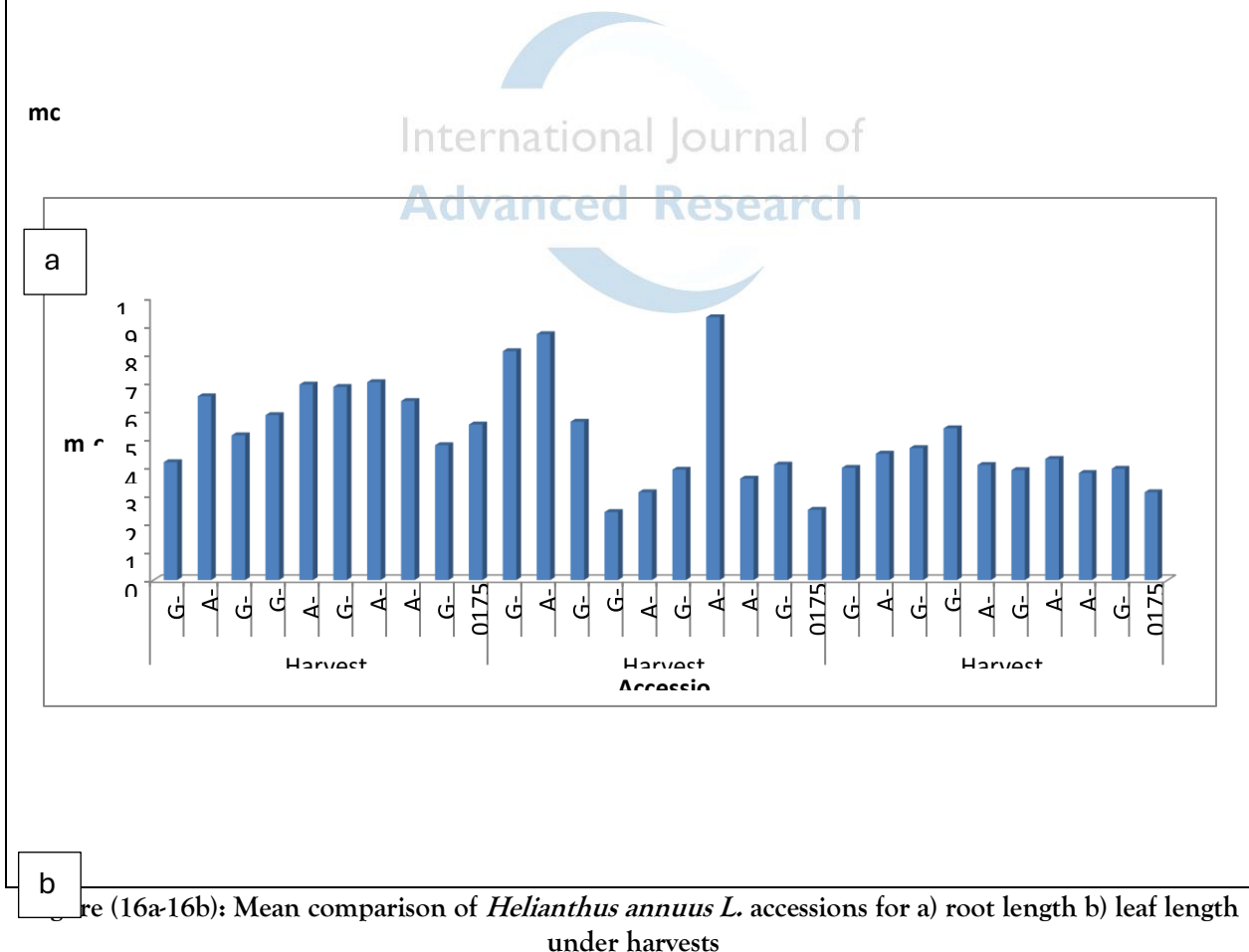
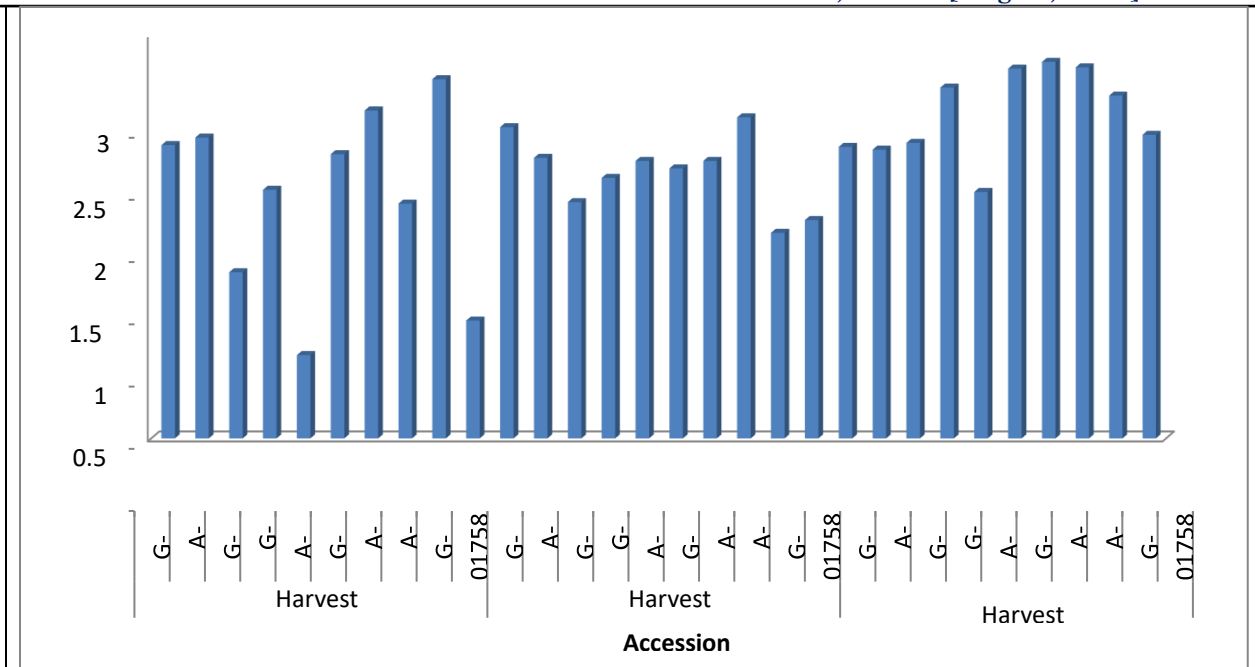
Variance analysis indicated that differences among accessions, harvests and Accessions × Harvest (interactions) were significant in leaf length. The longest leaf length occurred in accession G-30 followed by A-9 and A-2; the shortest leaf length was found in A-12 followed by 017583 and G-16 in Harvest 1. For Har62,

accession A-6 had the greatest leaf length followed by G-61, A-2 and A-12, and G-30 had the smallest leaf length followed by 017583 and G-16. Accession A-9 had the longest leaves in Harvest 3, followed by A-6, G-13, and G-1; accession A-12 had the shortest leaves, followed by A-2 and G-61.

