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Optimizing plant population and weed control methods for enhanced physiological growth and yield response of sunflower (*Helianthus annuus* L.) in the Nigerian Sudan savanna

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Abstract

Sunflower (Helianthus annuus L.) production in the Sudan Savannah agroecological zone of Nigeria is significantly influenced by multiple agronomic factors, particularly plant population and weed control methods. This study was conducted at the Teaching and Research Farms of Bayero University Kano (BUK) and the National Horticultural Research Institute (NIHORT), Bagauda, during the 2018 and 2019 rainy seasons to assess the physiological growth, yield response, and weed control efficiency of sunflower under varying plant populations and weed control methods. The treatments consisted of three plant populations (22,500,000, 48,750,000, and 52,500,000 plants ha^{-1}) and eight weed control methods, including mechanical, chemical, and allelopathic approaches. These were laid out in a split-plot design with three replications, with plant population and weed control methods the main plot and sub plots, respectively. Results revealed that the highest plant population (52,500,000 plants ha^{-1}) significantly enhanced the physiological growth characters. The highest (0.07 g wk^{-1}) relative growth rate (RGR) was recorded in 2019 at Bagauda, while the combined analysis showed 0.05 and 0.16 g wk^{-1} at Bagauda and BUK. Similarly, CGR peaked at 126.40 g cm^{-2} wk^{-1} in 2019 at Bagauda and 106.40 g cm^{-2} wk^{-1} in the combined analysis at BUK, while LAI reached its highest value at 4.59 in 2019 at Bagauda. However, kernel yield per hectare decreased at the highest plant population due to increased intraspecific competition. Among the weed control methods, (T3) application of pre-emergence Tithonia diversifolia extract fb post-emergence at 6 WAS recorded the highest weed control efficiency (WCE) of 76.3% at Bagauda and 82.88% at BUK, and significantly improved sunflower growth and yield components. The optimal plant population of 48,750,000 plants/ha combined with T3 was the most effective strategy for maximizing kernel yield while ensuring sustainable weed management. The weedy check consistently resulted in the lowest performance across all parameters. These findings suggest that an optimal plant population combined with allelopathic-based weed management can enhance sunflower productivity while minimizing weed interference in the Sudan Savannah region of Nigeria.

***Key words**: Plant population, Growth indices, Weed control, Allelopathy, Sunflower, yield*

Introduction

Sunflower (*Helianthus annuus* L.) is a vital oilseed crop known for its adaptability to diverse agroecological zones, including the Sudanian savanna region of Nigeria. According to Adeleke and Babalola (2020), it plays a crucial role in the global vegetable oil market and serves as a valuable source of edible oil, livestock feed, and biofuel production. The production potential of sunflower in the Sudano-Sahelian agro-ecology of Nigeria is influenced by multiple agronomic factors, particularly plant population density and weed control methods (Puttha *et al*., 2023). Optimal plant population ensures efficient resource utilization, while weed management strategies directly impact sunflower growth, yield, and oil quality (Ibrahim *et al.*, 2023).

Weed interference is one of the most significant constraints limiting sunflower productivity. According to Debaeke *et al*. (2021), weeds compete with sunflower for essential resources such as nutrients, light, and moisture, leading to yield reductions and lower oil content. Effective weed management strategies, including cultural, mechanical, and chemical control methods, are crucial to ensuring high productivity (Garba, 2021). Additionally, sunflower plant population density plays a significant role in determining plant architecture, resource allocation, and overall yield performance (Ndor *et al.,* 2019).

Despite the economic importance of sunflower, limited research has been conducted to assess the interactive effects of plant population and weed control methods in the Sudano-Sahelian agro-ecology of Nigeria. Understanding the physiological growth responses and yield performance of sunflower under varying plant populations and weed control measures is crucial for optimizing agronomic practices and improving productivity in this region. Improper plant density can lead to poor light interception, excessive competition among plants, and reduced seed yield (Nasir, 2018). Moreover, weeds pose a major threat to sunflower productivity, with uncontrolled weed infestations leading to significant yield losses due to competition for nutrients and moisture (Bello *et al*., 2022; Shittu *et al.*, 2023 a & b; Shittu *et al.*, 2024).

Although various weed management approaches have been tested in different crops, there is limited information on their effectiveness in sunflower production under Sudanian ecological conditions of Nigeria. The combined effect of plant population and weed control methods on sunflower growth and yield remains inadequately explored, necessitating further research to develop appropriate agronomic recommendations.

The plant competition theory postulates that crop performance is influenced by the density of plants and their competition for limited resources such as water, nutrients, and light (Waldah *et al.,* 2022). Higher plant populations may lead to increased competition, whereas lower populations may result in underutilization of available resources. Thus, the resource allocation model explains how plants distribute available resources between vegetative growth and reproductive development. Effective weed control reduces competition and allows sunflowers to allocate more energy towards reproductive structures, leading to increased seed yield (Ibrahim *et al.*, 2018).

