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Synergistic effects of herbicides and gibberellic acid on wheat yield and quality

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Gibberellic acid (GA_3) is commercially applied to stimulate the growth and productivity of various agricultural crops. However, its impact on the yield and chemical properties of wheat under weed stress is still unclear. In this investigation, the influence of weed control (sulfosulfuron (sulfo-s), florasulam 7.5% + flumetsulam 10% (derby), pyroxsulam (pallas), and untreated check) and GA_3 (0, 100, and 200 mg/L) treatments on the narrow-leaved weed (i.e., *Avena fatua* L.) and broad-leaved weeds as well as yield and chemical properties of wheat (cv. Sakha 94) was explored. The findings showed that the wheat plants were infested by seven weed species. Such weeds were notably controlled using herbicidal treatments, particularly annual sowthistle (*Sonchus oleraceus* L.) (94.1 and 92.0%) and field binder (*Convolvulus arvensis* L.) (91.5 and 93.6%) were very highly susceptible to pallas herbicide in both seasons. Likened to control group, the application of GA_3 (especially at 200 mg/L) or pallas herbicide observably decreased the dry weight of wild oat (*Avena fatua* L.) and broad-leaved weeds, which contributed positively to the increase of plant height, No. of spikelet's/spike, 1000-grain weight, and grain yield ($P < 0.05$) in both seasons. Moreover, spraying of sulfo-s herbicide maximized spike length of wheat plants (16.0 cm) in the 2nd season, whereas plots treated with derby had the highest spike weight (7.64 and 7.17 g) and No. of grains/spike (62.0 and 58.8) in two seasons. Furthermore, the maximal grain yield was recorded following the synergistic spraying of pallas and GA_3 at 200 mg/L (7278 kg/ha in the 1st season) as well as sulfo-s and GA_3 at 200 mg/L (6935 kg/ha in the 2nd season). Relative to control, significant increases in protein (by 46.99 and 50.47%) and nitrogen content (by 46.93 and 50.54%) were also noticed after the use of derby and 200 mg/L GA_3 in 1st and 2nd season, respectively ($P < 0.05$), implying the improvement in the quality of wheat grains. Most remarkably, Pearson's correlation demonstrated that the reduction in *Avena fatua* L. and broad-leaved weeds was accountable strongly for 66 to 96% of the enhancement in yield and chemical properties of wheat under the application of herbicides and GA_3 treatments. The current findings may be very relevant in guiding farmers in the selection of suitable agronomic treatments (i.e., herbicides and GA_3) that may maximize wheat yield and quality.

Keywords Wheat, Herbicidal treatment, Gibberellic acid, Biological yield, Protein content, Correlation analysis

The global demand for wheat in human nutrition is anticipated to upsurge in the coming 2–3 decades, due to the exponential growth in human population. Wheat (*Triticum aestivum* L.) is a key staple crop for ensuring food security, which provides around 74% of dietary calories from cereal in the developed countries, 35% in the developing countries, and 41% worldwide through direct consumption[1]. Besides, it is a main source of carbohydrates and protein for human consumption; contains starch (60–90%), protein (11.0–16.5%), fat (1.5–2.0%), inorganic ions (1.2–2.0%), and vitamin E and B-complex[2]. Accordingly, resilient agronomic practices are required to maintain its future role in fighting food insecurity, hunger, and undernutrition. Wheat is cultivated over a wide range of agro-climatic conditions in the world with an area of 220.41 M ha and productivity of 3.63 ton/ha in 2023[3]. Such low productivity of wheat is mainly attributable to biotic (e.g., weeds, pathogens, and insects, etc.) and abiotic (e.g., heat, salinity, and drought) factors. Among them, weeds are very serious competitor of wheat for nutrients, light, water, and carbon dioxide[4], causing a substantial reduction in wheat yield by 37–50%[5]. These losses have the potential to overshadow the damages stimulated by pests, pathogens, and adverse climatic conditions[6]. Apart from reducing the wheat production, weeds also increase harvesting costs

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and decrease quality of wheat grains[7]. In that sense, controlling the weeds during wheat growth could efficiently minimize its production losses. Earlier reports indicated that herbicidal application is a good option for the effectual management of weeds owing to the scarce labour and lower feasibility of manual or mechanical weeding in wheat[8]. Besides, chemical control is faster, cheaper, and provides better control of weeds over mechanical and manual weeding[9]. Nonetheless, farmers are usually not aware of the suitable utilization of herbicides. They use the same chemical groups for years in the same field which may quickly induce the development of herbicide-resistant weeds. For instance, literature showed that *Phalaris minor* had resistance against isoproturon[10]. To overcome such problem, some alternate herbicides (e.g., sulfosulfuron and clodinafop-propargyl) were recommended to control the isoproturon resistant *Phalaris minor* in wheat. Recently, these herbicides, however, were found ineffective to control this weed due to the continuous application of such herbicides[11]. Furthermore, the repeated use of these herbicides has also led to a tremendous increase in density of broad-leaved weeds e.g., *Anagallis arvensis* L., *Chenopodium album* L., *Convonvulus arvensis* L., etc. The choice of appropriate herbicides is therefore imperative to overcome the risk of development of herbicide resistance against weeds in wheat.

