



Sustainable use of Vinasse as a Foliar Amendment to Enhance Growth, Physiology, and Yield of Sunflower Crops (*Helianthus annuus* L.)

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Abstract

Developing high-yielding sunflower cultivars and adopting eco-friendly fertilization strategies are essential for sustaining oil crop productivity under climate change pressures. Vinasse, a nutrient-rich byproduct of the distillery industry, offers a potential eco-friendly alternative to mineral fertilizers. This study evaluated three sunflower cultivars (Sakha 53, Giza 102, and Giza 120) under foliar vinasse application (0-, 50-, and 100-mL L⁻¹) for two summer seasons (2024–2025) in south of Egypt. Application of vinasse at 50 mL L⁻¹ significantly increased seed yield (4.09 t ha⁻¹), oil yield (1.79 t ha⁻¹), and oil content (38.14%) compared with the control ($p \leq 0.05$), while higher concentrations reduced performance due to vinasse salinity and acidity. Giza 102 showed superior adaptability, achieving the highest yield and growth indices, particularly when combined with 50 mL L⁻¹ vinasse. Significant interaction effects indicated that Giza 102 treated with 50 mL L⁻¹ vinasse offered the highest agronomic potential. Path coefficient analysis revealed that Net Assimilation Rate and Crop Growth Rate had the strongest direct effects on yield. Overall, foliar vinasse application at 50 mL L⁻¹ represents a sustainable fertilization strategy to enhance sunflower growth and oil production, with Giza 102 showing the highest agronomic potential for climate-resilient cultivation. The superior productivity of Giza 102 could be attributed to its genetic constitution and its efficient interaction with the environmental conditions of the experimental site, which likely contributed to enhanced physiological performance and yield compared with the other tested cultivars.

Keywords Cultivars · Vinasse · Sunflower · Seed and Oil yield · Correlation · Path analysis

Introduction

Sunflower is considered one of the most versatile oilseed crops cultivated globally and accounts for nearly 12% of the world's edible vegetable oil production (Sinha et al., 2025; Mahmood, 2021). The seeds are nutritionally valuable, containing approximately 40–50% oil characterized by a high proportion of unsaturated fatty acids, particularly oleic and linoleic acids, in addition to 28–32% protein (Li et al., 2024). Owing to its multiple uses in human nutrition, livestock feeding, and various industrial sectors, sunflower has attracted considerable attention from producers worldwide (Durmaz & Gökmen, 2010). Nevertheless, in several developing countries, including Egypt, domestic production is still unable to satisfy the increasing demand driven by rapid population growth. Reducing the existing yield gap necessitates the development of superior, high-yielding genotypes through effective breeding programs, alongside the application of integrated nutrient management

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approaches (Sandhu & Kumar, 2017). Although synthetic mineral fertilizers have long been employed to improve crop performance, their increasing economic burden and potential environmental risks have encouraged the exploration of more sustainable inputs. In this context, vinasse, an organic byproduct generated from sugar processing and distillation industries, has gained attention as a potential bio-stimulant capable of enhancing crop growth and productivity. In Egypt, the Sugar and Integrated Industries Company generates more than 2,000 m³ of vinasse per day (Martínez et al., 2018). This liquid byproduct contains substantial amounts of organic compounds, including amino acids and essential macronutrients. It is particularly notable for its high potassium (K) concentration, which may reach approximately 6.5%, a nutrient fundamentally involved in oil biosynthesis and assimilating translocation in oilseed crops. Despite its agronomic potential, improper disposal of vinasse represents a serious environmental concern. Traditional practices such as uncontrolled soil application may lead to soil salinity buildup (EC values of 25–30 dS m⁻¹), acidification, and increased emissions of greenhouse gases, including carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄) (Moran-Salazar et al., 2016). Therefore, to exploit its nutrient value while minimizing environmental risks, foliar fertilization can be considered a more sustainable management approach. Foliar spraying facilitates rapid nutrient uptake through leaf tissues, including the cuticle and stomata, thereby reducing nutrient fixation in soil and mitigating salinity-related constraints (Tejada et al., 2006).

To minimize the environmental risks associated with soil disposal while efficiently utilizing the nutrient-rich composition of vinasse, foliar fertilization represents a practical and sustainable alternative. Nutrients applied to foliage can be rapidly absorbed through leaf tissues, including the cuticular layer and stomatal openings, thereby reducing soil related constraints such as nutrient fixation and salinity stress (Tejada et al., 2006). Previous findings indicate

that even low concentrations of foliar-applied nutrients may substantially improve physiological performance and overall crop productivity (Asenjo et al., 2000). Building upon this rationale, the present study proposed that foliar spraying of vinasse could function as an effective nutrient delivery system to the plant canopy, enhancing photosynthetic capacity and strengthening source sink interactions without triggering the phytotoxic effects often observed under soil application. In addition, it was assumed that considerable genetic variability among sunflower cultivars may result in differential physiological and yield responses to this organic bio stimulant. A clear understanding of the physiological mechanisms underlying such responses is essential. Therefore, path coefficient analysis was employed to quantify the direct and indirect contributions of key physiological traits to seed yield, providing insight into trait interrelationships and supporting more efficient selection strategies. Accordingly, the objectives of this study were to (i) evaluate the agronomic and physiological performance of three sunflower cultivars subjected to foliar vinasse application; (ii) identify the concentration that optimizes productivity; and (iii) investigate the associations between physiological parameters and yield components to determine the major determinants of sunflower yield.

Materials and Methods

Site Description and Experimental Treatments

Field experiments were conducted during the summer seasons of 2024 and 2025 at the experimental farm of the department of agronomy, faculty of agriculture, Assiut University, Egypt (27°08'20.8" N, 31°19'40.5" E). The soil physicochemical properties of the experimental site are detailed in Table 1.