Table 5: Analysis of variance of *Helianthus annuus* L. accessions for leaf length under various harvests

SOV	DF	SS	MSS	F
Accessions (A)	9	9.6461	1.07179	9.84**
Harvests (H)	2	5.2977	2.64885	24.33**
H × A	18	8.9192	0.49551	4.55**
Error	60	6.5324	0.10887	
Total	89	30.3953		

SOV= Sources of variations, DF= Degrees of freedom, SS= Sum of square and MSS= Mean sum of square, F_{cal}= F calculated, *=Significant, **= Highly significant



Leaf width

Analysis of variance demonstrated significant differences among accessions, harvests and their interaction (Accessions $\times$ Harvest) in leaf width. The largest leaf width was measured on accession A-9 and the smallest on accession 017583 in Harvest 1, while accession G-13 and A-6 tied for second largest leaf width and accession G-1 and

G-61 tied for second smallest leaf width in Harvest 1. Harvest 2 accessions A-6, A-12 had the widest leaves and G-30 had the narrowest leaves followed by G-13 and A-9. Harvest 3 accession A-9 had the greatest leaf width followed by accession G-16, while G-13 had the lowest leaf width followed by accession A-12.

Table 6: Analysis of variance of *Helianthus annuus* L. accessions for Leaf width under various harvests

SOV	DF	SS	MSS	Fcal
Accessions (A)	9	394.85	43.8728	4.73**
Harvests (H)	2	132.54	66.2712	7.15**
H $\times$ A	18	712.4	39.5778	4.27**
Error	60	556.44	9.274	
Total	89	1796.24		

SOV= Sources of variations, DF= Degrees of freedom, SS= Sum of square and MSS= Mean sum of square, F_{cal}= F calculated, *=Significant, **= Highly significant

No of leaves

The number of leaves per plant differed among accessions, harvests and Accessions $\times$ Harvests (ANOVA). Of the four accessions in Harvest 1, G-30 produced the highest number of leaves, G-16 next, followed by A-9, and A-2 had the lowest number of leaves followed by 017583 and G-30. In Harvest 2 accession G-61 had the most

number of leaves per plant, followed by A-2, G-1 and A-9, with G-13 having the fewest followed by A-12 and G-30. In Harvest 3, accession G-1 showed the most leaves per plant followed by accession A-9, G-16 and G-13, while accession A-2 exhibited the least number of leaves followed by accession 017583

Table 7: Analysis of variance of *Helianthus annuus* L. accessions for No. of leaves per plant under various harvests

SOV	DF	SS	MSS	Fcal
Accessions (A)	9	32.576	3.6195	6.98**
Harvests (H)	2	74.198	37.099	71.55**
H $\times$ A	18	45.131	2.5073	4.84**
Error	60	31.11	0.5185	
Total	89	183.014		

SOV= Sources of variations, DF= Degrees of freedom, SS= Sum of square and MSS= Mean sum of square, F_{cal}= F calculated, *=Significant, **= Highly significant

