Effect of plant spacing and some growth regulators on growth, yield and antioxidant activity of flax

Zahraa Abdel Karim Mazhar1*, Maher H. S. Al-Mohammad2 and
Rafid Saleh Nahhab3
Department of Field Crops, College of 1,3 Agriculture, Al-Qasim Green University, Babylon, Iraq
Department Horticulture & Landscape, 2College of Agriculture, Al-Qasim Green University, Babylon, Iraq
Correspondence Zahraa Abdel Karim*

Department of Field Crops ,College of Agriculture, Al-Qasim Green University, Babylon, Iraq ,
Email: zahraa.abdullkarim@agre.uoqassim.edu.iq

Abstract

A field experiment was conducted during the 2024 growing season at the Umm Gharagher Station of the Karbala Agriculture Directorate, on the effect of Horticulture and Nursery Development plant spacing and some growth regulators on the growth, productivity and antioxidant activity of flax ying of growth plants. The studied factors included: Plant spacing between plants (5 cm and 15 cm), spra ,1-GA at a concentration of 200 mg L ,1-regulators (distilled water, IAA at a concentration of 2 mg L and their combination). The results showed the superiority of the 15 cm plant spacing as the highest stem diameter 1.9667 mm, ,1-ain branches 13.70 branches plantplant height was 87.25 cm, number of m -leaf area 0.9303 cm2, total chlorophyll content 5.261 mg 100 g ,1-number of leaves 124.85 leaves plant tal seed yield weight of 1000 seeds 8.556 g, to ,1-fresh weight, number of capsules 36.72 capsules plant 1 dry weight, 1-total phenols 15.17 mg g ,1-oil percentage 34.944%, total oil yield 94.4 kg ha ,1-t ha 2.669 dry weight, total antioxidant 1-dry weight, total carotenoids 2.784 mg g 1-total flavonoids 9.55 mg g and free radical scavenging efficiency 66.07%. The combination ,activity 62.44% ABTS inhibition treatment between IAA and GA3 also outperformed and achieved the highest number of main branches mg 100 total chlorophyll content 5.332 ,1-number of leaves 154.92 leaves plant ,1-branches plant 19.42 weight of 1000 seeds 9.790 g, total seed ,1-fresh weight, number of capsules 46.06 capsules plant 1-g dry 1-total phenols 16.06 mg g ,1-oil percentage 35.283%, total oil yield 125.4 kg ha ,1-yield 3.548 t ha dry weight, total 1-y weight, total carotenoids 2.960 mg gdr 1-weight, total flavonoids 10.25 mg g antioxidant activity 63.45% ABTS inhibition and free radical scavenging efficiency 67.58%. The P15 x IAA2 + GA200 interaction treatment achieved the highest number of main branches 19.94 branches weight of ,1-number of capsules 49.05 capsules plant ,1-number of leaves 159.80 leaves plant ,1-lantp ,1-oil percentage 36.090%, total oil yield 137.9 kg ha ,1-seeds 10.407 g, total seed yield 3.822 t ha 1000 dry weight, total 1-total flavonoids 11.33 mg g ,dry weight 1-total phenolics content 17.24 mg g dry weight, total antioxidant activity 64.30% ABTS inhibition and free radical 1-carotenoids 3.241 mg g .scavenging efficiency 68.80%

:Keywords *.(Flax, plant spacing, auxin (IAA), gibberellin (GA3*

Introduction

Linum usitatissimum L. is an economically important winter crop belonging to the Linaceae family and is cultivated in several regions of the world. Flax is cultivated for the purpose of oil and fiber production, as its rotein p %25-oil and 20 %47-seeds contain 35 Flaxseeds are characterized by their high .[20] content of unsaturated fatty acids, the most important of which are linoleic acid, belonging group, and linolenic acid, 6-to the omega