Table 1 Some physical and chemical properties of the experimental Soil

Property			Property		
Particle size distribution	2024	2025	Soluble Cations	2024	2025
Sand) % (	24.30	24.00	Ca ²⁺ meq Kg ⁻¹ soil	9.50	9.40
Silt) % (	26.40	26.60	Mg ²⁺	3.00	3.00
Clay) % (	49.30	49.40	Na ⁺	6.10	6.00
Soil texture class	Clay	Clay	K ⁺	2.00	2.00
Bulk density (g cm ⁻³)	1.21	1.20	Soluble Anions		
Field capacity (%)	40.30	40.20	CL ⁻	4.00	4.00
Wilting point (%)	21.00	21.00	HCO ³⁺ CO ₃	7.00	6.90
Infiltration rate (cm h ⁻¹)	0.13	0.12	SO ₄	10.50	10.40
CaCO ₃ (%)	3.50	3.45	Total nitrogen (%)	0.08	0.07
pH (1:2.5) unit	8.21	8.20	Available phosphorous (ppm)	11.20	11.20
Electrical conductivity (ECe) (dSm ⁻¹)	2.11	2.08	Available potassium (ppm)	240.00	235.00
Organic Matter (%)	1.51	1.50			

Table 2 Means of air temperature and relative humidity and precipitation obtained from meteorological station at Assiut, Egypt, during the two growing seasons

	Month	Temperature (C°)		Humidity (%)	Precipitation (cm ³)
		Min	Max		
2024	May	21.0	35.5	29.0	0
	June	25.0	38.0	30.0	0
	July	25.0	39.0	33.0	0
	August	24.0	38.0	38.0	0
	September	23.0	37.2	36.0	0
2025	May	20.8	35.5	26.0	0
	June	25.1	40.4	27.0	0
	July	25.0	39.9	28.0	0
	August	26.5	39.4	30.0	0
	September	24.0	36.4	40.0	0

Table 3 Chemical analysis of vinasse of Abo-Korkas sugarcane factory at El-Minya; Egypt (2024)

Property	Unit	Value
pH		4.20
EC	dS m ⁻¹	15.35
Organic carbon	%	2.78
Organic matter	%	4.79
Total N	ppm	5900.00
Total P (P ₂ O ₅)	ppm	2300.00
Total K (K ₂ O)	ppm	30000.00
Total Na	ppm	4350.00
Total Fe	ppm	432.55
Total Mn	ppm	26.00
Total Zn	ppm	32.31
Total Cu	ppm	10.46

Meteorological data, including air temperature, relative humidity, and precipitation, were recorded by the local meteorological station during the growing periods and are presented in Table 2.

The study was performed using a strip-plot arrangement within a Randomized Complete Block Design (RCBD) with three replications. The experiment **consisted of** two factors, vertical strips (genotypes) which represented by three different sunflower cultivars (Sakha 53, Giza 102, and Giza 120) obtained from the oil crops research department, Agricultural Research Center (ARC), Egypt. Horizontal strips (bio-stimulant) which were represented by three different concentrations of vinasse (control, distilled water, low 50 mL L⁻¹, and high “100 mL L⁻¹). The vinasse concentrations were selected based on previous studies and preliminary observations indicating that moderate vinasse levels can improve plant growth and productivity, while higher concentrations may have adverse effects due to salinity and acidity according by (Algur & Kadioğlu, 1992).

This design resulted in a total of 27 experimental units. The chemical composition of the vinasse used in the study is outlined in Table 3. Each experimental plot covered an area of 10.5 m², consisting of five ridges, each 3.0 m length and 60 cm width.

Seeds were sown on May 18 and May 19 for the 2024 and 2025 seasons, respectively. Sowing was performed manually at a spacing of 20 cm between hills on both sides of the ridge, with thinning to one healthy plant per hill after emergence. Foliar vinasse treatments were applied at three physiological stages: 30, 40, and 50 days after sowing (DAS). Applications were performed using a knapsack sprayer, ensuring complete wetting of the foliage. All other agronomic practices, including tillage, irrigation, mineral fertilization, and pest control, were maintained uniformly across all plots according to the local recommendations for sunflower production.

Measurements

Growth and Physiological Traits

To evaluate crop growth analysis and physiological performance, plant samples were collected at two specific physiological stages: 60 days (T₁) and 75 days (T₂) after sowing. At each sampling date, five plants were randomly selected from the middle rows of each experimental plot. These samples were separated into leaves and stems, and leaf area was measured using an Area Meter (Model AM 350). Subsequently, Samples were randomly collected and oven-dried at 70 °C until constant weight was achieved to determine total dry matter accumulation (W).

Leaf area index (LAI) was calculated as the ratio of the total functional leaf area per plant to the ground area occupied by each plant, following Bremner and Taha (1966):

$$LAI = \frac{\text{Leaf area per plant (cm}^2\text{)}}{\text{Ground area per plant (cm}^2\text{)}}$$

Leaf area duration (LAD) represents the persistence of leaf surface area during the defined growth period and was calculated according to Woodward and Hunt (1983) as follows:

$$LAD = \frac{(LA_2 + LA_1) \times (T_2 - T_1)}{2}$$

where LAI₁ and LAI₂ are the leaf area indices at times t₁ and t₂ (days), respectively.

Equivalently, LAI_1 represents the leaf surface area of the plant during the first period t_1 , and LAI_2 represents the leaf surface area during the second period.

Total chlorophyll content: it was measured non-destructively at 60 days after sowing using a SPAD-502 Plus chlorophyll meter (Konica Minolta, Japan). Measurements were taken from the fully expanded upper leaves. SPAD values were converted to total chlorophyll concentration (mg m^{-2}) using the calibration equation reported by (Dash et al., 2007):

$$Y = 0.118x^2 + 0.919x + 7.925$$

where Y represents chlorophyll concentration in mg m^{-2} X represents SPAD value.

Net assimilation rate (NAR) Based on dry matter and leaf area, NAR was estimated using was calculated according to Watson (1958) as follows.

$$NAR = \frac{W_2 - W_1}{LA_2 + LA_1} \times \frac{\log_e LA_2 - \log_e LA_1}{T_2 - T_1}$$

Where: W_1 and W_2 are plant dry weight (dried at 70°C till constant weight) in the first period (T_1) and second period (T_2), $\log_e$ is Néperien logarithm $= 2.303 \times \log_{10}$.