On the other hand, gibberellic acid (GA_3) is one of the most important plant growth regulators used for agronomic and scientific research[12]. GA_3 shows positive influences on seeds germination, stem elongation, leaf expansion, and flowering and trichome initiation[13], which directly contributes to the augmentation of the plant growth as well as seed yield and quality. It also enhances the tolerance of various plants against the environmental stresses by regulating the antioxidant enzyme activity and reducing the extreme amount of intracellular reactive oxygen species (ROS) under stressful conditions[14]. Previously, Islam et al.[15] noticed that the application of GA_3 remarkably augmented the plant height (89.9 cm), No. of spikes/plant (4.1), No. of spikelet's/spike (19.0), filled grains/spike (30.4), spike length (17.0 cm), weight of 1000-grain (45.5 g), straw yield (4.6 t/ha), grain yield (3.9 t/ha), and biological yield (8.5 t/ha) reference to control group. Similarly, earlier study illustrated that the foliar spraying of GA_3 (at 60 mg/L) significantly maximized weight of 1000-grain, grain yield, and harvest index[16].

Although some investigations indicate that post-emergence herbicides and GA_3 have already been used to augment the yield of agricultural crops, however very few studies have previously been reported to investigate their synergistic effects on the dry weight of *Avena fatua* L. and broad-leaved weeds as well as yield and chemical characteristics of wheat. In this context, this observation aimed to explore the effect of sequential application of three herbicides (sulfosulfuron, florasulam 7.5% + flumetsulam 10%, and pyroxsulam) and GA_3 (0, 100, and 200 mg/L) on the dry weight of *Avena fatua* L. and broad-leaved weeds. The changes in the yield and its components as well as chemical traits of wheat were also examined. Besides, the interrelationship among the dry weight of *Avena fatua* L. and broad-leaved weeds as well as yield and chemical traits of wheat was established using Pearson's correlation and Principal Component Analysis.

Materials and methods

Experimental site and design

The experiment was undertaken in split plot-layout using 10.50 m^2 experimental plots with three replicates during the two wheat growing seasons of 2021/2022 and 2022/2023 at the Research and Experimental Station, Faculty of Agriculture, Benha University, Egypt (31.10° E longitude and 30.45° N latitude). The main-plots involved four weed control treatments, whereas the sub-plots consisted of the foliar application of wheat with GA_3. The location of the investigational site is portrayed in Fig. 1. The experiment was carried out in loamy clay soil with high organic matter (OM). The soil samples were collected using an auger from the experimental plots at two various depths of 0–20 cm and 20–40 cm before the sowing of wheat. Mechanical and chemical characteristics of soil samples were analyzed as previously outlined by Piper[17] and Jackson[18], and the outcomes are listed in Table 1. Besides, Fig. 2 displays the climatic data (i.e., maximum and minimum temperature and relative humidity) for the experimental site during two seasons.

Agronomic practices

Trial field was ploughed, pulverized, and thereafter leveled to provide smooth bed for seeds. The plot area was 10.5 m^2 with a 3.50 m length and 3.00 m width. Wheat seeds (cv. Sakha 95) were purchased from Field Crops Research Institute, Agricultural Research Center (ARC), Ministry of Agriculture and Land Reclamation, Egypt. The seeds were broadcasted (at a rate of 143 kg/ha) on November 25th and 22nd in 2021/2022 and 2022/2023, respectively, and afterward irrigated immediately. The irrigation was continued during the growing seasons according to the plant necessity. Nitrogen fertilizer was broadcasted before the first irrigation (with equal amounts for all the plots) at a rate of 179 kg/ha in the form of ammonium nitrate (33.5%). Wheat plants were harvested on May in both growing seasons when the plants reached maturity.

Experimental treatments

The performance of three herbicides (i.e., sulfosulfuron, florasulam 7.5% + flumetsulam 10%, and pyroxsulam) as post-emergence was evaluated and compared with control to determine weed control efficacy. The composition and application rate of these herbicides are listed in Table 2. The herbicides were sprayed at tillering stage (usually starts when the plant has three or four leaves) of wheat plants after 30 DAS (days after sowing) using manual pressure sprayer with a rate of 476 L_{water}/ha. Sulfosulfuron (75%WG) was purchased from Indo Crop Solutions Pvt. Ltd. (Delhi, India). Florasulam 7.5% + flumetsulam 10% (17.5% SC) was bought from Zhejiang Zhongshan Chem. Ind. Co. Ltd. (Zhejiang, China). Pyroxsulam (4.5% OD) was acquired from Corteva Agriscience Co. Ltd. (South Africa).

The wheat plants were sprayed at booting stage (after 45 DAS) with gibberellic acid (GA_3—10%) at three concentrations (0 (only distilled water), 100, and 200 mg/L). The spraying of GA_3 on wheat plants was performed in the early morning. The GA_3 (2, 4a, 7-trihydroxy-1-methyl-8-methylenegibb-3-ene-1,10-carboxylic acid 1- 4 lactone) used in this experiment was acquired from Zhangjianang Kangyuan New Mat. Co. Ltd. (China).