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group, which are 3-belonging to the omega tive role in the associated with an effec prevention and treatment of some chronic diseases, such as thrombosis, cardiovascular diseases and atherosclerosis [18]. It also -contains oleic acid, which belongs to the omega inflammatory properties -group and has anti 9 e to improving insulin and may contribut sensitivity, and flax oil is suitable for human consumption [22]. Approximately 80% of flax oil is used in various industries, such as the production of paints, varnishes and printing or inks, due to its ability to dry quickly, and as f the press cake (solid residue after pressing the seeds), it is used in animal feed because it contains about 36% protein, in addition to its value as an organic fertilizer, and some residues are used in the manufacture of insulation .[materials [7

ultural practices, especially the Agric organization of plant spacing, is a pivotal factor that effectively affects plant growth and productivity. The choice of the optimal plant spacing (distance between rows and between tor in plants within the row) is a critical fac determining the spatial area available to the plant, and the size of the soil that allows the root system to expand and spread efficiently, and this agricultural organization provides a suitable spatial environment to intercept solar radiation onvert it into chemical energy, which is and c invested in the formation of dry matter and stored in the reproductive organs or developing parts of the plant, which reflects positively on the physiological performance and productivity .[of the crop [26

-gulators are defined as nonGrowth re nutritive organic compounds that possess effects similar to natural growth hormones in plants, but are synthesized outside plant tissues, and are used to induce specific changes in plant growth ieve the and physiological functions to ach highest yield and quality of the crop [2]. Foliar spraying of these regulators, within specific concentration ranges, is an effective way to regulate growth processes, either by promoting or inhibiting, or by maintaining the normal rate ic activity of the plant [8]. Auxin of metabol especially IAA) acts as a key regulator of plant) cell growth. It promotes cell elongation by stimulating cell wall digestion factors such as expansin [12]. Under environmental stress, of root auxin is involved in the remodeling system architecture, in collaboration with ABA and signal transduction factors such as DRO1 and SAURs to ensure deep and dense root growth [14]. Gibberellin (GA3) stimulates cell elongation in the stem and leaves and increases hich is reflected in plant internodal length, w height and productivity [14]. Gibberellin is a key driver in secondary cell wall development xylogenesis), enhancing cambium activity and) activating gene expression of cellulose .[production pathways [6

ims to determine Therefore, the research a the best distance to plant flax according to the conditions of the experimental area and determine the best concentration of spraying the growth regulators auxin and gibberellin that increase some vegetative growth indicators, omponents, oil content, secondary seed yield c metabolites, total antioxidant capacity and free .radical scavenging efficacy

Materials and Methods

The field experiment was conducted at the Horticulture and Nursery Development Station re in Umm Gharagher, Karbala Agricultu Directorate, at longitude 44.12 E and latitude N, according to a randomized complete 32.71 block design (RCBD) with a factorial arrangement with three replications. Data were analyzed using GenStat statistical software ared using th edition) and means were comp19) the Least Significant Difference (LSD) test at a probability level. Ten random samples were %5 taken from the soil of the two experimental sites before planting to analyze the physical and .(chemical properties of the soil (Table S1

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Table S1. Physical and chemical properties of the experimental soil.

Soil Texture Soil	% Soil Separates			Organic Matter OM %	Available Elements ($^{1-}$mg kg)			Electrical Conductivity EC) dslm(	Reaction Degree pH)(	Analysis Parameter	Location
	Sand	Silt	Clay		Potassium	Phosphorus	Nitrogen				
	180	512.3	307.7	1.3	400	11.8	63	8.8	7.8	Soil	Season First
								1.15	7.5	Irrigation Water	

Climatic conditions (temperature, humidity, and rainfall) recorded during the growing season are .presented in Table S2

Table S2. Monthly climatic conditions during the growing season (2024–2025).