Crop growth rate (CGR) CGR was estimated via following Bremner and Taha (1966).

$$CGR = NAR \times LAI$$

Relative Growth Rate (RGR) The relative growth rate is defined as the increase in the dry matter of the plant in a period in relation to weight at the beginning of this period, and it is calculated from the following equation. As decided by Grime and Hunt (1975): -

$$RGR = \frac{\log_e W_2 - \log_e W_1}{T_2 - T_1}$$

Agronomical Traits

At physiological maturity, five representative plants were randomly selected from the central rows of each experimental plot to determine the following yield attributes. Plant height (cm) was measured from the soil surface to the insertion of the capitulum (head) using a graduated ruler. Stem diameter (cm) measured at a height of 20 cm above

the soil surface using a vernier caliper. Head diameter (cm) was measured across the center of the air-dried head. Head weight (g) represented by the average weight of the total air-dried capitulum (including seeds and receptacle). Number of seeds per head (n. head^{-1}) was calculated by counting the total number of achenes filled from the five sampled heads and averaging the value. Thousand Seed Weight (TSW, g) was determined by weighing two random samples of 1000 seeds from each plot. Seed weight per head (g head^{-1}): The average weight of the separated seeds obtained from the five sampled heads. All heads from the central area of each experimental unit (10.5 m^2) were harvested, air-dried for two weeks, and threshed. The obtained seed weight was adjusted to a moisture content of 10% and converted to tons per hectare to calculate the seed yield (t ha^{-1}). Seed oil content (%) was determined using the Soxhlet extraction method with petroleum ether as a solvent (boiling point $60\text{--}80^\circ\text{C}$), following the procedures outlined by (AOAC, 2005). Oil yield (t ha^{-1}) was calculated using the following formula:

$$\text{Oil yield (t ha}^{-1}\text{)} = \text{Seed yield (t ha}^{-1}\text{)} \times \text{Oil content (\%)} / 100.$$

Statistical Analysis

All collected data were subjected to analysis of variance (ANOVA) appropriate for the experimental design using (SAS, 2008). Prior to analysis, the homogeneity of error variances between the two growing seasons were verified using (Bartlett, 1937; Gomez & Gomez, 1984). Since the variances were found to be homogeneous, a combined analysis over the two seasons was performed. To satisfy the assumptions of ANOVA, data recorded as percentages were subjected to arcsine transformation; however, for clarity of interpretation, the means presented in tables and figures are non-transformed values. Mean comparisons were performed using Fisher's Protected Least Significant Difference (LSD) test at the 5% probability level ($p \leq 0.05$). Pearson's correlation coefficients were calculated to determine the relationships between seed weight, physiological traits, and agronomic attributes using (R Studio, 2020; SPSS, 2010). Furthermore, to determine the specific contribution of these traits to yield.

Path coefficient analysis was conducted by Dewey and Lu (1959) to examine the direct and indirect effects of growth and physiological traits on seed weight head^{-1} , as well as agronomical traits on seed weight head^{-1} , and the results are presented in Figs. 1 and 2.

Fig. 1 Path diagram showing the direct and indirect effects of growth and physiological traits—Leaf Area Index (LAI), Leaf Area Duration (LAD), Chlorophyll (Chl), Net Assimilation Rate (NAR), Crop Growth Rate (CGR), and Relative Growth Rate (RGR)—on Seed Weight per Head (SWH)

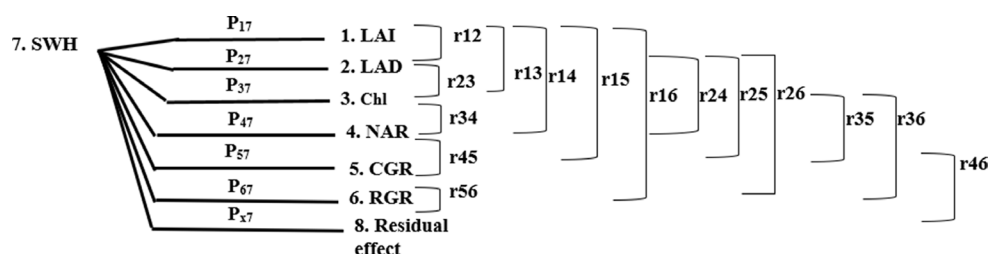
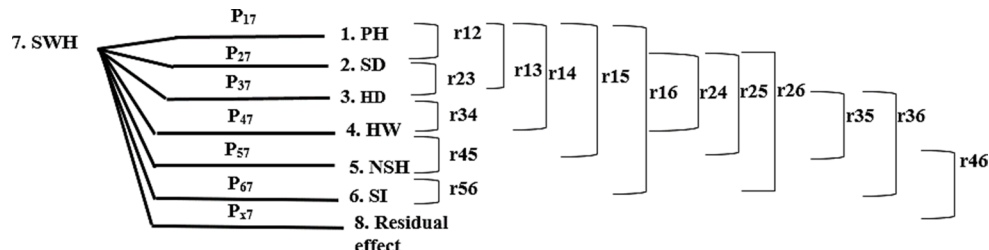


Fig. 2 Path diagram showing the direct and indirect effects of agronomic traits—Plant Height (PH), Stem Diameter (SD), Head Diameter (HD), Head Weight (HW), Number of Seeds per Head (NSH), and 100-Seed Weight (SI)—on Seed Weight per Head (SWH)



Results and Discussion

Analysis of Variance

The combined analysis of variance (ANOVA) summarized in Tables 4 and 5 demonstrated that both foliar vinasse application and cultivar exerted highly significant effects ($p < 0.01$) on all evaluated photo-assimilatory indices, in addition to yield and oil-related parameters. These results emphasize that sunflower productivity is strongly influenced by both genetic background and nutrient management strategy.

Although the growing season significantly affected several physiological characteristics—namely Leaf Area Duration (LAD), Net Assimilation Rate (NAR), Crop Growth Rate (CGR), plant height, head diameter, and oil content—the interactions between year and the tested factors (Year $\times$ Vinasse and Year $\times$ Cultivar) were generally not significant.

This pattern indicates that cultivar ranking and responsiveness to vinasse treatments remained stable across the two experimental seasons, despite slight environmental fluctuations. Therefore, interpretation based on the combined dataset is statistically appropriate.

In contrast, the second-order interaction between vinasse levels and cultivars (V $\times$ C) was highly significant for most of the investigated traits, reflecting differential genotypic responses to foliar vinasse concentrations. For instance, certain cultivars, such as Giza 102, exhibited superior efficiency in utilizing the supplemented nutrients compared with others. Meanwhile, the three-way interaction (Year $\times$ Vinasse $\times$ Cultivar) did not reach significance for any measured variable. Overall, the ANOVA results indicate that vinasse application and genotype constituted the principal sources of variation, and their significant interaction underscores the necessity of optimizing cultivar–fertilizer combinations to achieve maximum oil productivity.