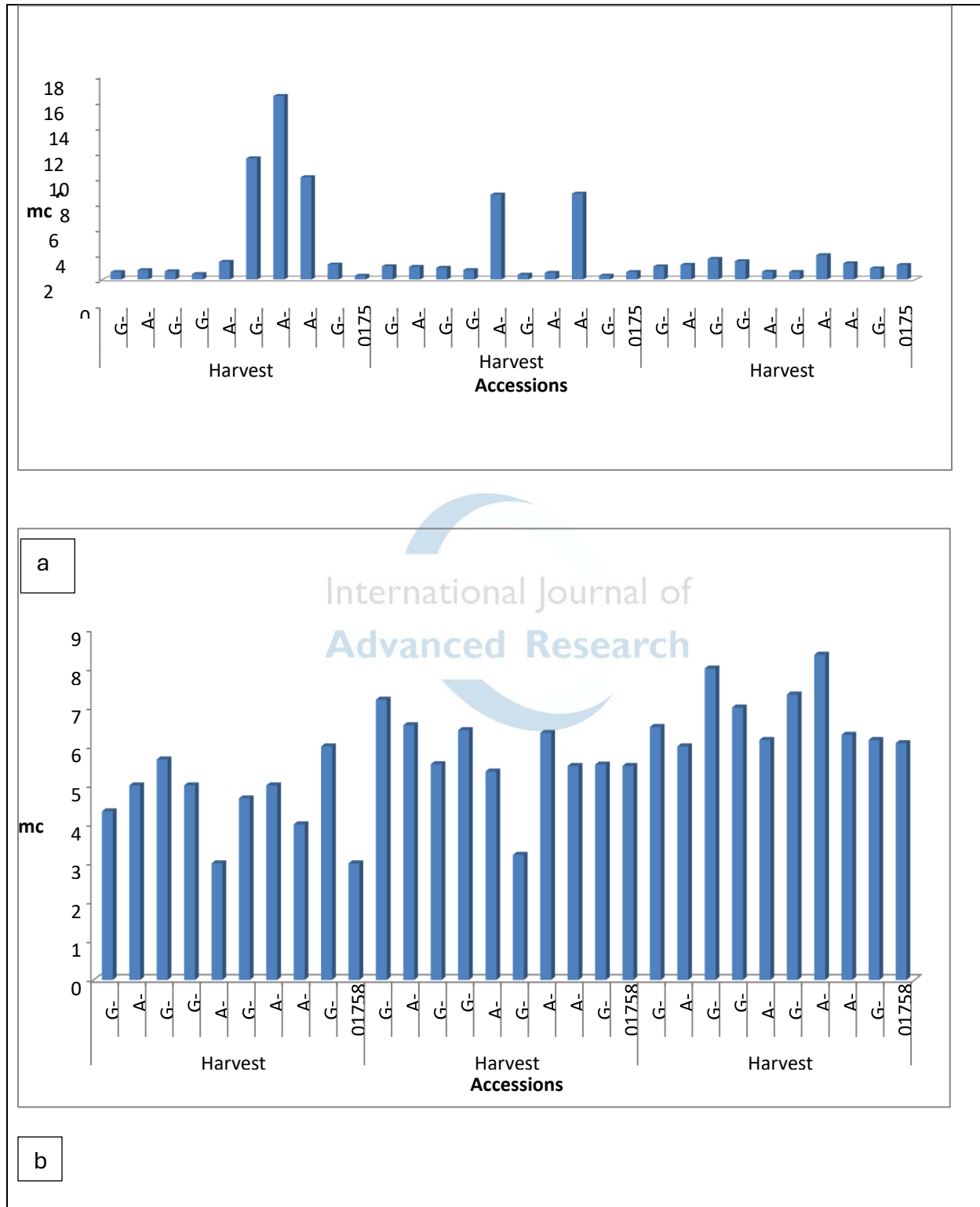


Figure (17a-17b): Mean comparison of *Helianthus annuus* L. accessions for a) leaf width b) No of leaves under harvests

Genotypic correlation under all harvests

Genotypic correlation of root length with other traits under all harvests

Root length showed negative and non-significant genotypic correlation with shoot length under harvest 1 i.e. after 18 days of sowing. Genotypic correlation with shoot length under harvest 2 i.e. after 26 days of sowing was positive and non-significant correlation. Genotypic correlation with shoot length under harvest 3 i.e. after 32 days of sowing was positive and highly significant.

Genotypic correlation for leaf length with other traits under all harvests

Under harvest 1 i.e. after 18 days of sowing leaf length had positive significant correlation with shoot height and it had negative non-significant correlation with root length.

Under harvest 2 i.e. after 26 days of sowing leaf length had positive and non-significant correlation with shoot height and it had negative non-significant correlation with root length.

Under harvest 3 i.e. after 32 days of sowing leaf length had negative and non-significant correlation with shoot height and root length.

Genotypic correlation for leaf width with other traits under all harvests

Under harvest 1 i.e. after 18 days of sowing leaf width had positive significant correlation with root length and it also had positive significant correlation with leaf length. It had negative non-significant correlation with shoot length

Under harvest 2 i.e. after 26 days of sowing leaf width had positive and non-significant correlation with shoot length, root length and leaf length.

Under harvest 3 i.e. after 32 days of sowing leaf width had negative and significant correlation with shoot length. It had positive and non-significant correlation leaf length and negative and non-significant correlation with root length.

Genotypic correlation for No. of leaves per plant number with other traits under all harvests

Under harvest i.e. after 18 days of sowing No. of leaves per plant had highly positive and significant correlation with leaf length. It also had positive and significant correlation with shoot length. It had positive non-significant correlation with leaf width. It had negative non-significant correlation with root length.

Under harvest 2 i.e. after 26 days of sowing No. of leaves per plant had positive and highly significant correlation with root length. It had negative and significant correlation with shoot length. It had positive and non-significant correlation with leaf width and leaf length

Under harvest 3 i.e. after 32 days of sowing No. of leaves per plant had positive and highly significant correlation with leaf width and positive and significant leaf length. It had positive and non-significant correlation with root length. It had negative and non-significant correlation shoot length.

Genotypic correlation for No. of secondary roots per plant with other traits under all harvests

Under harvest 1 i.e. after 18 days of sowing No. of secondary roots per plant had highly positive and significant correlation with No. of leaves per plant and leaf length. It also had positive significant correlation with leaf width. It had negative non-significant correlation with shoot length and leaf length.

Under harvest 2 i.e. after 26 days of sowing No. of secondary roots per plant had positive and highly significant correlation with No. of leaves per plant and it had negative and highly significant correlation root length. It also had positive and significant correlation with leaf length. It had negative non-significant correlation with shoot length and leaf width.

Under harvest 3 i.e. after 32 days of sowing No. of secondary roots per plant had positive and highly significant correlation with shoot length and it had positive and significant correlation with root length. It had positive and non-

significant correlation with No. of leaves per plant and leaf length. It had negative and non-significant correlation with leaf width.

Genotypic correlation for fresh seedling weight with other traits under all harvests

Under harvest 1 i.e. after 18 days of sowing fresh seedling weight had highly positive and significant correlation with No. of secondary roots per plant and it also had positive and significant correlation with No. of leaves per plant and leaf length. It had positive non-significant correlation with leaf width, shoot length and root length.

Under harvest 2 i.e. after 26 days of sowing fresh seedling weight had positive and non-significant correlation with shoot length, leaf length, leaf width, No. of leaves per plant and No. of secondary roots per plant. It had negative and non-significant correlation with root length.

Under harvest 3 i.e. after 32 days of sowing fresh seedling weight had positive and highly significant correlation with leaf length and No. of secondary roots per plant. It had negative and highly significant correlation with leaf width. It had positive and non-significant correlation with shoot length, root length and No. of secondary roots per plant.

Genotypic correlation for dry seedling weight with other traits under all harvests

Under harvest 1 i.e. after 18 days of sowing dry seedling weight had highly positive and significant correlation with No. of secondary roots per plant and it also had positive and significant correlation with No. of leaves per plant and leaf length. It had positive non-significant correlation with leaf width, shoot length, root length and fresh seedling weight.

Under harvest 2 i.e. after 26 days of sowing dry seedling weight had negative and highly significant correlation with shoot length and leaf width. It had negative and significant correlation with No. of secondary roots per plant and fresh seedling weight. It had positive and non-significant correlation with leaf length and it had negative non-significant correlation with No. of leaves per plant and root length.

Under harvest 3 i.e. after 32 days of sowing dry seedling weight had positive and highly significant correlation with No. of secondary roots per plant and negative significant correlation with No. of leaves per plant. It had positive and non-significant correlation with shoot length, root length, leaf length and fresh seedling weight.