*First Season				
Amount Rainfall (mm)	Solar Radiation (^{2}MJ m)	Mean Relative Humidity (%) (%)	Mean Temperature (C°)	Weekly Averages
1.1	1	67.7	13.8	2024-11-11/2024-1
2	28	75.4	14.3	2024-11-18/2024-1
2.5	22	59.4	6.9	2024-11-25/2024-1
1.5	16	60.9	10.7	2024-12-02/2024-1
1.9	6	59.6	9.5	2024-12-09/2024-1
2.3	17	53.3	11.2	2024-12-16/2024-1
2.3	25	58.1	10.7	2024-12-23/2024-1
2.1	5	69.3	17.5	2024-12-30/2025-0

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2.1	26	66.7	22	2025-01-06/2025-(
1.9	27	62.1	21.7	2025-01-13/2025-(
1.9	23	61.3	24.1	2025-01-20/2025-(
2	8	59.1	20.4	2025-01-27/2025-(
2.4	17	59	22.6	2025-02-03/2025-(
2.4	11	58.3	22.3	2025-02-10/2025-(
1.6	28	52.7	19.3	2025-02-17/2025-(
2.8	20	59.1	22.4	2025-02-24/2025-(
2	18	58.1	23.5	2025-03-03/2025-(
2.5	19	54.4	22.8	2025-03-10/2025-(
1.8	10	53.7	23.2	2025-03-17/2025-(
1.7	23	71.1	20.3	2025-03-24/2025-(
1.7	16	56.1	21	2025-03-31/2025-(
1.9	17	58.7	21.5	2025-04-07/2025-(
2.8	12	54	22.5	2025-04-14/2025-(

The soil was prepared by tillage, smoothing and leveling, and then animal and supercomplex fertilizer 1-manure at 32 t ha were added [4] 1-NPK) at 200 kg ha 15:15:15) during tillage. Then, the field was divided into of 2 m three sectors, leaving a buffer distance between sectors, and corridors to separate the experimental units. Each sector was divided into experimental units, each unit was 3 m2 (1 m x 8 m), with 4 rows per unit and a distance of 30 3

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cm from all sides of the unit. Plants were ws 30 cm apart, leaving a 1 m gap planted in ro between units to ensure that the spray does not fly. Flax seeds were planted on 15/11/2024 [3], which were obtained from the Abu Ghraib Agricultural Research Department of the .Ministry of Agriculture

ed two factors: The The experiment includ first factor: the plant spacing [11] which is 5 cm approximately 200 plants/experimental unit) based on 4 rows x 10 plants per row spacing 30 cm apart) and 15 cm (approximately 65 plants/experimental unit based on 4 rows x 10 row with wider spacing). The plants per difference in plant numbers between the two plant -spacings is attributed to the wider between distance in the row at 15 cm compared to 5 cm within the same row length of 3 m. The second [25] factor : spraying of growth regulators which is distilled water only, spraying auxin gibberellin ,1-IAA at a concentration of 2 mg L and IAA ,1-GA3 at a concentration of 200 mg L x gibberellin 1-at a concentration of 2 mg L Spraying .1-GA3 at a concentration of 200 mg L first 30 days after planting was done twice (the leaves appeared and the second 60 6-when 4 .[leaves) [2 10-days after the appearance of 8

Plant height, number of main branches, main stem diameter, total number of leaves, leaf area, total chlorophyll content, number of es, number of seeds per capsule, weight capsul of 1000 seeds, total seed yield, percentage of oil, total oil yield and total phenolics were measured at physiological maturity approximately 120 days after planting) at the) plant) time of harvest. Vegetative growth traits height, branches, stem diameter, leaves, leaf area, and chlorophyll) were measured 70 days after planting. Yield components (capsule seed weight, seed -number, seed number, 1000 yield, oil percentage, and oil yield) and nolics, flavonoids, biochemical traits (total phe carotenoids, and antioxidant activity) were measured after full physiological maturity and harvest. Total phenolics were estimated according to the method used by [9] using Ciocalteu reagent. Five grams of seeds of -Folin al unit were randomly taken, each experiment ground well, 50 ml of 80% methanol was added and placed in a water bath at 45C for three hours, then the sample was placed in a rotary evaporator to reduce the sample volume to 5 ml. Then 100 ul of sample extract was taken and Ciocalteu reagent and 1.5 ml of -ul of Folin 500 sodium carbonate solution was added, the sample was mixed and distilled water was added to a volume of 10 ml, then the sample was left for 2 hours. The optical absorbance reading was nm and Gallic acid 765 taken at a wavelength of .was used as a standard