Table 4 Combined analysis of variance for growth and physiological traits affected spraying with vinasse solution of the 3 cultivars of sunflower

Source of Variation	d.f.	LAI	LAD	Chl	NAR	CGR	RGR
Years (Y)	1	0.022	84.8**	126.8	29.8**	626.6**	0.006
Error a	4	0.013	3.70	26.4	0.317	11.9	0.001
Vinase (V)	2	8.77**	1030.4**	42714.6**	440.2**	26752.0**	0.047**
Y $\times$ V	2	0.0004	3.1053	2.2387	0.0017	7.1242	0.00004
Error b	8	0.012	0.928	7.713	0.109	11.533	0.002
Cultivars (C)	2	1.53**	109.0**	3802.2**	99.0**	2380.8**	0.104**
Y $\times$ C	2	0.002	2.06	6.47	2.25	48.53	0.0001
Error c	8	0.007	3.00	6.35	0.58	12.45	0.002
V $\times$ C	4	0.459**	17.43**	3076.0**	3.16**	447.3**	0.006*
Y $\times$ V $\times$ C	4	0.0001	0.49	1.83	0.21	2.23	0.0003
Error d	16	0.01	1.25	22.05	0.28	9.40	0.002

d.f. = degrees of freedom; LAI=Leaf Area Index; LAD=Leaf Area Duration; Chl=Chlorophyll content; NAR=Net Assimilation Rate; CGR=Crop Growth Rate; RGR=Relative Growth Rate. *, ** significantly at 0.05 and 0.01 levels of probability, respectively

Effect of Foliar Spraying with Vinasse Solution on the Growth and Yield and its Component

Foliar application of vinasse at 50 ml L⁻¹ resulted in superior vegetative growth compared with the higher concentration of 100 ml L⁻¹. As shown in Table 5, increasing the vinasse concentration from 50 to 100 ml L⁻¹ led to a decline in key growth indicators, including leaf area index (LAI), leaf area duration (LAD), chlorophyll content, net assimilation rate (NAR), crop growth rate (CGR), and relative growth rate (RGR) of sunflower plants.

The stimulatory effect observed at the lower concentration may be associated with the balanced supply of essential nutrients present in vinasse, particularly K, P, N, and micro-nutrients such as Fe, Zn, Mn, and Cu. These elements play pivotal roles in regulating physiological processes, including carbohydrate synthesis and metabolism, starch turnover, and sugar translocation. Moreover, adequate nutrient availability enhances enzymatic activity and coordinates the function of various metabolic pathways, ultimately promoting vegetative growth and biomass accumulation (Dewey & Lu, 1959; Kaur et al., 2023).

In contrast, the reduction observed at the higher concentration (100 ml L⁻¹) may be associated with phytotoxic effects, such as leaf scorching, likely due to the accumulation of chloride ions and soluble salts, which can induce osmotic stress and impair physiological activity (Corsi et al., 2015).

Net primary productivity increased slightly (approximately 2.5%) under vinasse treatments, reflecting the contribution of its organic and inorganic constituents (Kadioğlu and Algur, 1990). However, differences among treatments (control, 50 ml L⁻¹, and 100 ml L⁻¹) were not statistically significant for all growth traits across the two growing seasons, indicating relative stability in treatment responses. These findings are consistent with previous studies (Meshref et al.,

2010; Yadav et al., 2020; Ali et al., 2007; Zaki & Williams, 2013; Ahmed et al., 2015).

The results presented in Tables 6 and 7 demonstrate that increasing vinasse concentration from 0 to 50 ml L⁻¹ significantly enhanced seed yield (ton ha⁻¹) and its associated components, including stem diameter, head diameter, head weight, number of seeds per head, 1000-seed weight, oil percentage, and oil yield. In contrast, application at 100 ml L⁻¹ did not produce a significant improvement in oil percentage compared with the untreated control. The yield enhancement observed at the moderate concentration can be attributed to improved vegetative growth, which was subsequently translated into greater assimilate production and allocation to reproductive structures.

The beneficial effects of vinasse may also be related to improved nitrogen dynamics and assimilate partitioning, ensuring adequate nutrient supply to competing sinks, particularly developing reproductive organs (Singh & Kuhad, 2005). Moreover, potassium and other nutrients present in vinasse play essential roles in photosynthesis, assimilate translocation, protein synthesis, stomatal regulation, ionic balance, and enzymatic activation, all of which collectively contribute to yield formation (Marschner et al., 2011). Similar positive responses of sunflower yield to foliar vinasse application have been documented in earlier studies (Yadav et al., 2020; Ali et al., 2007; Zaki & Williams, 2013; Ahmed et al., 2015; Mohamed et al., 2025).

Quantitatively, the 50 ml L⁻¹ treatment recorded the highest values for plant height (217.2 cm), stem diameter (4.63 cm), head diameter (24.4 cm), head weight (102.7 g), number of seeds per head (1157.5), 100-seed weight (7.94 g), seed weight per head (64.46 g), seed yield (4.09 ton ha⁻¹), and oil yield (1.79 ton ha⁻¹), exceeding both the control and the 100 ml L⁻¹ treatment, which showed comparatively moderate performance. The decline observed at the higher concentration may be

Table 5 Combined analysis of variance for the effects of sprang traits yields components affected spraying with vinasse solution of the 3 cultivars of sunflower

S.O.V	d.f.	Plant height (cm)	Stem diameter (cm)	Head diameter (cm)	Head weight (g)	Seeds (head ⁻¹)	TSW (g)	Seed weight (head ⁻¹)	Seed yield (t ha ⁻¹)	Oil (%)	Oil yield (t ha ⁻¹)
Years (Y)	1	114**	0.17	21.7**	47.9**	158.7	0.01	36.2**	0.014**	12.6**	0.035**
Error a	4	4.12	0.11	0.30	0.13	174.1	0.06	0.84	0.001	0.12	0.0002
Vinasse (V)	2	14,623**	7.47**	305.4**	3570.2**	913,081**	30.4**	2097.9**	4.53**	96.9**	1.45**
Y × V	2	1.53	0.002	0.11	0.21	2.99	10 ⁻⁴	0.13	0.0002	0.20	0.001**
Error b	8	1.92	0.04	0.10	0.47	22.7	0.063	0.81	0.0005	0.09	0.0001
Cultivars (C)	2	2214**	0.19*	41.35**	142.4**	301,068**	24.5**	886.3**	1.14**	57.2**	0.48**
Y × C	2	1	0.001	0.2	0.02	7.38	10 ⁻⁴	0.07	0.001	0.28	0.0002
Error c	8	15	0.003	0.16	0.23	543	0.021	0.51	0.001	0.38	0.0003
V × C	4	221**	0.67**	4.31**	23**	13,331**	0.99**	22.5**	0.07**	1.12**	0.008**
Y × V × C	4	0.49	0.01	0.15	0.11	3.41	10 ⁻⁴	0.22	0.0004	0.08	0.0002
Error d	16	21.8	0.05	0.27	0.40	203.0	0.069	0.40	0.0004	0.1	0.0002

S.O.V=sources of variation; d.f. = degrees of freedom; *, ** significantly at 0.05 and 0.01 levels of probability, respectively

associated with impaired root development and reduced nutrient and water uptake, possibly due to oxygen limitation or excessive salt accumulation (Hammond et al., 1955; Mohamed et al., 2025).