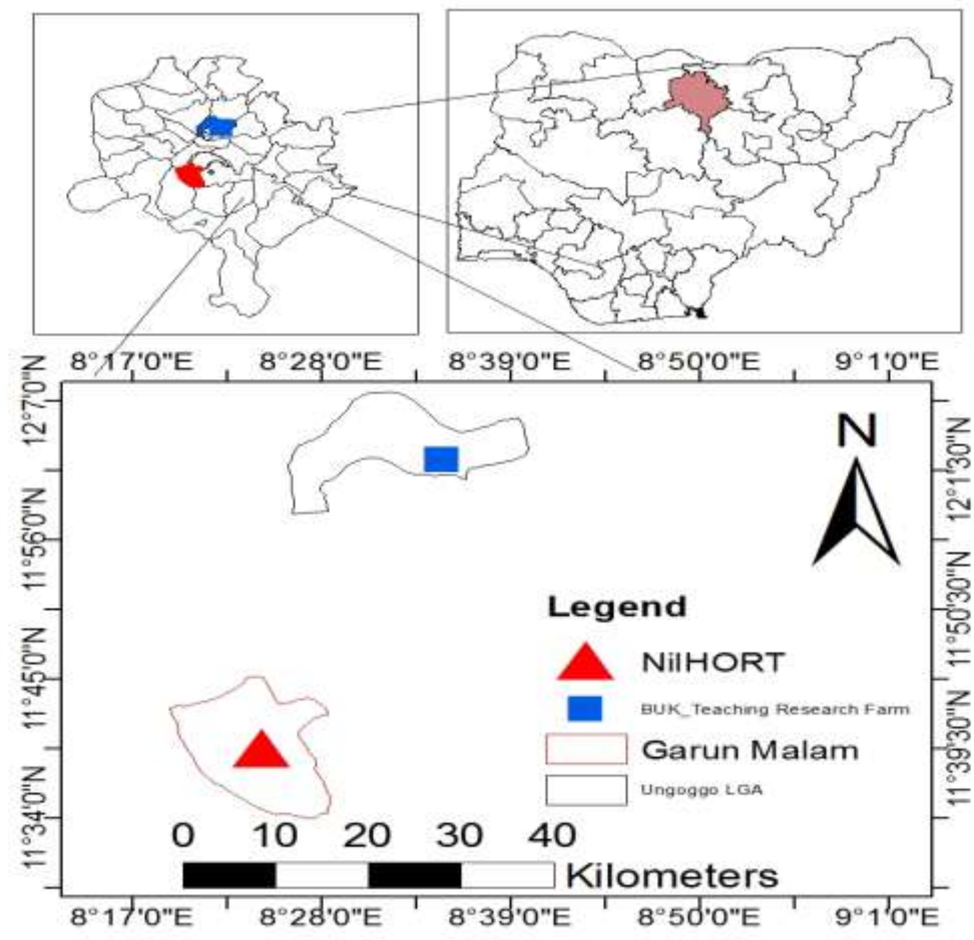
The study conducted with the aim of evaluating the physiological growth and yield response of sunflower to varying plant population densities and weed control strategies in the Sudano agro-ecology of Nigeria while the specific objectives were to:

i. assess the impact of different plant populations on sunflower growth, yield components, and oil content.
ii. evaluate the effectiveness of various weed control strategies on sunflower performance and weed suppression.
iii. determine the interactive effects of plant population and weed control methods on sunflower physiological responses and overall productivity.

Materials and Methods

Experimental Site

Two field experiments were conducted during the 2018 and 2019 rainy seasons at the Teaching and Research Farm of Bayero University, Kano (Latitude 11°58' N and Longitude 8° 25E, with an altitude of 476 m above sea level) and the Teaching and Research Farm of the National Horticultural Research Institute, NIHORT, Bagauda (Latitude 11° 33' N and Longitude 8° 23' E, with an altitude of 481 m above sea level). Both locations are situated in the Sudan Savannah agroecology zone of Nigeria. The areas are characterized by a monomodal rainfall pattern, with a mean annual rainfall of 955 and 1033.3 for the combined seasons of BUK and Bagauda, respectively. The areas had an average temperature of 23–32 ºC during the growing seasons and a dry season of 6–9 months (Abubakar et al., 2024).



Treatments and Experimental Design

The treatments consisted of three plant population (22,500, 000, 48,750,000, 52,500,000) and eight weed control methods (T1=Weedy Check; T2= Hoe Weeding at 3 and 6 WAS; T3= Pre emergence application of *Tithonia* plant extract *fb* POE application of *Tithonia* plant extract at 6 Weeks after sowing (WAS); T4=Pre emergence application of *Tithonia* plant extract *fb* Hoe weeding at 6 WAS; T5=Pre emergence application of *Tithonia* plant extract followed by (*fb)* Post emergence (POE) application of Fluazifop at 0.8 kg a.i ha^{-1} at 6 WAS; T6=Pre emergence application of Metolachlor at 0.8 kg a.i *fb* Hoe weeding at 6 WAS; T7=Pre emergence application of Metolachlor at 0.8 kg a.i ha^{-1} *fb* POE application of Fluazifop at 0.8 kg a.i ha^{-1} at 6 WAS; T8= Hoe weeding at 3 WAS *fb* POE application of Fluazifop at 0.8 kg a.i ha^{-1} at 6 WAS). These were factorially combined, laid out in a split plot design, and replicated three times. Intra-row spacing was assigned to the main plot, while weed control methods were placed in the sub-plot. The gross and net plot sizes were 13.5 m^2 (4.5 x 3 m) and 9 m^2 (3 x 3 m), respectively.