Total flavonoids were estimated by the AlCl3 aluminum chloride method using the same sample extract [9]. A 250 ul aliquot of sample extract was taken with 1.25 ml of ion; distilled water and 75 ul of 5% NaNO2 solut after 5 minutes, 150 ul of 10% aluminum chloride solution was added. After filtering with filter paper, 500 ul of 1 M NaOH 3-Whatman solution and 750 ul of distilled water were added, and optical absorbance was measured at nt of carotenoids nm wavelength. The conte 510 at 480 nm wavelength was estimated according to the method of Goodwin [13]. The results were converted into units of milligrams per .gram of fresh weight of plant tissue

The total antioxidant capacity was ibed by [5]. calculated using the method descr The ABTS solution was diluted to give an at a wavelength of 0.02 -absorbance of 0.70 +/ nm, then 3 ml of the above solution was 734 added to 0.3 ml of each concentration of the compounds used. The tubes were shaken and ature for 10 minutes. incubated at room temper The inhibition of ABTS radical was estimated At/Ar)] x 100, where)-according to: PI (%) = [1 At and Ar are the absorbances of the sample and ABTS, respectively. Results were expressed as percentage inhibition (% ABTS radical .(g activityscavengin

The free radical scavenging efficiency was

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calculated using the method described by [17]. -2-Diphenyl-The reagent DPPH (1,1 picrylhydrazyl) at a concentration of 0.1 mmol was prepared and optical absorbance was nm. Then 1 17synchronised at a wavelength of 5 ml of the extract of each plant sample was taken and 1 ml of the reagent was added, the tubes were mixed well and left in a dark place for 4 minutes at laboratory temperature. Free radical scavenging efficiency (%) = [(absorbance of bsorbance of sample) / absorbance of a -blank .blank] x 100

Results and Discussion

Vegetative growth traits -1

The results of Table (1) indicated that plant spacing and spraying treatment with indoleacetic acid (IAA) at a concentration of 2 with gibberellin (GA3) at and treatment 1-mg L and their 1-a concentration of 200 mg L interaction led to a significant increase in vegetative growth traits. The plant spacing of 15 cm achieved the highest plant height of 87.25 cm, number of main branches of 13.70 branches stem diameter of 1.9667 mm, number of ,1-ntpla leaf area of ,1-leaves of 124.85 leaves plant cm2, and total chlorophyll content of 0.9303 fresh weight compared to the 1-mg 100 g 5.261 cm plant spacing which recorded 85.37 cm, 5 leaves, 59.branches, 1.9005 mm, 119 11.26 respectively. ,1-cm2 and 5.163 mg 100 g 0.8858 This may be because the increase in plant spacing (15 cm) provided more space for roots to absorb water and nutrients, thereby increasing the physiological efficiency of plants by nthetic capacity and leaf area, increasing photosy followed by improving stem and branch growth and the total number of leaves. In addition, the increased ventilation between plants at low density improved the efficiency of chlorophyll metabolism, thus increasing the total hlorophyll content compared to the narrow c plant spacing (5 cm) that limited the area available for growth and led to higher .[competition between plants [27

The results showed that the combination treatment between IAA and GA3 achieved the f main branches of 19.42 highest number o 1-number of leaves of 154.92 leaves ,1-branches -and total chlorophyll content of 5.332 mg 100 g fresh weight, while the spraying treatment 1 with indole acetic acid at a concentration of 2 f achieved the highest plant height o 1-mg L cm and leaf area of 0.9453 cm2 compared 97.94 to the distilled water treatment which recorded the lowest plant height of 74.60 cm, number of stem ,1-main branches of 6.70 branches diameter of 1.3183 mm, number of leaves of phyll content of and total chloro 1-leaves 97.28 fresh weight. The superiority 1-mg 100 g 4.998 of IAA2 + GA200 treatment may be attributed to the hormonal integration between auxin and gibberellin, which contributes to increasing the efficiency of cell division and elongation as well photosynthetic and pigmentation pathways as The superiority of IAA alone in plant .[16] height and leaf area is attributed to its role in regulating cell expansion and stem elongation P15 x IAA2 + GA200 treatment achieved .[10] nches of 19.94 the highest number of main bra and number of leaves of 159.80 1-branches while P15 x IAA2 treatment recorded ,1-leaves the highest plant height of 98.01 cm and total fresh 1-chlorophyll content of 5.393 mg 100 g .weight