Table 8: Genotypic correlation of various traits in Sunflower accessions traits for harvest

	SL	RL	LL	LW	L. NO.	SR
RL	-0.322					
LL	0.438*	-0.104				
LW	-0.179	0.657*	0.362*			
L. NO.	0.407*	-0.234	0.825**	0.701		
SR	0.318	0.016	0.753**	0.395*	0.967**	
FW	0.101	0.305	0.392*	0.272	0.362*	0.692**
DW	0.101	0.305	0.392*	0.272	0.362*	0.692**

SL= Shoot length, RL= Root length index, LL= Leaf length, LW= Leaf width, L No.=Number of Leaves, SR= No. of secondary roots, FW= Fresh weight, DW= Dry weight

Table 9: Genotypic correlation of various traits in Sunflower accessions traits for harvest 2

	SL	RL	LL	LW	L. NO.	SR	FW
RL	0.635						
LL	0.149	-0.121					
LW	0.396	0.149	0.332				

L. NO.	-0.116*	0.002**	0.440	0.640			
SR	-0.532	-0.381**	0.076*	-0.133	0.251**		
FW	0.067	-0.137	0.796	0.510	0.814	0.311	
DW	-0.015**	-0.288	0.050	-0.168**	-0.395	-0.597*	-0.253*

SL= Shoot length, RL= Root length index, LL= Leaf length, LW= Leaf width, L No.=Number of Leaves, SR= No. of secondary roots, FW= Fresh weight, DW= Dry weight

Table 10: Genotypic correlation of various traits in Sunflower accessions traits for harvest 3

	SL	RL	LL	LW	L. NO.	SR	FW
RL	0.056**						
LL	-0.148	-0.275					
LW	-0.271*	-0.188	0.058				
L. NO.	-0.450	0.562	0.150*	0.208**			
SR	0.104**	0.488*	0.374	-0.009	0.601		
FW	0.081	0.033	0.320**	-0.159**	0.289**	0.219	
DW	0.712	0.126	0.123	-0.530	-0.332*	0.421**	0.398

SL= Shoot length, RL= Root length index, LL= Leaf length, LW= Leaf width, L No.=Number of Leaves, SR= No. of secondary roots, FW= Fresh weight, DW= Dry weight

Phenotypic correlation under all harvests

Phenotypic correlation of root length with other traits under all harvests

Under harvest 1 i.e. after 18 days of sowing root length of treatment 1 had negative non-significant correlation with shoot length. Under harvest 2 i.e. after 26 days of sowing root length of treatment 2 had positive non-significant correlation with shoot length. Under harvest 3 i.e. after 32 days of sowing root length of treatment 3 had positive and highly significant correlation with shoot length.

Phenotypic correlation for leaf length with other traits under all harvests

Under harvest 1 i.e. after 18 days of sowing leaf length had positive significant correlation with shoot height and it had negative non-significant correlation with root length.

Under harvest 2 i.e. after 26 days of sowing leaf length had positive and non-significant correlation with shoot height and it had negative non-significant correlation with root length.

Under harvest 3 i.e. after 32 days of sowing leaf length had negative and non-significant correlation with shoot height and root length.

Phenotypic correlation for leaf width with other traits under all harvests

Under harvest 1 i.e. after 18 days of sowing leaf width had positive significant correlation with root length and it also had positive significant correlation with leaf length. It had negative non-significant correlation with shoot length.

Under harvest 2 i.e. after 26 days of sowing leaf width had positive non-significant correlation with shoot height, root length and leaf length.

Under harvest 3 i.e. after 32 days of sowing leaf width had negative and significant correlation with shoot length. It had positive and non-significant correlation leaf length and negative and non-significant correlation with root length.

Phenotypic correlation for No. of leaves per plant number with other traits under all harvests

Under harvest 1 i.e. after 18 days of sowing No. of leaves per plant had positive and strong significant correlation with leaf length. It also had positive non-significant correlation with shoot length and leaf width. It had negative non-significant correlation with root length.

Under harvest 2 i.e. after 26 days of sowing No. of leaves per plant had negative and significant

correlation with root length. It had positive non-significant correlation with leaf length and leaf width. It had negative non-significant correlation with shoot length.

Under harvest 3 i.e. after 32 days of sowing No. of leaves per plant had positive and highly significant correlation with leaf width and positive and significant leaf length. It had positive and non-significant correlation with root length. It had negative and non-significant correlation with shoot length.

Phenotypic correlation for No. of secondary roots per plant with other traits under all harvests

Under harvest 1 i.e. after 18 days of sowing No. of secondary roots per plant had positive and highly significant correlation with No. of leaves per plant and leaf length. It also had positive significant correlation with leaf width. It had positive non-significant correlation with shoot length and root length.

Under harvest i.e. after 26 days of sowing No. of secondary roots per plant had positive and significant correlation with leaf length and No. of leaves per plant. It had negative and highly significant correlation with root length and it also had negative non-significant correlation with shoot length and leaf width.

Under harvest 3 i.e. after 32 days of sowing No. of secondary roots per plant had positive and highly significant correlation with shoot length and it had positive and significant correlation with root length. It had positive and non-significant correlation with No. of leaves per plant and leaf length. It had negative and non-significant correlation with leaf width.

Phenotypic correlation for fresh seedling weight with other traits under all harvests

Under harvest 1 i.e. after 18 days of sowing fresh seedling weight had positive and highly significant correlation with No. of secondary roots per plant and it also had positive and significant correlation with leaf length. It had

positive non-significant correlation with leaf width, shoot length, root length and No. leaves per plant.

Under harvest 2 i.e. after 26 days of sowing fresh seedling weight had positive and non-significant correlation with shoot length, leaf width, root length, No. leaves per plant and No. of secondary roots per plant and it also had negative and non-significant correlation with root length.

Under harvest 3 i.e. after 32 days of sowing fresh seedling weight had positive and highly significant correlation with leaf length and No. of leaves per plant. It had negative and highly significant correlation with leaf width. It had positive and non-significant correlation with shoot length, root length and No. of secondary roots per plant.

Phenotypic correlation for dry seedling weight with other traits under all harvests

Under harvest 1 i.e. after 18 days of sowing dry seedling weight had positive and highly significant correlation with No. of secondary roots per plant and it also had positive and significant correlation with leaf length. It had positive non-significant correlation with leaf width, shoot length, No. of leaves per plant, root length and fresh seedling weight.

Under harvest 2 i.e. after 26 days of sowing dry seedling weight had negative and highly significant correlation with shoot length and leaf width and it had negative and significant correlation with No. of secondary roots per plant and fresh seedling weight. It had positive and non-significant correlation with leaf length. It had negative non-significant correlation with root length and No. of leaves per plant.