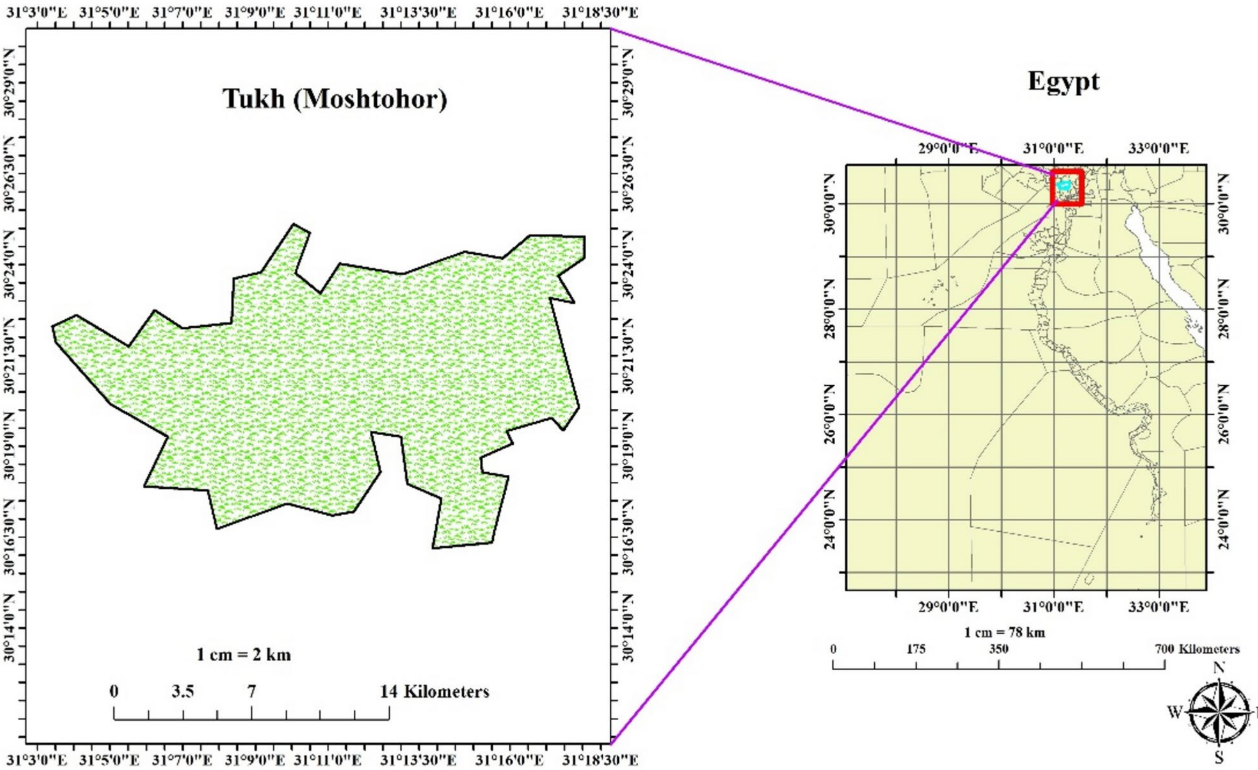

Fig. 1. Location of the experimental site [constructed by ArcGIS 10.8 software (Esri Inc., California, USA)].

Properties	1st season		2nd season	
	0–20 cm	20–40 cm	0–20 cm	20–40 cm
Mechanical parameters				
Coarse sand %	7.23	6.55	8.58	7.09
Fine sand %	26.5	25.9	25.9	24.9
Silt %	13.7	12.9	13.6	13.0
Clay%	52.6	54.7	51.9	55.0
Textural class*	Clay loam		Clay loam	
Chemical parameters				
pH	6.93	7.20	6.50	7.00
EC (dSm^{-1})	0.57	0.59	0.69	0.79
Organic matter %	1.50	2.30	1.64	2.60
Soluble cations (mmolcL^{-1})				
Ca++	2.80	1.50	3.02	2.13
K+	0.90	1.31	0.85	1.12
Soluble anions (mmolcL^{-1})				
Cl^-	1.60	2.03	1.50	2.30
CO_3^{--}	0.00	0.00	0.00	0.00
HCO_3^-	2.44	1.50	2.60	1.70
SO_4^{--}	4.10	3.80	4.50	3.65

Table 1. Mechanical and chemical properties of the investigational sites at 0–20 cm and 20–40 cm during two seasons.