Preparation of Aqueous Extracts of *T. diversifolia*

Aqueous extracts of *Tithonia diversifolia* were prepared according to the procedure of Hua *et al*. (2005). Fresh *T. diversifolia* plants were collected from NIHORT, Ibadan, and Kano along Zaria Road. The samples were cleaned, and leaves were removed from the stem. The leaves were air-dried at room temperature (27 ± 2 °C) to a constant weight. The dried leaf materials were milled into fine powder with an A2 grinder and sieved through a ten-mm sieve. One thousand grams (1000 g) of the powder of plant parts were dried, and the grinded materials were extracted in ten liters of distilled water for 24 hours at room temperature (27 ± 2 °C) to obtain 10% (w/v concentration). The resulting mixtures were sieved through four layers of muslin cloth and reserved for use. The extracted filtrate was designated as having 100% strength. This full-strength filtrate was used directly at a 10% (w/v) concentration.

Cultural Practices

The experimental field was ploughed and harrowed into a fine tilth and ridge before planting. It was then marked to the required plot size. The seeds were sown manually based on the treatment combination at an intra-row spacing of 30, 65, and 70 cm and an inter-row spacing of 75 cm to arrive at plant population of 22,500, 000, 48,750,000, 52,500,000 ha^{-1}. Three seeds were sown per hole by the dibbling method at a depth of 5 cm. After germination, the seedlings were thinned to one plant per stand two weeks after sowing. The pre-emergence herbicides and *Tithonia* plant extract were applied immediately after planting. Metolachlor at the rate of 0.8 kg a.i. ha^{-1} and Fluazifop at 0.8 kg a.i. ha^{-1} were used as post-emergence herbicides which contains 250 g/kg of fluazifop-p-butyl in the form of a water-dispersible granule.

Hoe weeding was carried out at 3 and 6 WAS to check the growth of weeds in the concerned plots, while in weedy check plots, no weeding was imposed throughout the period of the trials. The fertilizer was applied in two split doses at the rate of 60 kg N, 30 kg P_2O_2 and 30 kg K_2O per hectare using AS, while the remaining half of N was top dressed at 6 WAS using Urea (46% N). Similarly, Tricel insecticides with chlorpyriphos (48% E.C.) were applied at a rate of 0.5 kg a.i. ha^{-1} using a Knapsack sprayer to control larvae that feed on the leaf, stem, root, and flower. It was applied between 3 and 6 weeks after sowing. The crop was harvested when the raceme was fully mature and tuned deep brown. The raceme was cut manually using a sickle. The racemes were heaped on tumpline, threshed, and winnowed. The electrical weighing balance was used to measure the weight of the kernel per plot. The kernels were stored in jute bags and stored in a well-ventilated store in order to protect their quality.

Data collection and analysis

Data were collected on some physiological growth characters such as leaf area index, relative growth rate, and crop growth rate; and yield and yield-related characters such as raceme weight plant^{-1}, kernel weight plant^{-1}, and kernel yield per hectare. Additionally, weed characteristics were also computed, such as weed cover score, weed density, weed dry biomass, and weed control efficiency, using standard agronomic procedures, and measurement of weight-related attributes was done using a digital weighing balance (Mettler Toledo PM 4000). All data collected were subjected to analysis of variance (ANOVA) as described by Snedecor and Cochran (1967) using Genstat (17th edition). Significant treatment means were separated using the Student Newman-Keuls test (SNK) at a 5% probability level.

Results

Leaf area index

Table 1 presents the relative growth rate of Sunflower as affected by Plant population and Weed control methods during 2018, 2019 seasons and combined at Bagauda and BUK. The result indicates that plant population and weed control methods significantly influenced the leaf area index (LAI) of sunflower. The highest LAI was recorded at a plant population of 48,750,000 plants/ha in the combined analysis at BUK (4.76), showing a superior canopy structure and improved resource capture. Weed control treatments also had a significant impact, with T3 (Pre-emergence application of Tithonia plant extract followed by post-emergence application at 6 WAS) consistently producing the highest LAI across locations and years. The interaction between plant population and weed control methods were not significant ($P > 0.005$) across both locations and seasons.