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Table (1): Effect of Plant Spacing and Some Growth Regulators on Growth Parameters of Flax

Treats	PH	MB	MSD	LN	LA	TCH
P5	85.37	11.26	1.9005	119.59	0.8858	5.163
P15	87.25	13.70	1.9667	124.85	0.9303	5.261
LSD (0.05)	0.970	0.883	0.02079	1.569	0.01422	0.1434
GR0	74.60	6.70	1.3183	97.28	0.9412	4.998
IAA2	97.94	9.91	1.5620	115.34	0.9453	5.250
GA200	82.28	13.88	2.7800	121.33	0.9177	5.267
IAA2 + GA200	90.42	19.42	2.0740	154.92	0.8278	5.332
LSD (0.05)	1.372	1.249	0.02939	2.219	0.02011	0.2029
P5 x GR0	72.11	6.16	1.3000	95.66	0.9207	4.967
P5 x IAA2	97.87	9.90	1.5073	111.84	0.9453	5.107
P5 x GA200	82.19	10.07	2.7600	120.81	0.9177	5.267
P5 x IAA2 + GA200	89.30	18.89	2.0347	150.05	0.7593	5.310
P15 x GR0	77.09	7.25	1.3367	98.91	0.9617	5.030
P15 x IAA2	98.01	9.92	1.6167	118.84	0.9453	5.393
P15 x GA200	82.37	17.70	2.8000	121.85	0.9177	5.267
P15 x IAA2 + GA200	91.54	19.94	2.1133	159.80	0.8963	5.353
LSD (0.05)	1.940	1.766	0.04157	3.138	0.02843	0.2869

PH = Plant Height (cm), MB = Main Branch No., MSD = Main Stem Diameter (mm), LN = Leaves Leaf Area (cm2), TCH = Total = No., LA (FW 1-Chlorophyll (mg 100g

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Yield characteristics -2

The results of Table (2) showed that the plant spacing of 15 cm achieved the highest ,1-number of capsules of 36.72 plant capsules weight of 1000 seeds of 8.556 g, total seed yield percentage of oil of 34.944% ,1-of 2.669 t ha while 5 cm 1-g haand total oil yield of 94.4 k plant spacing recorded the lowest rates of 31.20 %32.573 ,1-g, 2.105 t ha 7.567 ,1-plant capsules respectively. The reason for ,1-and 69.5 kg ha the superiority in productive traits at 15 cm plant spacing may be due to the fact that this spacing reduces competition for nutrients, water and light, allowing each plant to fully utilize the available resources for leaf and branch growth. The wider plant spacing improves the exposure of the leaves to sunlight, which increases the ynthesis and the accumulation of rate of photos carbohydrates, which is the main source of energy for the formation of reproductive organs capsules), and this helps the plant to allocate) more nutrients to develop seed size and increase as increase the the weight of 1000 seeds, as well .[oil content inside the seeds [28

The results indicated that the IAA2 + GA200 combination treatment achieved the highest ,1-number of capsules of 46.06 capsules plant seeds weight of 9.790 g, total seed yield of 1000 percentage of oil of 35.283% ,1-tons ha 3.548 while the ,1-kg ha 4.and total oil yield of 125 GR0 treatment recorded the lowest rates of ,1-g, 1.275 tons ha 6.875 ,1-plant capsules 25.95 respectively. The ,1-and 40.7 kg ha %31.930 superiority of IAA2 + GA200 treatment in productive traits may be due to IAA being an rmone that regulates cell elongation essential ho by modulating gene expression of structural polymers and activating proton transporters ATPase) to expand cell walls, while GA3 -H+) promotes the growth of stems and reproductive ate cell organs by activating enzymes that facilit elongation and tissue differentiation [19]. The interaction of IAA and GA3 may increase the plant's ability to stabilize carbohydrates and efficiently transport sugars to the capsules, increasing seed weight and oil content and ld [21]. The P15 x IAA2 + enhancing total yie GA200 interaction treatment achieved the highest number of capsules with 49.05 capsules seed weight of 10.407 g, total seed 1000 ,1-plant oil percentage of 36.090% ,1-yield of 3.822 t ha the P5 while ,1-and total oil yield of 137.9 kg ha x GR0 interaction treatment recorded the lowest ,g 6.827 ,1-averages of 25.13 capsules plant ,1-and 38.3 kg ha %31.140 ,1-t ha 1.230 .respectively