Under harvest 3 i.e. after 32 days of sowing dry seedling weight had positive and highly significant correlation with No. of secondary roots per plant and negative significant correlation with No. of leaves per plant. It had positive and non-significant correlation with shoot length, root length, leaf length and fresh seedling weight.

Table 11: Phenotypic correlation of various traits in Sunflower accessions traits for harvest 1

	SH	RL	LL	LW	L. NO.	SR
RL	-0.322					
LL	0.437*	-0.103				
LW	-0.179	0.656**	0.361*			
L. NO.	0.274	-0.152	0.583**	0.049		
SR	0.317	0.014	0.747**	0.393*	0.658**	
FW	0.099	0.298	0.383*	0.264	0.282	0.666**
DW	0.099	0.298	0.383*	0.264	0.282	0.666**

SL= Shoot length, RL= Root length index, LL= Leaf length, LW= Leaf width, L No.=Number of Leaves, SR= No. of secondary roots, FW= Fresh weight, DW= Dry weight

Table 12: Phenotypic correlation of various traits in Sunflower accessions traits for harvest 2

	SL	RL	LL	LW	L. NO.	SR	FW
RL	0.525						
LL	0.148	-0.088					
LW	0.383	0.911	0.318				
L. NO.	-0.108	-0.008*	0.393	0.597			
SR	-0.532	-0.327**	0.076*	-0.128	0.226*		
FW	0.067	-0.114	0.793	0.498	0.742	0.311	
DW	-0.012**	-0.215	-0.051	-0.155**	-0.389	-0.576*	-0.242*

SL= Shoot length, RL= Root length index, LL= Leaf length, LW= Leaf width, L No.=Number of Leaves, SR= No. of secondary roots, FW= Fresh weight, DW= Dry weight

Table 13: Phenotypic correlation among different traits of sunflower accessions during Harvest 3

	SL	RL	LL	LW	L. NO.	SR	FW
RL	0.055**						
LL	-0.149	-0.272					
LW	-0.270*	-0.187	0.058				
L. NO.	-0.345	0.435	0.113*	0.146**			
SR	0.104**	0.485	0.371	-0.007	0.438		
FW	0.074	0.035	0.322**	-0.152**	0.156**	0.208	
DW	0.712	0.013	0.123	-0.529	-0.257*	0.419**	0.387

SL, shoot length; RL, root length index; LL, leaf length; LW, leaf width; L No., number of leaves; SR, number of secondary roots; FW, fresh weight; DW, dry weight.

Discussion

Shoot Length

Shoot length is a good indicator of the seedling vigor and early establishment in sunflower. Analysis of variance showed that there was a high genetic variation among the evaluated sunflower accessions, with significant differences noted for shoot length among accessions, harvests and their

interaction in the present study. The superior performance of accessions G-61, A-12 and G-1 at various harvests indicated that these accessions have higher genetic potential in terms of shoot elongation, while the poor performing accessions showed relatively low shoot elongation. The results suggest genetic and developmental factors affect shoot growth.

Differences in the length of the shoots may be due to variations in genetic factors controlling cell division, cell elongation, nutrient absorption and photosynthetic rates. Rapid growth of the shoot allows the seedlings to absorb more light, grow quickly and produce more biomass in the early days of development. Significant accession $\times$ harvest interaction further suggests that the growth performance of individual genotypes was different across the harvests, which may be due to differences in adaptation and growth dynamics. The results are similar to those reported by Kitajima (1996), Reich et al. (1998), and Wang et al. (2006), who also found high genetic variability in shoot growth among sunflower genotypes (Pereyra-Irujo et al., 2008).

The present results confirm that shoot length is a good morphological characteristic to identify superior sunflower accessions at the seedling stage. Genotypes that have showed higher shoot elongation throughout the harvests could have higher vigor and better adaptation and therefore should be considered for sunflower improvement. Shoot length can thus be used as a good selection tool to identify superior early growth genotypes with higher crop establishment potential in a variety of growing environments.

Root Length

One of the significant morphological characteristics is root length which would be responsible for efficient water and nutrient uptake during early seedling development. The results of the present study showed that there were significant differences among the sunflower accessions, among the different harvests and between the accessions and harvests for root length, indicating that there was a high level of genetic variation among the accessions evaluated. Accessions A-9 and G-1 also consistently grew the most roots, while accession 017583 generally grew the shortest roots. These results indicate that the root development is a function of both genetics and growth stage and therefore, root length can be used as a measurement of seedling vigor (Palta & Watt, 2009; Xu et al., 2020).

This observed root length variation could have been caused by the variation in the capacity for elongation of the roots, partitioning of assimilates and genetic potential among the accessions. Longer root systems can typically be more effective in extracting soil moisture and nutrients and, as such, improve the early establishment and adaptation of seedlings in differing environmental conditions. Shashidhara (2009) and Geetha et al. (2012) have also reported high genetic variation in sunflower genotype for root length and its importance as a sunflower selection criterion in breeding programs.

Leaf Length

The length of the leaves is one of the important morphological characters with relation to the photosynthetic capacity and vegetative growth of sunflower seedlings. Analysis of variance for leaf length in the present study indicated that there was significant difference among accessions, harvests and interaction between accessions and harvests, which showed that there is a high level of genetic variability among the sunflower accessions evaluated. In various harvests accessions G-30, A-6, and A-9 had the longest leaves, while accession A-12 always had the shortest leaves. The results indicated that the leaf expansion is genetically controlled and also is affected by developmental stage (Gonzalez et al., 2010; Kessler & Sinha, 2004; Muller et al., 2007).

The difference in leaf length observed could be explained by the different cell expansion or photosynthetic rate or different allocation of assimilates between sunflower genotypes. Enhanced light interception (higher leaf surface due to larger leaves) at early growth stages leads to improved photosynthesis and biomass at early stage. The genetic variation observed in leaf length among sunflower genotypes by Mahender et al. (2015) and Snider et al. (2020) indicated that this character should be considered as an effective selection parameter to improve seedling vigor and overall crop performance.