Overall, the findings suggest that foliar application of vinasse at low concentrations represents an effective strategy to enhance sunflower yield and oil production. Utilizing vinasse in diluted form not only improves crop performance but also offers an environmentally sustainable approach for recycling agro-industrial effluents and mitigating potential pollution hazards.

Effect of Cultivars on the Growth and Yield and its Component

The data presented in Table 6 indicate that the interaction between sunflower cultivar and vinasse application had a significant effect on growth parameters throughout all developmental stages, from sowing onward. Overall, the combination of Giza 120 and Giza 102 cultivars with a vinasse concentration of 50 mL L⁻¹ produced the most favorable outcomes for all measured traits. Application of higher vinasse concentrations, however, appeared to inhibit water and nutrient uptake, leading to reduced metabolic activities such as photosynthesis and respiration, which consequently limited plant growth. Similar inhibitory effects have been associated with elevated levels of chloride and other soluble salts (Algur and Kadioğlu, 1992).

Significant variation was observed among the cultivars for leaf area index (LAI), leaf area duration (LAD), chlorophyll content, net assimilation rate (NAR), crop growth rate (CGR), and relative growth rate (RGR). Both Giza 120 and Giza 102 consistently outperformed Sakha 53 across all growth stages examined (Table 5). The superior chlorophyll content of Giza 120 is primarily attributable to its genetic potential (Singh et al., 2004; Mekki & Ahmed, 2005; Gehan & Mervat, 2016). Moreover, the increases in LAI, LAD, chlorophyll content, NAR, CGR, and RGR observed in Giza 120 at the foliar application stages can be linked to

enhanced plant height and expanded photosynthetic surface area, including greater leaf area per plant (Table 6).

Foliar application of vinasse at 50 mL L⁻¹ significantly improved physiological traits, including chlorophyll content, LAI, LAD, NAR, CGR, and RGR, which were positively reflected in yield components such as plant height, stem diameter, head diameter, head weight, seed number, 100-seed weight, seed yield, oil content, and oil yield. These improvements are likely associated with the role of vinasse as a source of essential macro- and micronutrients that enhance enzymatic activity and physiological processes (Cabello-Pasini & Macías-Carranza, 2011; Al-Atrushy, 2019). Similar findings were reported by Bakhoun et al. (2022), emphasizing the role of biostimulants in improving crop performance, while excessive application may reduce these benefits (Iqbal et al., 2022).

Among the tested cultivars, Giza 102 consistently exhibited the highest LAI and associated growth indices, including LAD, chlorophyll content, NAR, CGR, and RGR, followed by Giza 120 and Sakha 53. The superior performance of Giza 102 can be attributed to its genetic potential, growth habits, and efficient partitioning of assimilates (Ahmed et al., 2015, 2020; Rauf et al., 2012). Similarly, Giza 120 displayed high performance for most traits, reflecting enhanced nutrient uptake, assimilate accumulation, and improved growth rate, although Sakha 53 consistently showed the lowest values across all measured parameters.

Quantitatively, the 50 mL L⁻¹ treatment produced the highest values for all yield-related traits, while the 100 mL L⁻¹ treatment showed comparatively moderate performance. Among cultivars, Giza 102 recorded the highest values for most traits, followed by Giza 120, whereas Sakha 53 consistently showed the lowest performance.

Recent studies have emphasized the substantial genetic variability among sunflower genotypes with respect to agronomic traits and oil quality. For instance, Aboelkassem et al. (2021) reported considerable differences in seed yield and oil content among Egyptian sunflower genotypes, while Abdel-satar et al. (2020) highlighted the importance of selecting

Table 6 Means and stander error of growth traits of three cultivars of sunflower under spring with vinasse as average of two seasons

Treatments		LAI	LAD	Chl	NAR	CGR	RGR
Control	Sakha 53	2.73 ^{±0.03} f	26.16 ^{±0.46} f	262.4 ^{±3.72} g	21.36 ^{±0.36} i	58.4 ^{±0.93} g	0.627 ^{±0.01} d
	Giza 102	4.55 ^{±0.02} a	37.87 ^{±1.01} d	323.0 ^{±1.39} c	31.77 ^{±0.26} c	144.4 ^{±1.09} b	0.760 ^{±0.003} bc
	Giza 120	3.45 ^{±0.02} e	34.99 ^{±0.82} e	288.2 ^{±1.93} de	23.72 ^{±0.22} h	81.7 ^{±0.96} e	0.667 ^{±0.05} d
50 ml L ⁻¹	Sakha 53	3.70 ^{±0.06} d	26.87 ^{±0.30} f	263.4 ^{±0.44} g	24.67 ^{±0.49} g	91.2 ^{±2.14} d	0.760 ^{±0.01} bc
	Giza 102	4.50 ^{±0.01} a	40.79 ^{±0.45} b	355.2 ^{±1.27} b	33.43 ^{±0.48} b	150.5 ^{±2.42} a	0.803 ^{±0.003} b
	Giza 120	4.03 ^{±0.02} c	38.79 ^{±0.69} cd	295.7 ^{±1.37} d	27.36 ^{±0.46} e	110.2 ^{±2.11} c	0.692 ^{±0.004} cd
100 ml L ⁻¹	Sakha 53	2.75 ^{±0.04} f	27.93 ^{±0.52} f	274.2 ^{±0.58} f	25.60 ^{±0.48} f	70.3 ^{±1.85} f	0.795 ^{±0.002} b
	Giza 102	4.31 ^{±0.05} b	45.87 ^{±0.93} a	402.1 ^{±0.58} a	35.46 ^{±0.48} a	153.0 ^{±2.83} a	0.887 ^{±0.02} a
	Giza 120	3.63 ^{±0.07} d	39.99 ^{±1.28} bc	284.4 ^{±0.50} e	29.73 ^{±0.38} d	108.0 ^{±2.92} c	0.828 ^{±0.005} ab