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Table (2): Effect of Plant Spacing and Some Growth Regulators on Seed and Oil Yield Parameters of Flax

Treats	CN	SN	WS	SY	OP	OY
P5	31.20	8.713	7.567	2.105	32.573	69.5
P15	36.72	8.273	8.556	2.669	34.944	94.4
LSD (0.05)	1.853	0.1813	0.0983	0.1494	0.0444	5.23
GR0	25.95	7.143	6.875	1.275	31.930	40.7
IAA2	28.18	9.823	7.315	2.028	33.858	68.8
GA200	35.64	9.118	8.265	2.697	33.963	92.7
AA2 + GA200	46.06	7.888	9.790	3.548	35.283	125.4
LSD (0.05)	2.621	0.2564	0.1391	0.2114	0.0629	7.40
P5 x GR0	25.13	7.177	6.827	1.230	31.140	38.3
P5 x IAA2	28.09	9.647	7.103	1.927	32.317	62.3
P5 x GA200	28.51	9.743	7.163	1.990	32.360	64.4
P5 x AA2 + GA200	43.07	8.287	9.173	3.274	34.477	112.9
P15 x GR0	26.78	7.110	6.923	1.319	32.720	43.2
P15 x IAA2	28.28	10.000	7.527	2.130	35.400	75.4
P15 x GA200	42.78	8.493	9.367	3.404	35.567	121.1
P15 x AA2 + GA200	49.05	7.490	10.407	3.822	36.090	137.9
LSD (0.05)	3.706	0.3626	0.1967	0.2989	0.0889	10.46

WS = Weight 1000 seed (g), SY = Seed ,(1-SN = Seed No. (Capsules ,(1-CN = Capsules No. (plant (1-OP = Oil (%), OY = Oil Yield (Kg ha ,(1-Yield (tons ha

Chemical qualities -3

The results of Table (3) showed that the plant spacing of 15 cm recorded the highest content of dry weight, total 1-total phenols 15.17 mg g dry weight, total 1-flavonoids 9.55 mg g dry weight, total 1-carotenoids 2.784 mg g

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S inhibition, antioxidant activity 62.44% ABT and free radical scavenging efficiency 66.07% compared to the 5 cm plant spacing which ,1-recorded the lowest values of 12.19 mg g ABTS %59.61 ,1-mg g 2.400 ,1-mg g 7.46 inhibition and 61.69%, respectively. The reason fact that the use of 15 may be attributed to the cm plant spacing reduces competition among plants for growth requirements facilitating better photosynthesis, thereby promoting the synthesis of phenolic and flavonoid compounds as well as carotenoids, all of which act as natural ntioxidants [15]. The generation of secondary a compounds (phenols, flavonoids, and carotenoids), which are compounds with the ability to effectively resist oxidative stress by interacting with and breaking down free radicals .[24]

e IAA2 + GA200 The results showed that th blending treatment achieved the highest content dry weight, 1-of total phenols of 16.06 mg g dry weight, 1-total flavonoids of 10.25 mg g dry weight, 1-total carotenoids of 2.960 mg g total antioxidant activity of 63.45% ABTS free radical scavenging inhibition, and efficiency of 67.58%, while