Table 1: Leaf area index of sunflower as affected by plant population and weed control methods during 2018, 2019 seasons and combined at Bagauda and BUK

Treatment	Baguada			BUK		
	2018	2019	Combined	2018	2019	Combined
Plant population (#/ha)						
22,500, 000	1.84	3.78	2.81	4.41	3.56	3.99b
48,750,000	1.94	3.99	2.98	3.01	6.56	4.76a
52,500,000	2.23	4.59	3.50	3.70	4.16	3.93b
P of F	0.27	0.37	0.61	0.27	0.44	0.02
SE±	1.15	1.55	1.00	1.87	1.53	0.04
Weed control methods (WCM)						
T1	1.81	1.69	1.74	1.48	2.32	1.86d
T2	1.98	1.91	1.95	4.23	3.07	3.65bc
T3	2.24	4.70	3.38	5.65	4.27	4.96a
T4	2.16	2.45	3.34	3.11	4.13	3.62bc
T5	2.16	3.15	2.65	2.61	3.73	3.17bc
T6	1.99	3.97	3.00	3.69	3.06	3.37b
T7	1.50	3.35	3.05	2.45	3.13	2.79bc
T8	1.95	3.72	2.89	3.49	3.58	3.54c
P of F	0.87	0.72	0.18	0.31	0.06	▯001
SE±	1.21	1.39	1.62	1.75	1.53	1.57
Interaction						
PP x WC	0.84	0.51	0.30	0.92	0.64	0.05

Means followed by the similar letter (s) are not significantly different at 5 % level of probability using Student Newman Keuls Test.

T1=Weedy Check; T2= Hoe Weeding at 3 and 6 WAS; T3= Pre emergence application of *Tithonia* plant extract *fb* POE application of *Tithonia* plant extract at 6 WAS; T4=Pre emergence application of *Tithonia* pl ant extract *fb* Hoe weeding at 6 WAS; T5=Pre emergence application of *Tithonia* plant extract *fb* POE application of Fluazifop at 0.8 kg a.i ha^{-1} at 6 WAS; T6=Pre emergence application of Metolachlor at 0.8 kg a.i *fb* Hoe weeding at 6 WAS; T7=Pre emergence application of Metolachlor at 0.8 kg a.i ha^{-1} *fb* POE application of Fluazifop at 0.8 kg a.i ha^{-1} at 6 WAS; T8= Hoe weeding at 3 WAS *fb* POE application of Fluazifop at 0.8 kg a.i ha^{-1} at 6 WAS. POE= Post emergence; Fb=Followed by; WAS=Weeks after sowing;

Relative growth rate (g wk^{-1})

The relative growth rate (RGR) of sunflower as affected by plant population and weed control methods during the 2018 and 2019 seasons and combined at Bagauda and BUK is shown in Table 2. The results show that plant population and weed control methods significantly ($P < 0.001$) influenced the RGR of sunflower. The highest RGR was recorded at a plant population of 52,500,000 plants/ha in the 2019 season at Bagauda (0.07) and combined at Bagauda and BUK (0.05 and 0.16) compared with other plant populations that resulted in decrease value, demonstrating enhanced resource efficiency and biomass accumulation.

On the other hand, weed control treatments also had a significant impact on RGR, with T3 (Pre emergence application of *Tithonia* plant extract *fb* POE application of *Tithonia* plant extract at 6 WAS) and T4 (Pre emergence application of *Tithonia* plant extract *fb* Hoe weeding at 6 WAS) significantly produced the highest RGR in 2019 season and combined at Bagauda while T3 (Pre emergence application of *Tithonia* plant extract *fb* POE application of *Tithonia* plant extract at 6 WAS resulted in significantly higher RGR at BUK compared with weedy check that consistently resulted in lowest RGR across both seasons and locations. The interaction between plant population and weed control methods was not significant across both locations and seasons.

T1=Weedy Check; T2= Hoe Weeding at 3 and 6 WAS; T3= Pre emergence application of *Tithonia* plant extract *fb* POE application of *Tithonia* plant extract at 6 WAS; T4=Pre emergence application of *Tithonia* pl ant extract *fb* Hoe weeding at 6 WAS; T5=Pre emergence application of *Tithonia* plant extract *fb* POE application of Fluazifop at 0.8 kg a.i ha^{-1} at 6 WAS; T6=Pre emergence application of Metolachlor at 0.8 kg a.i *fb* Hoe weeding at 6 WAS; T7=Pre emergence application of Metolachlor at 0.8 kg a.i ha^{-1} *fb* POE application of Fluazifop at 0.8 kg a.i ha^{-1} at 6 WAS; T8= Hoe weeding at 3 WAS *fb* POE application of Fluazifop at 0.8 kg a.i ha^{-1} at 6 WAS. POE= Post emergence; *Fb*=Followed by; WAS=Weeks after sowing;

Crop growth rate (g cm^{-2} wk^{-1})

Table 3 presents the crop growth rate (CGR) of sunflower as impacted by plant population and weed control strategies during the 2018 and 2019 seasons and combined at Bagauda and BUK. The results indicate that plant population significantly influenced CGR, with the highest values recorded at a plant population of 52,500,000 plants/ha in 2018 (81.50), 2019 (126.40) and combine (103.90) at Bagauda and the combined analysis at BUK (106.40) compared with the rest of the plant population that resulted in lower CGR. Weed control treatments on the other hand also had a significant impact on CGR, where T3 (Pre-emergence application of Tithonia plant extract *fb* post-emergence application at 6 WAS) consistently produced the highest CGR across all locations and seasons. The combined analysis at BUK recorded the highest CGR value (130.00), indicating that Tithonia-based weed control effectively enhanced sunflower growth by reducing weed interference. The weedy check (T1) exhibited the lowest CGR, highlighting the detrimental impact of weed competition on sunflower growth. There was not significant ($P > 0.05$) interaction between plant population and weed control methods across both locations and seasons.