Means followed by the same letter or letters in the same column are not significant at the $p < 0.05$ level. SE=standard error. LAI=Leaf Area Index; LAD=Leaf Area Duration; Chl=Chlorophyll content; NAR=Net Assimilation Rate; CGR=Crop Growth Rate; RGR=Relative Growth Rate

Table 7 Means and stander error of yield and its attributes, as affected by foliar with vanessa, sunflower cultivars and their interaction as average of two seasons

Treatments		Plant height (cm)	Stem diameter (cm)	Head diameter (cm)	Head weight (g)	Seeds (n. head ⁻¹)	TSW (g)
Control	Sakha 53	176.0± ^{0.72} e	3.47± ^{0.04} e	18.4± ^{0.41} e	88.8± ^{0.44} g	680.2± ^{1.74} i	47.1± ^{0.7} f
	Giza 102	221.0± ^{1.55} bc	5.11± ^{0.05} a	25.6± ^{0.48} b	111.3± ^{0.72} c	1021.1± ^{9.19} e	70.9± ^{0.4} c
	Giza 120	188.9± ^{2.11} de	4.20± ^{0.06} cd	22.1± ^{0.30} c	91.0± ^{0.38} e	968.7± ^{5.74} f	54.3± ^{1.2} e
50 ML ⁻¹	Sakha 53	185.5± ^{0.43} de	4.03± ^{0.07} d	20.8± ^{0.31} d	90.5± ^{0.45} ef	868.0± ^{2.93} g	64.9± ^{0.03} d
	Giza 102	248.8± ^{0.95} a	5.22± ^{0.16} a	29.7± ^{0.26} a	120.7± ^{0.46} a	1382.8± ^{6.69} a	91.1± ^{0.2} a
	Giza 120	217.3± ^{2.87} c	4.63± ^{0.05} b	24.8± ^{0.27} b	96.7± ^{0.35} d	1191.8± ^{1.26} c	86.2± ^{1.1} b
100 ML ⁻¹	Sakha 53	182.3± ^{0.70} de	3.56± ^{0.11} e	20.3± ^{0.36} d	89.7± ^{0.35} fg	782.7± ^{0.78} h	55.5± ^{0.9} e
	Giza 102	243.3± ^{1.67} ab	4.58± ^{0.08} bc	28.9± ^{0.28} a	115.1± ^{0.54} b	1243.6± ^{10.21} b	83.4± ^{1.6} b
	Giza 120	202.1± ^{0.86} cd	4.48± ^{0.09} bc	22.8± ^{0.28} c	89.7± ^{0.35} fg	1092.5± ^{2.91} d	67.5± ^{0.7} cd

Means followed by the same letter or liters in the same column are not significant at the $p < 0.05$ level. SE=standard error

stable, high-performing cultivars across diverse environmental conditions to achieve consistent productivity. The enhanced performance of Giza 120 appears linked to its superior efficiency in assimilate accumulation, nutrient uptake, and growth rate, ultimately contributing to higher seed weight and overall yield (Mu et al., 2025; Alayafi et al., 2025).

Effect of Interaction between Vinasse Solutions × Cultivars on the Growth and Yield and its Component

The interaction between cultivar and vinasse application was significant for most measured traits. Specifically, the combination of Giza 102 with 50 mL L⁻¹ vinasse produced

Table 8 Means and stander error of seed and oil traits, as affected by foliar with vanessa, sunflower cultivars and their interaction as average of two seasons

Treatments		Seed weight (g head ⁻¹)	Seed yield (t ha ⁻¹)	Oil content (%)	Oil yield (t ha ⁻¹)
Control	Sakha 53	41.17± ^{0.30} h	3.23± ^{0.02} h	33.91± ^{0.23} f	1.095± ^{0.01} i
	Giza 102	62.43± ^{0.41} b	4.23± ^{0.02} c	37.90± ^{0.40} d	1.274± ^{0.01} g
	Giza 120	44.32± ^{0.50} g	3.35± ^{0.01} g	36.06± ^{0.11} e	1.342± ^{0.01} f
50 ML ⁻¹	Sakha 53	52.10± ^{0.50} e	3.58± ^{0.01} f	37.44± ^{0.27} d	1.602± ^{0.02} c
	Giza 102	72.87± ^{0.49} a	4.66± ^{0.01} a	42.11± ^{0.29} a	1.815± ^{0.01} b
	Giza 120	61.22± ^{0.60} c	4.01± ^{0.01} d	38.87± ^{0.28} c	1.961± ^{0.02} a
100 ML ⁻¹	Sakha 53	50.76± ^{0.42} f	3.56± ^{0.01} f	35.82± ^{0.29} e	1.206± ^{0.01} h
	Giza 102	72.25± ^{0.49} a	4.43± ^{0.01} b	41.00± ^{0.28} b	1.484± ^{0.01} e
	Giza 120	59.24± ^{0.39} d	3.92± ^{0.01} e	37.88± ^{0.20} d	1.560± ^{0.01} d

Means followed by the same letter or letters in the same column are not significant at the $p < 0.05$ level. SE=standard error

the highest growth, yield, and oil performance, whereas Giza 120 with either 50 or 100 mL L⁻¹ yielded comparable values for head weight, head diameter, and seed number per head. Overall, foliar application of vinasse substantially improved sunflower growth, yield, and oil productivity, with Giza 102 demonstrating the most pronounced response.

Analysis of data presented in Tables 6 and 7 confirmed that the tested cultivars differed significantly in all yield components. Both Giza 120 and Giza 102 surpassed Sakha 53 across multiple parameters, including plant height, stem diameter, head diameter, head weight, number of seeds per head, 1000-seed weight, seed yield, oil percentage, and oil yield. The superior performance of Giza 120 relative to Sakha 53 may be attributed to its enhanced capacity for yield and yield component development.