Weeds assessment

Weeds were manually pulled from 1 m^2 of each experimental plot (with three representative replicates) after heading stage of wheat plants (at 70 DAS). The collected weeds were identified into species and classified into two categories (narrow-leaved weed (*Avena fatua* L.) and broad-leaved weeds). The weeds were air-dried for 5

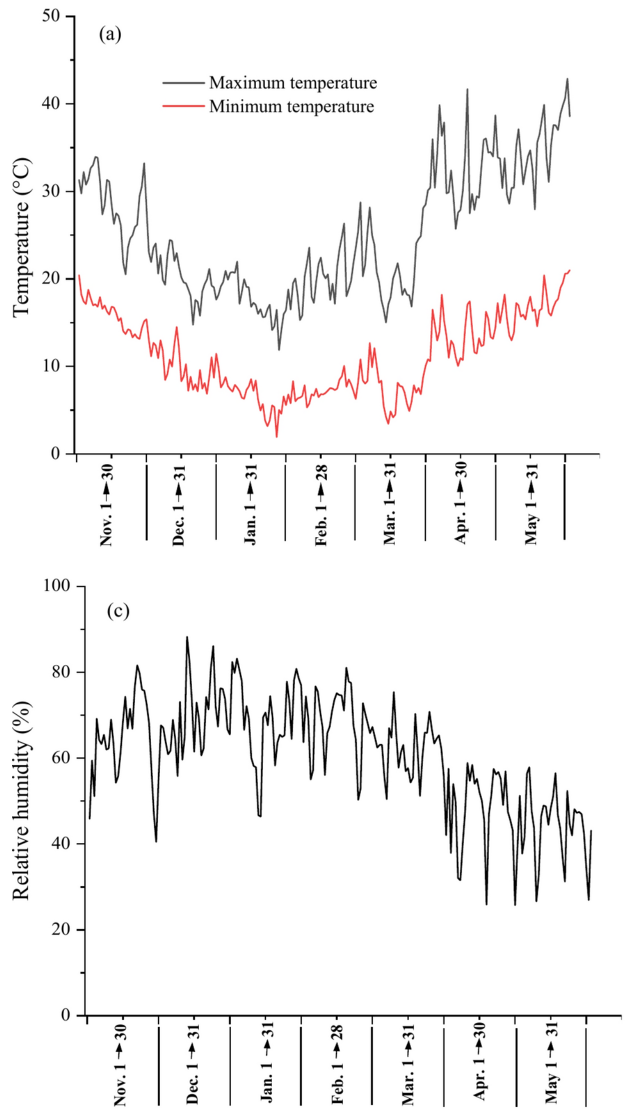

Fig. 2. Climatic data for the experimental site during two seasons*Source* Central Lab for Agriculture Climate, Agriculture Research Center, Ministry of Agriculture and Land Reclamation, Egypt.

Commercial name	Chemical name	Composition	Application rate	Weed control: Annual narrow leaves	Weed control: Annual broad leaves	Application
Sulfo-s	Sulfosulfuron	75% WG	47.6 g/ha	✓		Systematic selective post-emergence after 30 DAS
Derby	Florasulam 7.5% + flumetsulam 10%	17.5% SC	71.4 cm^3/ha		✓	
Pallas	Pyroxsulam	4.5% OD	381 cm^3/ha	✓	✓	

Table 2. The commercial name, chemical name, composition, application rate, weed control, and application of herbicides used in the current study.

days and afterward oven-dried (70 °C for 72 h). Then, the dry weight of *Avena fatua* L. and broad-leaved weeds was assessed.

Weed control efficacy (WCE)

WCE was assessed following the procedure outlined by Shahabuddin et al.[19] as follows:

$$WCE = \frac{DWC - DWT}{DWC} \times 100$$

where DWC and DWT represent dry weight of weeds in untreated and treated plots (g), respectively.

Susceptibility of different weed species to the treatments were categorized into seven groups as follows[20]: completely susceptible (CS) = 100%, very highly susceptible (VHS) = 90–99%, highly susceptible (HS) = 70–89%, moderately susceptible (MS) = 40–69%, poorly susceptible (PS) = 20–39%, slightly susceptible (SS) = 1–19%, and completely resistant = zero.

Yield characteristics

Yield characteristics of wheat were examined as previously detailed[21]. Wheat plants (with three replications), at maturity, were randomly selected from 1 m^2 in each plot as a representative of whole plot to determine the following parameters:

(a) Plant height was estimated from the base to the top of spike using a meter measure tape.
(b) Spike length was measured by a ruler.
(c) No. of spikelet's/spike was counted from randomly selected spikes.
(d) No. of grains/spike: No of grains was initially quantified with the aid of an Automatic Seed Counter (GA-234 A, Green Agritech Equipment Ltd., India) from the chosen spikes and thereafter averaged to determine the No. of grains/spike.
(e) Spike weight (g) was measured for the chosen spikes utilizing a Digital Balance (YHC weighing excellence, Wonderscales, China).
(f) Weight of 1000-grain (g): No of 1000-grain were counted by an Automatic Seed Counter, and subsequently weighed using a Digital Balance.
(g) Grain, straw, and biological yield of wheat plants were estimated from each plot and afterward converted to kg/ha.