Leaf Width

The width of leaves is an important part of leaf morphology which affects the development of the canopy, light interception and photosynthetic efficiency in sunflower seedlings. The present study showed that there is significant difference among accessions, harvests and interaction between accessions and harvests for leaf width which shows there is a considerable genetic variation among the evaluated sunflower accessions. The leaf width of accessions A-9 and A-6 were the widest in various harvests while narrow leaf width was generally observed in accessions G-30 and G-13. Both genotype and developmental stage are shown to have a significant effect on leaf expansion in this study. The variability in leaf width found could be due to variation in leaf development potential and assimilate partitioning among accessions of sunflower. Wider leaves increase the photosynthetic area and light capture and biomass production in early vegetation development (Jackson & Koch, 1997; Sadras & Trapani, 1999; Nunes-Nesi et al., 2016). The same has been reported by (Dudhe et al., 2020; Lecoeur et al., 2011) who observed a high variability in width of leaves among the genotypes of sunflower and recommended it as a selection criterion for identification of high yielding vigorous sunflower genotypes.

Number of Leaves per Plant

It is important to measure the number of leaves per plant as it shows the vegetative development and photosynthetic potential of sunflower seedlings. The number of leaves per plant exhibited significant differences among accessions, among harvests and between accessions × harvests in the present study, which meant that great genetic differences existed between the evaluated accessions of sunflower. The numbers of leaves produced by accessions G-30, G-61 and G-1 were greater at various harvests while accession A-2 had generally the lowest numbers of leaves. The results suggest that the number of leaves produced depends on both the

genetic constitution and the developmental state of the plant.

Differences in growth rate, meristem activity, nutrient use efficiency, and photosynthetic efficiency could be responsible for the variation among sunflower accessions. If more leaves are present on the plant, then the photosynthetic surface area will be larger, the carbohydrate production will be more, and the plant will be bigger (Coêlho et al., 2022; Muller et al., 2011). The marked accession × harvest interaction also indicates that the genotype response was different at various developmental stages of seedlings, further emphasizing the need to test accessions at different developmental stages. Lecoeur et al. (2011) and Varalakshmi et al. (2020) reported that there was high genetic variability for number of leaves among different sunflower genotypes.

There is high level of genetic variation for leaf number, suggesting that it can be applied as a selection criterion in sunflower breeding programs for vigorous genotype. Accessions with a higher leaf production later in early growth will likely have a higher photosynthetic ability and better seedling establishment, which will lead to better plant growth and yield potential in the field (Bharamappanavara et al., 2023).

Number of Secondary Roots

The number of secondary roots is an important parameter for root system architecture and is important for water and nutrient uptake efficiency in early plant development. Results indicated that there were significant differences between accessions of sunflower but the differences suggest that secondary root development is significantly influenced by genetic variability and stage of harvest. Genotypes with more secondary roots are likely to have a larger root system to exploit soil resources and adapt to different environmental conditions efficiently. Secondary roots increase the absorptive area of the root system which increases nutrient uptake, water acquisition, and seedling vigor. A good secondary root system also helps to provide anchorage and drought stress tolerance on early growth (Lynch et al., 2021; Ramachandran et al.,

2025). The same has been mentioned by da Silva et al., (2025) who highlighted the significance of root characteristic in the improvement of sunflower. The same significant differences in root traits among sunflower genotypes were also reported by previous studies McGrail et al. (2020) and Maqbool et al. (2022) which suggest that root architecture is important selection criterion for better breeding material.

The genetic variation observed for secondary root development indicates that selection programmes for enhancing nutrient-use efficiency, drought tolerance and early seedling establishment can include this trait. Thus, secondary root number is a valuable morphological parameter to characterize the superior sunflower genotypes with better growth potential.

Fresh Seedling Weight

Fresh seedling weight is an important biomass index and is a combined biomass product of shoot and root growth in early seedling development. The higher fresh weight genotype is generally found to have higher photosynthetic efficiency, better uptake of nutrients and more vigorous growth. Fresh seedling weight was not given in the mean comparison tables, but the correlation analysis showed that it was positively correlated with several key morphological characteristics, which means that it is closely correlated with seedling vigor (Cui et al., 2002).

The results indicated that fresh seedling weight was positively correlated with leaf length, number of leaves and secondary roots, indicating that more vegetative growth leads to more seedling biomass. Larger leaves and a well-developed root system make seedlings able to produce and accumulate more photosynthates, thus contributing to increased fresh biomass (Bazmi & Panichayupakaranant, 2023; Bi & Zhou, 2021; Mathur et al., 2018). Gopichand (2013) and Nichal et al. (2015) also reported similar correlations between fresh seedling weight and morphological traits which led to conclusion that the fresh seedling weight is an important criterion for screening promising sunflower

genotypes and it is an effective indicator of early vigor.

Dry Seedling Weight

One of the most reliable measures of biomass accumulation is dry seedling weight as it reflects the actual structural material produced by the plant after removing the water content. More DW correlates with better photosynthesis, assimilate translocated and biomass allocated in early seedling growth. Dry seedling weight had significant relationships with some morphological features which meant that the biomass accumulation was related to the vigor and vegetative growth of seedling. The superior shoot growth, leaf development and root characteristics of accessions were likely to yield more dry biomass because of their high physiological efficiency.

The positive relationship of dry seedling weight with leaf length, secondary roots and fresh seedling weight indicates that increases in photosynthetic efficiency and root system are directly related to increased biomass production.

The seedlings with higher dry matter accumulation usually have more growth potential and will have a higher establishment success in the field (Shi et al., 2020). Similarly, significant genetic variation was reported for biomass related traits among sunflower genotypes by (Hassanine et al., 2025; Wang et al., 2020) and highlighted the importance of these traits in selection of superior breeding material.

Correlation among Morphological Traits

Correlation analysis showed that some of the morphological traits were significantly correlated with each other, suggesting that betterment in some traits would also affect related traits. Vigorously growing plants that produce more leaves, higher leaf width, shoot length, and secondary roots, are associated with higher seedling biomass, which implies a positive correlation between these plant parameters and establishment and plant performance. On the other hand, a few negative correlations among some of the traits suggest that this may be the

case, that is, the allocation of resources during the early growth may differ among the different genotypes. These relationships are also valuable for indirect selection in sunflower breeding as traits with high positive correlations can be selected together.

The results obtained here are in good agreement with the previous work conducted which showed strong correlations between morphological traits during early development of sunflower. The significant positive correlations between the growth traits of seedlings were also reported by (Komel & Razzaq, 2019; Markulj Kulundžić et al., 2025) and stated that correlation analysis could be useful in selecting superior genotypes. Thus, the selection of sunflower lines based on shoot growth, root development, leaf morphology and biomass related characters simultaneously would be more efficient in the development of vigorous and high yielding cultivars.