Table 2: Relative growth rate of sunflower as affected by plant population and weed control methods during 2018, 2019 seasons and combined at Bagauda and BUK

	Bagauda			BUK		
Treatment	2018	2019	Combined	2018	2019	Combined
Plant population (#/ha)						
22,500, 000	0.02	0.06^{b}	0.04^{c}	0.02	0.21	0.11^{b}
48,750,000	0.02	0.07^{b}	0.06^{b}	0.05	0.25	0.17^{b}
52,500,000	0.03	0.07^{a}	0.05^{a}	0.06	0.26	0.16^{a}
P of F	0.512	0.050	<0.001	0.77	0.17	<0.001
SE±	0.03	0.03	0.08	0.042	0.041	0.012
Weed control methods (WCM)						
T1	0.02	0.06^{c}	0.04^{d}	0.01	0.17	0.09^{g}
T2	0.04	0.07^{b}	0.05^{ab}	0.04	0.24	0.14^{b}
T3	0.09	0.09^{a}	0.09^{a}	0.12	0.32	0.22^{a}
T4	0.08	0.07^{a}	0.08^{a}	0.05	0.35	0.20^{c}
T5	0.06	0.08^{ab}	0.07^{bc}	0.03	0.31	0.17^{d}
T6	0.05	0.07^{b}	0.06^{c}	0.08	0.22	0.15^{e}
T7	0.02	0.06^{b}	0.04^{c}	0.02	0.22	0.12^{f}
T8	0.03	0.07^{b}	0.05	0.04	0.24	0.14^{d}
P of F	0.512	0.031	<0.001	0.172	0.174	<0.001
SE±	0.012	0.022	1.092	0.032	0.044	0.033
Interaction						
PP x WCM	0.94	0.94	2.86	0.24	0.25	0.24

Means followed by the similar letter (s) are not significantly different at 5 % level of probability using Student Newman Keuls Test.

T1=Weedy Check; T2= Hoe Weeding at 3 and 6 WAS; T3= Pre emergence application of *Tithonia* plant extract *fb* POE application of *Tithonia* plant extract at 6 WAS; T4=Pre emergence application of *Tithonia* pl ant extract *fb* Hoe weeding at 6 WAS; T5=Pre emergence application of *Tithonia* plant extract *fb* POE application of Fluazifop at 0.8 kg a.i ha^{-1} at 6 WAS; T6=Pre emergence application of Metolachlor at 0.8 kg a.i *fb* Hoe weeding at 6 WAS; T7=Pre emergence application of Metolachlor at 0.8 kg a.i ha^{-1} *fb* POE application of Fluazifop at 0.8 kg a.i ha^{-1} at 6 WAS; T8= Hoe weeding at 3 WAS *fb* POE application of Fluazifop at 0.8 kg a.i ha^{-1} at 6 WAS. POE= Post emergence; Fb=Followed by; WAS=Weeks after sowing;

Yield and yield component

The raceme weight per plant, kernel weight per plant, and kernel yield per hectare of sunflower as affected by plant population and weed control methods during the 2018 and 2019 seasons (combined) at Bagauda and BUK is shown in Table 4. The results indicate that plant population significantly influenced these yield components, with the highest (115.66 g and 116.87 g) raceme weight per plant recorded at 52,500,000 plants/ha in both Bagauda and BUK, respectively. However, kernel yield per hectare decreased with increasing plant population, with the highest yield (1024.00 kg ha^{-1} and 1027.00 kg ha^{-1}) recorded at the lowest plant population of 22,500,000 plants/ha at Bagauda and BUK, respectively.

Table 3: Crop growth rate of sunflower as affected by plant population and weed control methods during 2018, 2019 seasons and combined at Bagauda and BUK

	Baguada			BUK		
Treatment	2018	2019	Combined	2018	2019	Combined
Plant population (#/ha)						
22,500, 000	60.90^{b}	95.60^{b}	78.30^{c}	62.40	99.10	80.90^{b}
48,750,000	65.81^{b}	102.91^{b}	84.41^{b}	67.31	106.41	86.91^{b}
52,500,000	81.50^{a}	126.40^{a}	103.90^{a}	83.00	129.90	106.40^{a}
P of F	0.022	0.033	□0.001	0.223	0.222	□0.001
SE±	7.13	10.69	0.35	7.13	10.69	9.35
Weed control methods (WCM)						
T1	48.10^{f}	78.60	63.40^{e}	49.60	79.90	64.90^{g}
T2	68.40^{bc}	101.90	85.20^{c}	72.01	114.71	93.81^{b}
T3	100.32^{a}	154.82	127.62^{a}	101.80	158.20	130.00^{a}
T4	73.81^{b}	112.91	93.41^{b}	84.40	118.50	102.50^{c}
T5	71.51^{b}	115.81	93.61^{b}	74.01	116.41	95.21^{d}
T6	65.80^{cd}	86.60	76.20^{d}	75.30	106.50	90.90^{e}
T7	54.12^{ef}	103.02	78.62^{d}	67.31	90.11	78.71^{f}
T8	60.21^{cd}	112.21	78.61^{d}	70.22	110.32	90.72^{e}
P of F	0.050	0.551	□0.001	0.05	0.05	□0.01
SE±	12.39	15.71	14.05	10.47	15.60	15.27
Interaction						
PP x WCS	0.61	0.07	0.04	0.54	0.61	0.04

Means followed by the similar letter (s) are not significantly different at 5 % level of probability using Student Newman Keuls Test.