Chemical analysis

Chemical analysis was conducted to quantify the content of nitrogen, potassium, and protein of wheat grains. Nitrogen and protein content were determined using a Kjeldahl method[22]. Before analysis, wheat grains were milled to pass through a 0.50 mm sieve and dried in oven at 70 °C for 48 h. The respective samples (0.20 g) were digested utilizing sulfuric and perchloric acids in heat-resistant tubes at 380 °C. Thereafter, the resulting solutions were diluted to 100 mL by distilled water. Aliquots of diluted solutions (10 mL) were then distilled with sodium hydroxide (20 mL) to convert the ammonium salt to ammonia. The ammonia obtained by distillation was trapped in boric acid (4%) and subsequently titrated using hydrochloric acid. Nitrogen and protein content were computed as follows:

$$N\,(\%) = \frac{(V_1 - V_2) \times C \times 0.014}{m \times (V_3/100)} \times 100$$

$$Proteincontent\,(\%) = N \times f$$

where N represents the nitrogen content (%); V_1 represents the volume of hydrochloric acid consumed by ammonium borate solution (mL); V_2 represents the volume of hydrochloric acid consumed by blank (mL); V_3 represents the volume of digest solution used for the distillation divided by the standardized volume of the digest solution; C represents the concentration of hydrochloric acid (mol/L); m represents the weight of sample (g); and f represents the nitrogen conversion factor (5.70).

For potassium content, samples were milled, digested, and diluted as aforementioned. Standard solution was prepared by dissolving potassium chloride in distilled water and then diluted to different concentrations (from 10 to 100 ppm). Thereafter, samples were quantified using a flame-photometer according to the method of Brown and Lilliland[23].

Statistical analysis

The obtained data were subjected to analysis of variance, according to Snedecor and Cochran[24]. Tukey's post-hoc was employed to compare the differences among means at $P < 0.05$ using MSTATC software (MSTAT-C with MGRAPH V-21). Pearson's correlation and Principal Component Analysis (PCA) were performed using OriginPro-2024 software (OriginLab, Northampton, USA).

Results and discussion

Weed control efficacy

The common name, family name, and life cycle for *Avena fatua* L. and broad-leaved weeds associated with wheat during the two growing seasons are listed in Table 3. Six broad-leaved weeds species including lambs quarter (*Chenopodium album* L.), asthma-plant (*Euphorbia hirta* L.), small-flowered mallow (*Malva parviflora* L.), blue pimpernel (*Anagallis arvensis* L.), annual sowthistle (*Sonchus oleraceus* L.), and field binder (*Convolvulus*

Categories	Scientific name	English name	Family	Life cycle
Broad-leaved weeds	*Chenopodium album* L.	Lambs quarter	Chaenopodiaceae	Annual
	Euphorbia hirta L.	Asthma-plant	Euphorbiaceae	Annual
	Malva parviflora L.	Small-flowered mallow	Malvaceae	Annual
	Anagallis arvensis L.	Blue pimpernel	Primulaceae	Annual
	Sonchus oleraceus L.	Annual sowthistle	Asteraceae	Annual
	Convolvulus arvensis L.	Field binder	Convolvulaceae	Perennial
Narrow-leaved weed	*Avena fatua* L.	Wild oat	Poaceae	Annual

Table 3. Common name, family name, and life cycle for broad- and narrow-leaved weeds associated with wheat.

	Broad-leaved weeds						Narrow-leaved weed
Treatment	*Chenopodium album* L.	*Euphorbiahirta* L.	*Malva parviflora* L.	*Anagallis arvensis* L.	*Sonchus oleraceus* L.	*Convolvulus arvensis* L.	*Avena fatua* L.
1st season							
Derby	71.1 (HS)	69.4 (MS)	76.1 (HS)	78.7 (HS)	94.5 (VHS)	82.1 (HS)	17.0 (SS)
Sulfo-s	25.4 (PS)	14.8 (SS)	19.8 (PS)	22.6 (PS)	30.2 (PS)	26.0 (PS)	79.2 (HS)
Pallas	77.2 (HS)	82.0 (HS)	84.2 (HS)	86.1 (HS)	94.1 (VHS)	91.5 (VHS)	84.0 (HS)
2nd season							
Derby	71.0 (HS)	69.8 (HS)	81.6 (HS)	82.2 (HS)	94.1 (VHS)	78.0 (HS)	16.4 (SS)
Sulfo-s	19.1 (PS)	26.0 (PS)	11.7 (SS)	17.2 (SS)	20.6 (PS)	24.0 (PS)	87.2 (HS)
Pallas	73.1 (HS)	77.7 (HS)	79.7 (HS)	91.5 (VHS)	92.0 (VHS)	93.6 (VHS)	91.2 (VHS)

Table 4. Susceptibility score (%) of weeds to herbicides after 70 DAS of wheat.

arvensis L.) were observed in experimental plots during both successive seasons, whilst one grassy weed (*Avena fatua* L.) was found.