The observed differences among sunflower cultivars in yield, yield components, and certain chemical attributes are likely a consequence of genetic variation. Such variation can influence the availability of glucose for the biosynthesis of chemical constituents in different plant organs, the partitioning of photosynthates among plant tissues, and the overall carbon allocation efficiency (Mandel et al., 2011; Lakshman et al., 2021). Additionally, genotypic differences in mineral nutrient concentrations may further contribute to the variability in growth and yield performance observed among cultivars (Lakshman et al., 2021).

Correlation Between Seed Weight Head⁻¹ and Growth Indices of Sunflower

The correlation analysis presented in Table 9 revealed that seed weight head⁻¹ was strongly and positively associated with all evaluated physiological traits. Specifically, leaf area index (LAI) showed a correlation coefficient of 0.81 with seed weight per head, while leaf area duration (LAD) and chlorophyll content exhibited correlations of 0.84 and 0.85, respectively. Net assimilation rate (NAR) demonstrated

Table 9 Correlation coefficient of seed weight head⁻¹ g and some physiological parameters

	LAI	LAD	Chl	NAR	CGR	RGR	Seed weight
Leaf Area Index	1						
Leaf Area Duration	0.78**	1					
Chlorophyll content	0.73**	0.84**	1				
Net Assimilation Rate	0.83**	0.87**	0.90**	1			
Crop Growth Rate	0.95**	0.85**	0.87**	0.96**	1		
Relative Growth Rate	0.40*	0.50**	0.58**	0.73**	0.59**	1	
Seed weight	0.81**	0.84**	0.85**	0.98**	0.94**	0.72**	1

LAI=Leaf Area Index; LAD=Leaf Area Duration; Chl=Chlorophyll content; NAR=Net Assimilation Rate; CGR=Crop Growth Rate; RGR=Relative Growth Rate. **. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed)

the strongest association (0.98), followed by crop growth rate (CGR, 0.94) and relative growth rate (RGR, 0.72). All reported correlations were statistically significant, with $p \leq 0.05$ (*) or $p \leq 0.01$ (**), indicating strong and meaningful relationships between seed weight per head and the evaluated physiological traits. These strong positive relationships indicate that enhanced photosynthetic capacity, prolonged leaf area persistence, and increased assimilation production are key determinants of seed development in sunflower. Higher LAI and LAD improve light interception and carbon assimilation, while elevated NAR and CGR reflect greater efficiency in biomass accumulation, which is ultimately allocated to developing seeds. The beneficial effect of vinasse application may further explain these associations, as it supplies essential macro- and micronutrients that enhance physiological activity and photosynthetic efficiency, thereby promoting greater assimilation availability for seed filling.

Correlation Between Seed Weight Head⁻¹ and Yield Traits with Sunflower Productivity

Seed weight head⁻¹ was strong and positively correlated with all evaluated yield components. Significant associations

were observed with plant height ($r=0.96$), stem diameter ($r=0.77$), head diameter ($r=0.94$), head weight ($r=0.88$), number of seeds per head ($r=0.91$), and 100-seed weight ($r=0.93$). Furthermore, seed weight per head showed robust correlations with total seed yield ($r=0.99$), oil percentage ($r=0.95$), and oil yield ($r=0.98$), indicating that improvements in vegetative growth and head traits directly translate into enhanced seed and oil productivity in sunflower. The observed correlations were statistically significant at $p \leq 0.05$ (*) or $p \leq 0.01$ (**), indicating strong and meaningful relationships between seed weight per head and the evaluated yield parameters, including plant height, stem diameter, head traits, seed yield, and oil content.

Physiological traits, including leaf area index (LAI), leaf area duration (LAD), chlorophyll content, net assimilation rate (NAR), crop growth rate (CGR), and relative growth rate (RGR), also exhibited strong positive correlations with seed weight per head, highlighting the close linkage between photosynthetic efficiency, growth dynamics, and reproductive output. Similarly, plant growth traits such as plant height, stem diameter, head diameter, head weight, number of seeds per head, and 1000-seed weight maintained consistently positive correlations with per-plant seed yield. These results agree with previous studies (Contreras-Contreras

Table 10 Correlation coefficient of seed weight head⁻¹ g and some yield parameters

	Plant height (cm)	Stem diameter (cm)	Head diameter (cm)	Head weight (g)	Seed (n. head ⁻¹)	TSW (g)	Seed weight head ⁻¹ (g)	Seed yield (t ha ⁻¹)	Oil (%)	Oil yield (t ha ⁻¹)
Plant height (cm)	1									
Stem diameter (cm)	0.85**	1								
Head diameter (cm)	0.99**	0.82**	1							
Head weight (g)	0.95**	0.79**	0.94**	1						
Seed (n. head ⁻¹)	0.93**	0.79**	0.93**	0.79**	1					
TSW (g)	0.92**	0.72**	0.88**	0.78**	0.93**	1				
Seed weight head ⁻¹ (g)	0.96**	0.77**	0.94**	0.88**	0.91**	0.93**	1			
Seed yield (t ha ⁻¹)	0.97**	0.83**	0.96**	0.93**	0.89**	0.92**	0.99**	1		
Oil (%)	0.94**	0.72**	0.94**	0.85**	0.94**	0.95**	0.95**	0.94**	1	
Oil yield (t ha ⁻¹)	0.98**	0.80**	0.97**	0.92**	0.92**	0.94**	0.98**	0.99**	0.98**	1

TSW (g) = Thousand Seed Weight (g). **. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed)

Table 11 The direct and indirect effects of physiological parameters on of seed weight per head

Traits	Direct effect	Indirect effect through						Total effect
		LAI	LAD	Chl	NAR	CGR	RGR	
LAI	0.002	-	-0.0003	-0.09	0.87	0.022	0.006	0.81
LAD	0.002	-0.0004	-	-0.1	0.92	0.02	0.004	0.84
Chl	0.002	-0.0004	-0.12	-	0.94	0.02	0.004	0.85
NAR	0.002	-0.0004	-0.11	1.05	-	0.02	0.005	0.98
CGR	0.002	-0.0004	-0.1	1	0.023	-	0.004	0.94
RGR	0.002	-0.0003	-0.08	0.85	0.015	0.006	-	0.8

LAI=Leaf Area Index; LAD=Leaf Area Duration; Chl=Chlorophyll content; NAR=Net Assimilation Rate; CGR=Crop Growth Rate; RGR=Relative Growth Rate

et al., 2020; Manivanna et al., 2005; Nasim et al., 2016; Machikowa & Saetang, 2008; González et al., 2013; Marin et al., 2025; Afreen et al., 2024).