The application of T3 (Pre-emergence application of *Tithonia* plant extract *fb* post-emergence at 6 WAS consistently produced the highest kernel weight per plant and kernel yield per hectare across locations. At Bagauda, T3 recorded a kernel weight per plant of 102.58 g and a kernel yield of 1041.00 kg ha^{-1}, while at BUK, the corresponding values were 80.24 g and 924.51 kg ha^{-1}. This highlights the effectiveness of Tithonia extract in suppressing weed competition and enhancing crop performance.

T1=Weedy Check; T2= Hoe Weeding at 3 and 6 WAS; T3= Pre emergence application of *Tithonia* plant extract *fb* POE application of *Tithonia* plant extract at 6 WAS; T4=Pre emergence application of *Tithonia* pl ant extract *fb* Hoe weeding at 6 WAS; T5=Pre emergence application of *Tithonia* plant extract *fb* POE application of Fluazifop at 0.8 kg a.i ha^{-1} at 6 WAS; T6=Pre emergence application of Metolachlor at 0.8 kg a.i *fb* Hoe weeding at 6 WAS; T7=Pre emergence application of Metolachlor at 0.8 kg a.i ha^{-1} *fb* POE application of Fluazifop at 0.8 kg a.i ha^{-1} at 6 WAS; T8= Hoe weeding at 3 WAS *fb* POE application of Fluazifop at 0.8 kg a.i ha^{-1} at 6 WAS. POE= Post emergence; *fb*=Followed by; WAS=Weeks after sowing.

Table 4: Raceme weight per plant, kernel weight per plant, and kernel yield per hectare of Sunflower as affected by plant population and weed control methods during 2018 and 2019 seasons (Combined Season) at Bagauda and BUK

	Bagauda			BUK		
Treatment	Raceme weight plant^{-1}	Kernel weight plant^{-1} (g)	Kernel yield (kg ha^{-1})	Recame weight plant^{-1}	Kernel weight plant^{-1} (g)	Kernel yield (kg ha^{-1})
Plant population (#/ha)						
22,500, 000	107.12^{c}	80.91^{b}	1024.00^{a}	102.25^{c}	82.75^{b}	1027.00^{a}
48,750,000	110.14^{b}	94.66^{a}	652.60^{b}	110.02^{b}	95.02^{a}	619.71^{b}
52,500,000	115.66^{a}	95.15^{a}	477.90^{c}	116.87^{a}	98.87^{a}	587.50^{c}
P of F	0.001	0.005	0.005	0.003	0.005	0.002
SE±	0.352	1.491	45.41	0.321	1.492	59.31
Weed control methods (WCM)						
T1	75.59^{f}	61.48^{e}	115.91^{e}	39.95^{e}	27.24^{d}	104.80^{e}
T2	93.06^{e}	88.44^{d}	840.31^{a}	87.22^{b}	66.67^{c}	881.30^{b}
T3	121.60^{a}	102.58^{a}	1041.00^{a}	114.12^{a}	80.24^{a}	924.51^{a}
T4	113.86^{c}	99.82^{b}	557.21^{b}	94.71^{b}	78.84^{b}	579.31^{bc}
T5	119.01^{b}	91.03^{c}	411.80^{c}	110.16^{a}	70.12^{b}	437.60^{c}
T6	115.55^{c}	92.33^{c}	475.10^{c}	77.02^{c}	62.27^{c}	491.51^{c}
T7	93.06^{e}	88.42^{d}	391.01^{d}	58.40^{d}	60.30^{c}	336.61^{d}
T8	101.54^{d}	88.44^{d}	440.90^{c}	64.92^{c}	67.60^{bc}	402.30^{c}
P of F	0.281	<0.001	<0.001	<0.001	0.003	<0.001
SE±	0.611	1.581	27.24	0.091	2.972	25.75
Interaction						
PP x WCM	0.411	0.001	0.361	0.002	0.002	0.361

Means followed by the similar letter (s) are not significantly different at 5 % level of probability using Student Newman Keuls Test.

Weed characters

Table 5 presents the weed cover score (WCS), weed density (WD), weed dry biomass (WDW), and weed control efficiency (WCE) of sunflower as affected by plant population and weed control methods during the 2018 and 2019 seasons (combined) at Bagauda and BUK. The results indicate that plant population significantly influenced weed suppression, with the highest plant population (52,500,000 plants/ha) recording the highest WCE at Bagauda (63.60%) and BUK (71.08%) while WCS and WD were not significantly (P >0.05) affected by plant population across both locations. The application of T3 (Pre-emergence application of Tithonia plant extract *fb* post-emergence application at 6 WAS recorded the lowest weed density and weed dry biomass, with the highest (76.3% and 82.88%) weed control efficiency at Bagauda and BUK, respectively.