Conclusion

The current study found high genetic heterogeneity across sunflower accessions for all investigated seedling morphological features throughout three developmental phases, indicating the presence of potential genetic resources for breeding enhancement. The study found significant interactions between accession and harvest, highlighting the need to evaluate germplasm at various growth phases. Accessions G-61, A-9, G-1, G-30, and A-6 consistently outperformed in key growth traits, but accession 017583 had poor seedling development. Strong positive genotypic and phenotypic correlations between leaf growth, secondary root formation, fresh biomass, and dry biomass suggest that these traits are excellent predictors of early seedling vigour and can be used for indirect selection. The combination of shoot growth, root architecture, leaf morphology, and biomass parameters provide a solid foundation for identifying superior breeding materials. These findings have important implications for sunflower improvement projects and support the use of early seedling phenotyping as an effective technique for accelerating the production of

high-yielding, vigorous, and environmentally adaptable sunflower cultivars.

REFERENCES

- Kitajima, K., 1996. Ecophysiology of tropical tree seedlings. In *Tropical forest plant ecophysiology* (pp. 559-596). Boston, MA: Springer US.
- Wang, G.G., Bauerle, W.L. and Mudder, B.T., 2006. Effects of light acclimation on the photosynthesis, growth, and biomass allocation in American chestnut (*Castanea dentata*) seedlings. *Forest Ecology and Management*, 226(1-3), pp.173-180.
- Reich, P.B., Tjoelker, M.G., Walters, M.B., Vanderklein, D.W. and Buschena, C., 1998. Close association of RGR, leaf and root morphology, seed mass and shade tolerance in seedlings of nine boreal tree species grown in high and low light. *Functional ecology*, 12(3), pp.327-338.
- Pereyra-Irujo, G.A., Velázquez, L., Lechner, L. and Aguirrezábal, L.A., 2008. Genetic variability for leaf growth rate and duration under water deficit in sunflower: analysis of responses at cell, organ, and plant level. *Journal of experimental botany*, 59(8), pp.2221-2232.
- Palta, J. and Watt, M., 2009. Vigorous crop root systems: form and function for improving the capture of water and nutrients. *Applied crop physiology: boundaries between genetic improvement and agronomy*. Academic, San Diego, pp.309-325.
- Xu, X., Ye, J., Yang, Y., Zhang, M., Xu, Q., Feng, Y., Yuan, X., Yu, H., Wang, Y., Yang, Y. and Wei, X., 2020. Genome-wide association study of rice rooting ability at the seedling stage. *Rice*, 13(1), p.59.
- Shashidhara, K.N., 2009. *Identification and Validation of High Water Use Efficient and Better Root Type Sunflower (Helianthus Annuus L) Inbreds and Parental Lines for Improved Drought Tolerance* (Doctoral dissertation, University of Agricultural Sciences).

- Geetha, A., Suresh, J. and Saidaiah, P., 2012. Study on response of sunflower (*Helianthus annuus* L.) genotypes for root and yield characters under water stress.
- Gonzalez, N., De Bodt, S., Sulpice, R., Jikumaru, Y., Chae, E., Dhondt, S., Van Daele, T., De Milde, L., Weigel, D., Kamiya, Y. and Stitt, M., 2010. Increased leaf size: different means to an end. *Plant physiology*, 153(3), pp.1261-1279.
- Kessler, S. and Sinha, N., 2004. Shaping up: the genetic control of leaf shape. *Current Opinion in Plant Biology*, 7(1), pp.65-72.
- Muller, B., Bourdais, G., Reidy, B., Bencivenni, C., Massonneau, A., Condamine, P., Rolland, G., Conéjéro, G., Rogowsky, P. and Tardieu, F., 2007. Association of specific expansins with growth in maize leaves is maintained under environmental, genetic, and developmental sources of variation. *Plant physiology*, 143(1), pp.278-290.
- Mahender, A., Anandan, A. and Pradhan, S.K., 2015. Early seedling vigour, an imperative trait for direct-seeded rice: an overview on physio-morphological parameters and molecular markers. *Planta*, 241(5), pp.1027-1050.
- Snider, J.L., Pilon, C. and Virk, G., 2020. Seed characteristics and seedling vigor. *Cotton seed and seedlings*, pp.9-23.
- Sadras, V.O. and Trapani, N., 1999. Leaf expansion and phenological development: key determinants of sunflower plasticity, growth and yield. In *Crop Yield: Physiology and Processes* (pp. 205-233). Berlin, Heidelberg: Springer Berlin Heidelberg.
- Jackson, L.E. and Koch, G.W., 1997. The ecophysiology of crops and their wild relatives. *Ecology in agriculture*, pp.3-37.
- Nunes-Nesi, A., Nascimento, V.D.L., de Oliveira Silva, F.M., Zsögön, A., Araújo, W.L. and Sulpice, R., 2016. Natural genetic variation for morphological and molecular determinants of plant growth and yield. *Journal of experimental botany*, 67(10), pp.2989-3001.
- Dudhe, M.Y., Mulpuri, S., Meena, H.P., Ajjanavara, R.R., Kodeboyina, V.S. and Adala, V.R., 2020. Genetic variability, diversity and identification of trait-specific accessions from the conserved sunflower germplasm for exploitation in the breeding programme. *Agricultural Research*, 9(1), pp.9-22.
- Lecoeur, J., Poiré-Lassus, R., Christophe, A., Pallas, B., Casadebaig, P., Debaeke, P., Vear, F. and Guilioni, L., 2011. Quantifying physiological determinants of genetic variation for yield potential in sunflower. *SUNFLO: a model-based analysis. Functional plant biology*, 38(3), pp.246-259.
- Cui, K., Peng, S., Xing, Y., Xu, C., Yu, S. and Zhang, Q., 2002. Molecular dissection of seedling-vigor and associated physiological traits in rice. *Theoretical and Applied genetics*, 105(5), pp.745-753.
- Bazmi, R.R. and Panichayupakaranant, P., 2023. The role of roots, stems, and leaves in plant function: Structural and physiological perspectives for optimized plant growth. *Australian Herbal Insight*, 6(1), pp.1-5.
- Bi, Y. and Zhou, H., 2021. Changes in peanut canopy structure and photosynthetic characteristics induced by an arbuscular mycorrhizal fungus in a nutrient-poor environment. *Scientific reports*, 11(1), p.14832.
- Mathur, S., Sharma, M.P. and Jajoo, A., 2018. Improved photosynthetic efficacy of maize (*Zea mays*) plants with arbuscular mycorrhizal fungi (AMF) under high temperature stress. *Journal of Photochemistry and Photobiology B: Biology*, 180, pp.149-154.
- Nichal, S.S., Chawhan, R.G., Tayade, S.D. and Ratnaparkhi, R.D., 2015. Correlation of seed and seedling characters with yield of sunflower (*Helianthus annuus* L.) hybrids. *International Journal of Economic Plants*, 1(2), pp.65-68.
- GOPICHAND, C.R., 2013. CORRELATION BETWEEN SEED, SEEDLING,