Further, results illustrated that *Chenopodium album* L., *Euphorbia hirta* L., *Anagallis arvensis* L., and *Avena fatua* L. were highly susceptible (HS) with scores of ~ 77 –86% by pallas herbicide in the first season, whereas *Sonchus oleraceus* L. *and Convolvulus arvensis* L. were very highly susceptible (VHS) with scores from ~ 92 to 94% in both seasons (Table 4). On the other hand, *Chenopodium album* L., *Sonchus oleraceus* L., and *Convolvulus arvensis* L. were poorly susceptible (PS) with range from ~ 19 to 30% by sulfo-s herbicide in the two seasons. Furthermore, the outcomes indicated that pallas herbicide effectively controlled all weeds (except *Malva parviflora* L. in the 2nd season and *Sonchus oleraceus* L. in both seasons) compared to other herbicidal treatments, implying that the application of pallas herbicide efficiently controls both *Avena fatua* L. and broad-leaved weeds. Besides, the highest WCE (94.5 and 94.1%) was observed for *Sonchus oleraceus* L. following the application of derby herbicide in the first season and second season, respectively. Implicit from this is that, *Sonchus oleraceus* L. was very highly susceptible to derby treatment over other herbicides. This observation was possibly due to the effective weed control under the application of herbicides at early growth stage and removing both early and late emerging weeds, which resulted in low weed density[25,26]. This may also be ascribed to the high efficiency of weed control treatments which subsequently led to reduction of weeds-wheat competition[27,28]. Remarkably, *Avena fatua* L. was slightly susceptible (17.0 and 16.40% in the 1st and 2nd season, respectively) by derby herbicide, confirming its ultra-low impact on the narrow-leaved weed. Further, reference to other herbicides (i.e., derby and pallas), sulfo-s herbicide resulted in the minimal WCE for broad-leaved weeds in both seasons. To end with, the application of pallas and derby herbicides effectively controlled all broad-leaved weeds, whereas a remarkable inhibition in the growth of *Avena fatua* L. was noticed following the foliar spraying of pallas and sulfo-s. Actually, such herbicides were sprayed at high relative humidity and low temperature which delayed the drying of spray droplets. This may have increased the absorption, penetration, and translocation of herbicides within the weeds, resulting in the inhibition of growth and development of weeds, thereby maximizing the herbicide activity and efficacy[29].

Dry weight of *Avena fatua* L. and broad-leaved weeds

Effect of weed control treatments

Herbicidal treatments led to a significant effect ($P < 0.05$) on the two classes of weeds (*Avena fatua* L. and broad-leaved weeds) (Table 5). The results indicated that the herbicidal practices had significant influence on decreasing the dry weight of *Avena fatua* L. and broad-leaved weeds in two growing seasons. The post-emergence application of pallas (pyroxsulam) herbicide at 30 DAS was found to be the most efficient treatment in reducing the weight of *Chenopodium album* L., *Euphorbia hirta* L., *Anagallis arvensis* L., and *Convolvulus arvensis* L. followed by derby (sulfosulfuron) and sulfo-s (florasulam 7.5% + flumetsulam 10%) compared to control. Notably, *Malva parviflora* L. (in the 2nd season) and *Sonchus oleraceus* L. (in both seasons) had the lowest weight following the spraying of derby, which was not statistically different with that sprayed with pallas ($P > 0.05$). Furthermore, pallas and sulfo-s efficiently controlled the growth of *Avena fatua* L. during two growing seasons compared with other

Treatment	Broad—leaved weeds (g/m²)						Narrow-leaved weed (g/m²)
	Chenopodium album L.	*Euphorbia hirta* L.	*Malva parviflora* L.	*Anagallis arvensis* L.	*Sonchus oleraceus* L.	*Convolvulus arvensis* L.	*Avena fatua* L.
1st season							
Control	10.5a	8.57a	12.3a	17.6a	19.3a	21.5a	13.9a
Derby	3.03c	2.62b	2.95c	3.75c	1.07c	3.84c	11.5b
Sulfo-s	7.83b	7.30a	9.89b	13.6b	13.5b	15.9b	2.89c
Pallas	2.39c	1.54b	1.94c	2.45c	1.14c	1.84c	2.22c
2nd season							
Control	9.71a	10.7a	16.2a	19.3a	21.2a	20.4a	17.5a
Derby	2.82b	3.23c	2.90b	3.44c	1.24c	4.49c	14.6b
Sulfo-s	7.86a	7.92b	14.3a	16.0b	16.8b	15.5b	2.23c
Pallas	2.61b	2.39c	3.21b	1.64c	1.69c	1.30c	1.54c

Table 5. Effect of weed control treatments on dry weight of annual weeds (g/m²) at 70 DAS of wheat.

GA_3 (mg/L)	Broad-leaved weeds (g/m²)						Narrow-leaved weed (g/m²)
	Chenopodium album L.	*Euphorbia hirta* L.	*Malva parviflora* L.	*Anagallis arvensis* L.	*Sonchus oleraceus* L.	*Convolvulus arvensis* L.	*Avena fatua* L.
1st season							
0	7.53a	7.54a	9.21a	12.5a	11.2a	13.3a	10.7a
100	5.78b	4.39b	6.58b	8.92b	8.39b	10.2b	7.00b
200	4.50c	3.09c	4.54c	6.58b	6.69c	8.88b	5.25c
2nd season							
0	7.53a	9.45a	14.1a	14.7a	12.6a	13.2a	11.8a
100	5.20b	5.60b	7.96b	10.2b	10.6b	9.88b	9.40b
200	4.53b	3.10c	5.43c	5.41c	7.51c	8.23b	5.77c

Table 6. Effect of gibberellic acid on dry weight of *Avena fatua* L. and broad-leaved weeds (g/m²) at 70 DAS of wheat.

treatments, thereby minimizing the dry weight of such weed. This decrease may be due to the repressive impacts of herbicides on the growth and development of weeds. Also, this was possibly linked to the consequence of herbicides activeness to its effective weed controlling ability to have a lowest weed density which drastically minimized the dry weight of weeds[21]. Reduction in dry weight of weeds following different herbicides were accompanied by a greatly increase in the chlorophyll contents of wheat leaves as well as increase in wheat yield[30]. The superiority of these treatments in controlling weeds could be attributable to the continuous destroying effect of the use of herbicides during vegetative growth of weeds. Similar results were also obtained by Mekky et al.[31].