T1=Weedy Check; T2= Hoe Weeding at 3 and 6 WAS; T3= Pre emergence application of *Tithonia* plant extract *fb* POE application of *Tithonia* plant extract at 6 WAS; T4 = Pre emergence application of *Tithonia* plant extract *fb* Hoe weeding at 6 WAS; T5=Pre emergence application of *Tithonia* plant extract *fb* POE application of Fluazifop at 0.8 kg a.i ha^{-1} at 6 WAS; T6=Pre emergence application of Metolachlor at 0.8 kg a.i *fb* Hoe weeding at 6 WAS; T7=Pre emergence application of Metolachlor at 0.8 kg a.i ha^{-1} *fb* POE application of Fluazifop at 0.8 kg a.i ha^{-1} at 6 WAS; T8= Hoe weeding at 3 WAS *fb* POE application of Fluazifop at 0.8 kg a.i ha^{-1} at 6 WAS. POE= Post emergence; *fb*=Followed by; WAS=Weeks after sowing.

Table 5: Weed cover score, weed density, weed dry biomass and weed control efficiency of sunflower as affected by plant population and weed control methods during 2018 and 2019 seasons (Combined Season) at Bagauda and BUK

Treatment	Baguada				BUK			
	Weed cover score	Weed density (n m^{-2})	Weed dry matter (kg ha^{-1})	Weed control efficiency (%)	Weed cover score	Weed density (n m^{-2})	Weed dry matter (kg ha^{-1})	Weed control efficiency (%)
Plant population (#/ha)								
22,500, 000	2.23	31.53	358.00^{b}	52.40^{b}	2.49	34.21	351.10^{c}	54.82^{c}
48,750,000	3.27	36.79	368.10^{b}	61.30^{a}	3.04	36.77	368.02^{b}	62.69^{b}
52,500,000	3.15	38.06	381.03^{a}	63.60^{a}	3.16	39.19	392.22^{a}	71.08^{a}
P of F	0.610	0.522	0.022	<0.001	0.690	0.233	0.032	<0.001
SE±	0.07	1.38	22.10	2.25	0.75	2.06	14.54	0.96
Weed control methods (WCM)								
T1	5.00^{a}	91.20^{a}	912.01^{a}	24.2^{f}	4.49^{a}	96.11^{a}	961.03^{a}	19.25^{f}
T2	3.05^{b}	30.20^{c}	306.00	63.1^{c}	3.00^{b}	29.39^{c}	294.11^{c}	68.58^{c}
T3	1.28^{d}	10.21^{f}	102.00^{f}	76.3^{a}	1.22^{d}	9.89^{f}	99.00^{e}	82.88^{a}
T4	2.83^{c}	19.20^{d}	192.01^{e}	71.9^{b}	2.83^{c}	19.11^{d}	191.11^{e}	76.37^{b}
T5	2.78^{c}	22.20^{e}	222.21^{d}	70.0^{b}	2.50^{c}	22.89^{e}	229.01^{d}	73.50^{b}
T6	3.44^{b}	40.11^{b}	401.01^{b}	55.8^{d}	2.50^{c}	38.89^{b}	385.11^{b}	61.89^{c}
T7	3.67^{b}	40.21^{b}	401.01^{b}	58.10^{d}	3.38^{b}	39.72^{b}	397.00^{bc}	60.94^{c}
T8	3.72^{b}	42.01^{b}	420.02^{b}	54.0^{e}	3.69^{b}	41.78^{b}	418.12	59.49^{d}
P of F	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
SE±	0.09	2.25	29.14	3.83	0.36	5.82	23.71	1.94
Interaction								
PP x WC	0.311	0.191	0.04	0.991	0.323	0.691	0.04	0.683

Means followed by the similar letter (s) are not significantly different at 5 % level of probability using Student Newman Keuls Test.

Discussion

Influence of plant population of growth and yield characters

The ability of a plant population of 52,500,000 plants/ha to significantly have higher physiological growth attributes demonstrates that increasing plant population enhanced RGR, CGR, likely due to enhanced resource use efficiency and biomass accumulation leading to denser canopy structures, optimizing light capture, photosynthetic efficiency, and radiation interception, resulting in higher dry matter production (Waldah *et al.*, 2022) and improved growth rates as described by Ndor et al. (2019). Additionally, findings align with those of Fangue-Yapseu *et al*. (2021), who reported that enhanced root proliferation and nutrient uptake in denser populations contribute to greater biomass accumulation, which correlates with increased CGR. According to Dominschek *et al*. (2019), higher plant populations can naturally suppress weeds by reducing competition for nutrients and water, allowing sunflowers to allocate more energy to vegetative growth, enhancing RGR and CGR.