- GROWTH AND YIELD CHARACTERS ON YIELD OF SUNFLOWER.
- Muller, B., Pantin, F., Génard, M., Turc, O., Freixes, S., Piques, M. and Gibon, Y., 2011. Water deficits uncouple growth from photosynthesis, increase C content, and modify the relationships between C and growth in sink organs. *Journal of experimental botany*, 62(6), pp.1715-1729.
- Coêlho, E.D.S., Souza, A.R.E.D., Lins, H.A., Santos, M.G.D., Freitas Souza, M.D., Tartaglia, F.D.L., de Oliveira, A.K.S., Lopes, W.D.A.R., Silveira, L.M., Mendonça, V. and Barros Júnior, A.P., 2022. Efficiency of nitrogen use in sunflower. *Plants*, 11(18), p.2390.
- Varalakshmi, K., Neelima, S., Reddy, R.N. and Sreenivasulu, K.N., 2020. Genetic variability studies for yield and its component traits in newly developed sunflower (*Helianthus annuus*L.) hybrids. *Electronic Journal of Plant Breeding*, 11(01), pp.301-305.
- Bharamappanavara, M., Madhyavenkatapura, A.S., Appaiah, M.C., Patil, B.S., Vijjeswarapu, A., Senguttuvel, P., Madhav, M.S., Rathod, S., Mondal, T.K., Ramappa, L. and Mathada, U.R., 2023. Genetic analysis of early seedling vigour in *Oryza glaberrima* accessions under laboratory and direct-seeded rice conditions. *Cereal Research Communications*, 51(4), pp.991-1002.
- Lynch, J.P., Strock, C.F., Schneider, H.M., Sidhu, J.S., Ajmera, I., Galindo-Castañeda, T., Klein, S.P. and Hanlon, M.T., 2021. Root anatomy and soil resource capture. *Plant and Soil*, 466(1), pp.21-63.
- Ramachandran, P., Ramirez, A. and Dinneny, J.R., 2025. Rooting for survival: how plants tackle a challenging environment through a diversity of root forms and functions. *Plant physiology*, 197(1), p.kiae586.
- McGrail, R.K., Van Sanford, D.A. and McNear Jr, D.H., 2020. Trait-based root phenotyping as a necessary tool for crop selection and improvement. *Agronomy*, 10(9), p.1328.
- Maqbool, S., Hassan, M.A., Xia, X., York, L.M., Rasheed, A. and He, Z., 2022. Root system architecture in cereals: progress, challenges and perspective. *The Plant Journal*, 110(1), pp.23-42.
- da Silva, O.B., de Castro, E.M., Vassura, Y., Pires, M.V., de Carvalho, C.G.P., de Carvalho, L.M. and Pereira, M.P., 2025. Root system morphoanatomy of sunflower genotypes under water deficit. *BMC Plant Biology*, 25(1), p.449.
- Shi, Z., Chang, T.G., Chen, F., Zhao, H., Song, Q., Wang, M., Wang, Y., Zhou, Z., Wang, C., Zhou, S.C. and Wang, B., 2020. Morphological and physiological factors contributing to early vigor in the elite rice cultivar 9,311. *Scientific reports*, 10(1), p.14813.
- Hassanine, N.N., Saleh, A.A., Essa, M.O.A., Adam, S.Y., Mohai Ud Din, R., Rehman, S.U., Ali, R., Husien, H.M. and Wang, M., 2025. Candidate genes, markers, signatures of selection, and quantitative trait loci (QTLs) and their association with economic traits in livestock: Genomic insights and selection. *International Journal of Molecular Sciences*, 26(16), p.7688.
- Wang, B., Lin, Z., Li, X., Zhao, Y., Zhao, B., Wu, G., Ma, X., Wang, H., Xie, Y., Li, Q. and Song, G., 2020. Genome-wide selection and genetic improvement during modern maize breeding. *Nature Genetics*, 52(6), pp.565-571.
- Markulj Kulundžić, A., Liović, I., Sudarić, A., Duvnjak, T., Matoša Kočar, M., Varga, I. and Mijić, A., 2025. Morpho-physiological adaptation of sunflower hybrids to varying plant densities. *Plants*, 14(22), p.3446.

- Komel, S. and Razzaq, A., 2019. Association among morphological and yield related traits in different accessions of sunflower (*Helianthus annuus* L.). *Russian Agricultural Sciences*, 45(2), pp.128-136.
- Rana, A.W., Gill, S. and Akram, I., 2022. *Promoting oil seed crops in Pakistan: Prospects and constraints*. Intl Food Policy Res Inst.
- Tan, A.S. and Kaya, Y., 2019. Sunflower (*Helianthus annuus* L.) genetic resources, production and researches in Turkey. *OCL*, 26, p.21.
- Mallick, R. and Kar, S., 2023. Influence of foliar nutrients on growth, yield attributes and yield of spring sunflower in southern part of West Bengal.
- Bekele, M., 2019. Major onion (*Allium cepa* L.) production challenges in Ethiopia: A review. *Journal of Biology, Agriculture and Healthcare*.
- Salgotra, R.K. and Chauhan, B.S., 2023. Genetic diversity, conservation, and utilization of plant genetic resources. *Genes*, 14(1), p.174.
- Gómez-Fernández, A. and Milla, R., 2022. How seeds and growth dynamics influence plant size and yield: integrating trait relationships into ontogeny. *Journal of Ecology*, 110(11), pp.2684-2700.
- Poorter, H., Hummel, G.M., Nagel, K.A., Fiorani, F., von Gillhaussen, P., Virnich, O., Schurr, U., Postma, J.A., van de Zedde, R. and Wiese-Klinkenberg, A., 2023. Pitfalls and potential of high-throughput plant phenotyping platforms. *Frontiers in plant science*, 14, p.1233794.