Interestingly, a significant positive association was observed between seed yield per plant and oil content, reflecting a trade-off between seed quantity and oil concentration, a pattern consistent with earlier reports (Machikowa & Saetang, 2008; Marin et al., 2025; Sharma & Kaila, 2025; Ravza et al., 2025). This may be attributed to dilution effects, where increased biomass and seed number reduce the relative accumulation of oil per seed.

Path Coefficient Analysis

Path coefficient analysis was performed to partition the direct and indirect effects of sunflower morphological and yield traits on seed weight per head. This approach decomposes correlation coefficients into causal components, enabling the identification of the traits that exert the greatest influence on seed accumulation and overall yield formation.

Path Coefficient Analysis for Seed Weight Head⁻¹ Via Growth Indices

The path coefficient analysis presented in Table 11 highlighted the relative contributions of six key photo-assimilatory traits—leaf area index (LAI), leaf area duration (LAD), chlorophyll content (Chl), net assimilation rate (NAR), crop growth rate (CGR), and relative growth rate (RGR)—to seed weight per head in sunflower. The analysis revealed that NAR and CGR exerted the highest direct effects on seed weight, with path coefficients of 1.05 and 1.00, respectively. In contrast, LAI, LAD, Chl, and RGR exhibited minimal direct influence but contributed indirectly by affecting NAR and CGR.

The total effects further confirmed that NAR (0.98) and CGR (0.94) are the primary determinants of head seed weight, whereas LAI (0.81), LAD (0.84), Chl (0.85), and RGR (0.80) play supportive roles through their enhancement of assimilate production and biomass accumulation. These findings suggest that efficient photosynthesis (as

reflected by NAR) and rapid crop growth (CGR) are the major drivers of seed weight per head, while leaf-related traits indirectly promote seed development by improving overall assimilate availability and growth efficiency.

Path Coefficient Analysis for Seed Weight Head⁻¹ Via Agronomical Traits

Path coefficient analysis (Table 11) was conducted to quantify the direct and indirect contributions of key yield component traits—plant height, stem diameter, head diameter, head weight, number of seeds per head, and 1000-seed weight—on seed weight per head in sunflower. The analysis revealed that plant height and head diameter exerted the highest direct effects (0.64 each), indicating that taller plants with larger heads significantly contribute to increased seed mass per head. Moderate direct effects were observed for stem diameter, head weight, number of seeds per head, and 1000-seed weight (0.55–0.61), with additional indirect contributions mediated through other traits. Overall, total effects highlighted plant height (0.96), head diameter (0.94), 1000-seed weight (0.93), and seed number per head (0.90) as the principal determinants of head seed weight, emphasizing the critical role of both plant architecture and seed traits in enhancing sunflower yield.

Similarly, path coefficient analysis was applied to assess the direct and indirect effects of physiological traits leaf area index (LAI), leaf area duration (LAD), chlorophyll content (Chl), net assimilation rate (NAR), crop growth rate (CGR), and relative growth rate (RGR) on seed weight per head across three sunflower cultivars and three vinasse levels over all growing seasons (Tables 8, 9, 10 and 11). The direct effects of physiological traits were generally low but positive, while indirect effects through NAR and CGR were more pronounced. For instance, chlorophyll content and NAR exerted the greatest influence on seed yield per plant via indirect pathways. Leaf traits such as LAI and LAD exhibited minimal positive direct effects and small negative indirect effects through Chl, NAR, CGR, and RGR, with values ranging from −0.0004 to −0.12 (Table 8). These

Table 12 The direct and indirect effects of crops yield components traits on of seed weight head⁻¹

Traits	Direct effect	Indirect effect through						Total effect
		Plant height (cm)	Stem diameter (cm)	Head diameter (cm)	Head weight (g)	Seeds (n. head ⁻¹)	Seed Index (g)	
Plant height (cm)	0.64	-	0.02	0.31	-0.13	-0.34	0.45	0.96
Stem diameter (cm)	0.55	0.03	-	0.28	-0.11	-0.31	0.37	0.81
Head diameter (cm)	0.64	0.02	0.32	-	-0.13	-0.34	0.44	0.94
Head weight (g)	0.61	0.02	0.30	-0.14	-	-0.29	0.38	0.88
Seeds (n. head ⁻¹)	0.60	0.02	0.30	-0.11	-0.37	-	0.45	0.90
Seed Index (g)	0.59	0.02	0.28	-0.11	-0.34	0.49	-	0.93

patterns are consistent with earlier reports (Baraiya et al., 2018; Arshad et al., 2010).

In line with phenotypic correlation analyses, crop component traits including plant height, stem diameter, head diameter, head weight, number of seeds per head, and 1000-seed weight showed the strongest direct effects on seed yield per plant across all seasons, with values of 0.64, 0.55, 0.64, 0.61, 0.60, and 0.59, respectively (Table 12). Negative indirect effects were observed for stem diameter and head diameter via other yield traits, indicating potential trade-offs among certain components. These results suggest that direct selection for plant height, head size, and seed traits would be effective for improving seed yield. Similar findings have been reported in previous studies (Machikowa & Saetang, 2008; Baraiya et al., 2018; Hassan et al., 2013).

Conclusions

The results of this study indicate that foliar application of vinasse can improve sunflower growth, seed yield, and oil production under the conditions of the present study. These improvements may be associated with enhanced photosynthetic capacity, water status, and overall physiological performance. Among the tested concentrations, vinasse application at 50 mL L⁻¹ showed relatively better performance in terms of growth, physiological traits, and achene yield. In addition, traits such as plant height, stem diameter, and number of seeds per head were positively associated with seed yield, suggesting their importance in yield improvement. The combination of 50 mL L⁻¹ vinasse with Giza 102 and Giza 120 cultivars resulted in comparatively higher productivity, which may be attributed to differences in genetic potential and their interaction with the environmental conditions. Path coefficient analysis further indicated that NAR, chlorophyll content, CGR, stem diameter, head diameter, head weight, and seed index contributed to yield formation. Overall, foliar application of vinasse at moderate concentrations may represent a promising agronomic

practice for improving sunflower productivity. In addition, the use of vinasse could contribute to the recycling of agro-industrial byproducts and reduction of environmental impacts. However, further studies across different locations and seasons are required to confirm the broader applicability of these findings.

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Declarations

Competing Interests The authors declare no competing interests.

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