The decrease in kernel yield at the highest plant population (52,500,000 plants/ha), despite the increase in other parameters such as raceme weight and kernel weight per plant, can be attributed to increased intra-specific competition for available growth resources leading to lower individual plant productivity, as affirmed by Waldah *et al.* (2022). Although as total biomass increases, individual plants may allocate more energy to vegetative growth rather than kernel production. Furthermore, the reduction in yield may be attributed to shading effects where dense plant populations lead to canopy crowding, reducing light interception for lower leaves, which limits photosynthesis and carbohydrate allocation to reproductive structures, resulting in smaller kernels or fewer kernels per plant, which ultimately reduced kernel yield per hectare. This is in line with the findings of Golmaei *et al*. (2023). Other schools of thought believed the decrease in yield to be associated with increased plant stress in the form of moisture and nutrition due to higher plant populations per given area, especially under rain-fed conditions, leading to kernel abortion or poor grain filling, as described by Mehdizadeh & Mushtaq (2020). In contrast, lower plant populations allow each plant to access sufficient resources, promoting better kernel development.

Influence of weed control methods on growth and yield character

The ability of T3 to outperform other weed control methods in increasing LAI, RGR, CGR, and yield of sunflower could be attributed to the fact that Tithonia plant extract has been reported to possess natural allelopathic compounds that suppress weed germination and growth. Thus, the combination of pre-emergence and post-emergence applications of the extract provided extended weed control, reducing weed resurgence and competition. This finding aligns with those of Ilori and Otusanya (2020) and Musabayana *et al*. (2024), who reported the allelopathic effects of Tithonia extracts on certain arable crops. In another development, Tithonia extracts enhance soil fertility, strengthening sunflower growth, thus reducing weed competition, which aligns with the findings of Ngonadi et al. (2019), who in their study reported that application of Tithonia aids in nutrient recycling within the soil rhizosphere, although it may have some inhibitory effect on plants at higher concentration. Thus, the combination of pre-emergence and post-emergence applications of the extract provided extended weed control, reducing weed resurgence and competition. This finding further aligns with those of Mehdizadeh and Mushtaq (2020) and Shittu *et al*. (2025), who reported the efficacy of allelopathic weed suppression in sustainable agriculture.

Additionally, Tithonia extracts enhance soil fertility, strengthening sunflower growth and reducing weed competition. This aligns with the findings of Golmaei *et al.* (2023), who reported that the application of allelopathic plant extracts aids in nutrient recycling within the soil rhizosphere, improving crop vigor and overall growth performance (Mehdizadeh & Mushtaq, 2020). However, excessive concentrations of allelopathic extracts may have inhibitory effects on crop plants, which necessitates further research to determine optimal application rates for sunflower cultivation.

Conversely, the lowest LAI, RGR, CGR, raceme weight per plant, kernel weight per plant and kernel yield per hectare values were recorded in the weedy check (T1), highlighting the adverse effects of weed competition on sunflower growth. The variations observed in different weed control methods further emphasize the importance of integrating mechanical and allelopathic approaches to optimize sunflower growth.

Weed characters

The weed suppressing ability of 52,500,000 plants/ha suggests that increasing plant population enhances crop competitiveness against weeds by reducing light penetration and resource availability for weed growth, thus smothering the growth of the weeds. The ability of T3 to resulted in lower WCS, WD, WDW and higher WCE highlights the strong allelopathic effects of Tithonia extract, which effectively suppresses weed germination and growth. The allelopathic effect of Tithonia extract had been reported by Ilori and Otusanya (2020) on some arable crops (cowpea, soybean, maize and sorghum). The integration of pre-emergence and post-emergence control methods, particularly using plant-derived bioherbicides, has been shown to be a sustainable alternative to synthetic herbicides, reducing environmental impact while maintaining crop yield (Alsaadawi *et al*., 2020; Golmaei *et al*., 2023).

Conversely, the weedy check (T1) exhibited the highest weed density and dry biomass, confirming the necessity of an effective weed management strategy to maximize sunflower productivity. The integration of pre-emergence and post-emergence control methods, particularly using plant-derived bioherbicides, has been shown to be a sustainable alternative to synthetic herbicides, reducing environmental impact while maintaining crop yield (Golmaei *et al*., 2023; Shittu *et al*., 2025).

Conclusion and Recommendation

The study demonstrated that both plant population and weed control methods significantly influenced sunflower physiological growth, yield, and weed suppression in the Sudan Savannah agroecology of Nigeria. Higher plant populations (52,500,000 plants/ha) improved RGR, CGR, and LAI due to enhanced resource utilization and canopy formation. However, excessive plant density reduced kernel yield per hectare, indicating the importance of optimizing plant population to balance growth and reproductive efficiency. Among the weed control methods, pre-emergence application of *Tithonia diversifolia* extract followed by post-emergence application at 6 WAS (T3) provided superior weed suppression, leading to increased sunflower growth and yield. The weedy check resulted in the lowest performance across all parameters, reinforcing the importance of effective weed management. Based on the findings of this study, a moderate plant population of 48,750,000 plants/ha could be recommended to balance biomass accumulation and kernel yield, avoiding excessive intra-specific competition as well as the use of *Tithonia diversifolia* extract as a pre-emergence and post-emergence weed control method for effective and sustainable weed suppression minimize dependency on synthetic herbicides and promote eco-friendly sunflower production.

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