GR0 treatment had the lowest values of 10.61 dry weight, 1-dry weight, 6.42 mg g 1-mg g dry weight, 57.77% ABTS 1-mg g 2.223 inhibition and 59.03%, respectively. The al role of auxin (IAA) and physiologic gibberellins (GA3) may be due to their role in promoting vegetative growth and stimulating primary and secondary metabolism in plants, where auxin activates cell division and elongation and increases carbon flux towards metabolic pathways, while secondary gibberellins increase photosynthetic efficiency and carbohydrate metabolism, providing energy and building blocks for the synthesis of phenolic compounds, flavonoids and carotenoids. The eads to interaction between these two regulators l a synergistic effect that enhances the accumulation of secondary compounds with antioxidant activity [23]. The results showed the superiority of the P15 x IAA2 + GA200 interaction treatment as it achieved the highest dry 1-mg g 24.content of total phenols of 17 dry 1-weight, total flavonoids of 11.33 mg g dry 1-weight, total carotenoids of 3.241 mg g weight, total antioxidant activity of 64.30% ABTS inhibition and free radical scavenging efficacy of 68.80% compared to the P5 x GR0 ent with the lowest rates of interaction treatm dry 1-dry weight, 5.72 mg g 1-mg g 9.34 dry weight, 56.00% ABTS 1-weight, 2.081 mg g .inhibition and 56.45%, respectively

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Table (3): Effect of Plant Spacing and Some Growth Regulators on Antioxidant Activity Parameters of Flax

Treats	TP	TF	TC	AC	DPPH
P5	12.19	7.46	2.400	59.61	61.69
P15	15.17	9.55	2.784	62.44	66.07
(LSD (0.05	0.108	0.026	0.0107	0.036	0.015
GR0	10.61	6.42	2.223	57.77	59.03
IAA2	13.37	8.11	2.519	60.91	63.78
GA200	14.69	9.25	2.666	61.95	65.14
IAA2 + GA200	16.06	10.25	2.960	63.45	67.58
(LSD (0.05	0.153	0.037	0.0151	0.051	0.021
P5 x GR0	9.34	5.72	2.081	56.00	56.45
P5 x IAA2	11.67	7.05	2.372	59.54	61.21
P5 x GA200	12.88	7.92	2.467	60.27	62.73
P5 x IAA2 + GA200	14.88	9.17	2.679	62.61	66.36
P15 x GR0	11.88	7.12	2.366	59.54	61.61
P15 x IAA2	15.06	9.18	2.667	62.28	66.34
P15 x GA200	16.50	10.59	2.864	63.62	67.54
P15 x IAA2 + GA200	17.24	11.33	3.241	64.30	68.80
(LSD (0.05	0.216	0.052	0.0214	0.072	0.029

1-DW), TC = Total Carotenoids (mg g 1-DW), TF = Total Flavonoids (mg g 1-g TP = Total Phenol (mg (%) DW), AC = Antioxidant Activity (% ABTS inhibition), DPPH = Free Radical Scavenging

Conclusions

Adopting a 15 cm plant spacing in flax cultivation is the best option to achieve an integrated balance between vegetative growth, productivity and accumulation of bioactive compounds. Foliar spraying with IAA2 + GA200 is the most efficient treatment in roving yield components, oil content, and imp quality traits related to antioxidant activity. These treatments also have a clear role in stimulating the plant's secondary metabolic pathways, which was reflected in the high and ,concentrations of phenols, flavonoids carotenoids, which are closely related to the plant's ability to resist biotic and abiotic stresses, as well as its vital role in enhancing the

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health and nutritional value of flax. From an economic standpoint, the 15 cm plant spacing pecific competition and s-reduced intra optimized resource use efficiency, which (1-translated into higher seed yield (2.669 t ha compared to the 5 (1-and oil yield (94.4 kg ha cm spacing. Combined application of IAA2 + GA200 further boosted yield by approximately er the untreated control, representing a ov %178 effective intervention given the low cost -cost and easy availability of these growth regulators. From an environmental perspective, the use of plant growth regulators as a substitute for r inputs represents a increased chemical fertilize more sustainable approach, reducing the risk of soil salinization and nutrient leaching associated with excessive fertilizer use. The use of growth regulators can be recommended as an -to-cost and easy-environmentally friendly, low ly agricultural input by farmers, as they do app not require advanced equipment or high technical expertise. Thus, their integration into flax farming systems represents a sustainable trend to improve the quantity and quality of accumulation of production while promoting the functionally important secondary metabolic .compounds

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