Effect of gibberellin treatment

Table 6 shows the effect of foliar spraying of gibberellin on the dry weight of *Avena fatua* L. and broad-leaved weeds (*Chenopodium album* L., *Euphorbia hirta* L., *Malva parviflora* L., *Anagallis arvensis* L., *Sonchus oleraceus* L., and *Convolvulus arvensis* L.). A remarkable decrease in the dry weight of *Avena fatua* L. and broad-leaved weeds was recorded ($P < 0.05$) subsequent to the spraying of GA_3 at different concentrations (100 and 200 mg/L) likened to plots treated with distilled water only (i.e., without GA_3) in both seasons. Importantly, the plots sprayed with GA_3 at 200 mg/L possessed significantly lower weight of *Euphorbia hirta* L., *Malva parviflora* L., *Sonchus oleraceus* L., and *Avena fatua* L. compared to that treated with 100 mg/L of GA_3. Deducing from this is that, GA_3 had a positive effect on the inhibition of the growth of weeds (i.e., narrow- and broad-leaved weeds). This outcome was principally attributable to the rapid growth of wheat plants following the spraying of GA_3[32], especially at 200 mg/L, thereby significantly impairing the growth of weeds due to smothering. Such observation was consistent with the plant height outcomes. However, there were no significant variations between two concentrations of GA_3 (100 and 200 mg/L) on *Convolvulus arvensis* L. (in two seasons), as well as *Anagallis arvensis* L. and *Chenopodium album* L. (in the 1st and 2nd season, respectively).

Effect of the interaction between weed control and gibberellin treatments

Figure 3 exhibits that the dry weight of *Avena fatua* L. and broad-leaved weeds in both growing seasons (2021/2022 and 2022/2023) was significantly affected by the synergistic application of herbicide and GA_3 treatments relative to control plots. The results revealed that pallas herbicide and foliar spray with GA_3 at high concentration (200 mg/L) caused substantial decreases ($P < 0.05$) in the dry weight of *Avena fatua* L. (Fig. 3g)

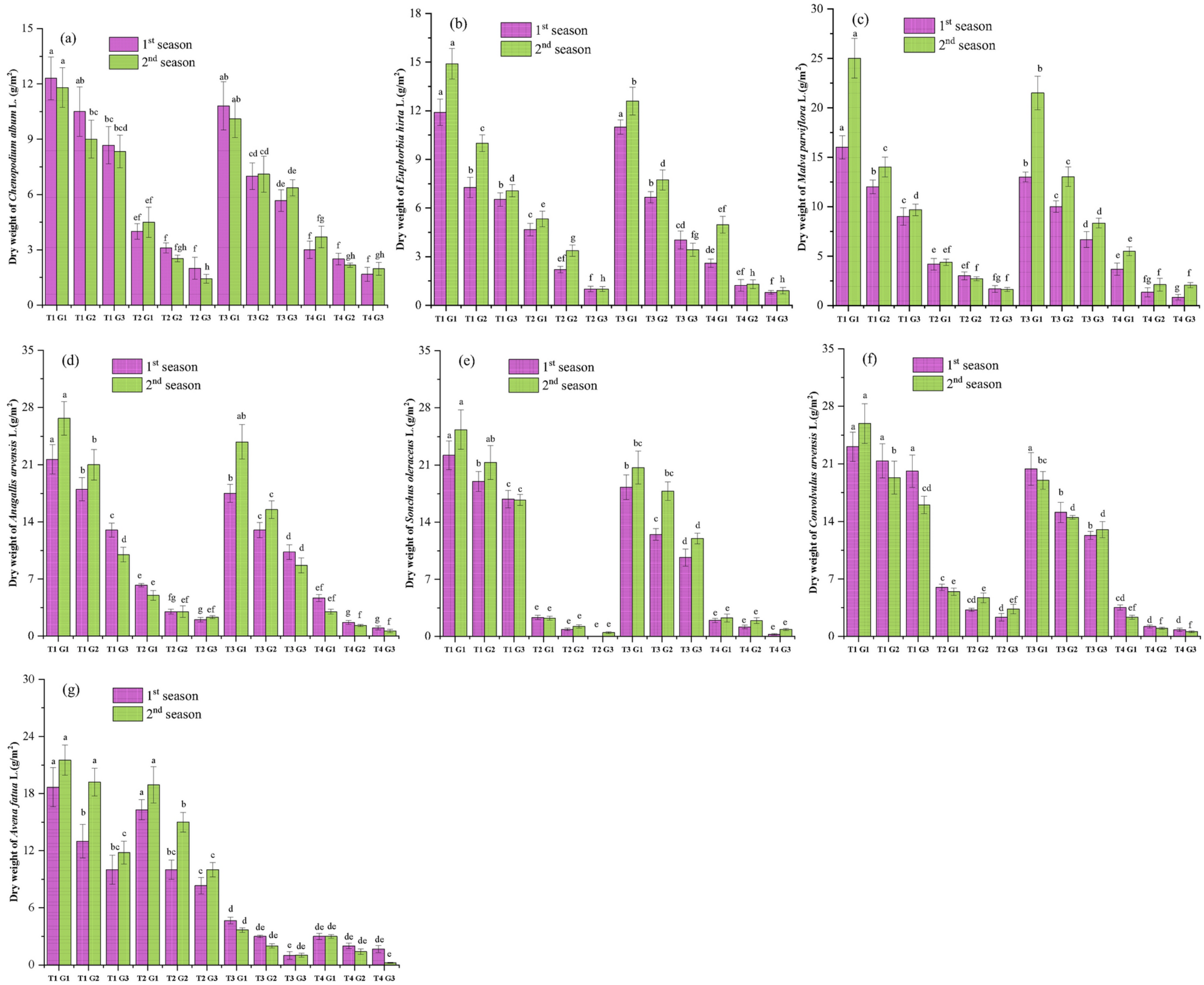

Fig. 3. Effect of weed control treatments and gibberellic acid on dry weight of *Chenopodium album* L. (**a**), *Euphorbia hirta* L. (**b**), *Malva parviflora* L. (**c**), *Anagallis arvensis* L. (**d**), *Sonchus oleraceus* L. (**e**), *Convolvulus arvensis* L. (**f**), and *Avena fatua* L. (**g**) at 70 DAS of wheat. T_1 = un-weed group, T_2 = derby, T_3 = sulfo-s, T_4 = pallas, G_1 = 0 mg/L GA_3, G_2 = 100 mg/L GA_3, and G_3 = 200 mg/L GA_3.

and broad- leaved weeds (Fig. 3a–f) in both seasons. This was mostly attributed to the inhibition of acetolactate synthase production, a primary enzyme that catalyzes the synthesis of the branched essential amino acids which are required for the process of cell division[33]. This led to the mortality of the most weeds, resulting in the decrease of dry weight of weeds compared to the control[34]. Inferring from this is that, the interaction between pallas herbicide and GA_3 was effective in inhibiting the growth of both *Avena fatua* L. and broad-leaved weeds, and thus impaired dry matter accumulation in weeds. Besides, the spraying of pallas and derby (at 0 mg/L GA_3) led to the inhibition in the growth of all broad-leaved weeds (*Chenopodium album* L., *Euphorbia hirta* L., *Malva parviflora* L., *Anagallis arvensis* L., *Sonchus oleraceus* L., and *Convolvulus arvensis* L.) (Fig. 3a–f) in both seasons reference to sulfo-s herbicide ($P < 0.05$), which contributed to the reduction in their dry weights. The observed outcomes imply the inhibition of electron transport in photosynthesis II in the mentioned weeds following the application of derby herbicide. Moreover, wheat plants are commonly infested by wild oat (*Avena fatua* L.), which negatively impacts their growth, yield, and quality. The analysis showed that there were no significant variations between pallas and sulfo-s on dry weight of *Avena fatua* L. under varied GA_3 concentrations.

Remarkably, an increase in dry weight of *Avena fatua* L. (16.3 and 18.9 g in the 1st and 2nd season) was noted after the application of derby herbicide at 0 mg/L GA_3, respectively, which was statistically different from the other herbicidal treatments (i.e., sulfo-s and pallas) under same concentration of GA_3 (0 mg/L). Nonetheless, no significant variation ($P > 0.05$) was observed between derby and control group for the dry weight of *Avena fatua* L. at 0 mg/L GA_3. This might be due to the significant inhibition of broad-leaved weeds following derby treatment, providing an opportunity for *Avena fatua* L. to uptake the available resources with larger amount due to the reduction in competition, and thereafter augmented its dry weight compared with other herbicidal treatments. Deducing from this is that, derby herbicide effectively controlled the broad-leaved weeds, whereas a little inhibition was detected in narrow weed (i.e., *Avena fatua* L.). Furthermore, sulfo-s herbicide observably reduced the dry weight of *Avena fatua* L. compared to derby at different GA_3 concentrations ($P < 0.05$).

Wheat yield and its components

Effect of weed control treatments

The effect of herbicides treatment resulted in a significant increase in wheat yield and its components in 2021/2022 and 2022/2023 seasons (Table 7). In two seasons, all herbicides caused significant enhancement in spike weight, plant height, No. of spikelet's/spike, weight of 1000-grain, No. of grain/spike relative to control ($P < 0.05$). Plant height of the treated plots, observably after the application of pallas and derby ($P < 0.05$), increased by 3.37–7.21% in two growing seasons over the control group. The increase in the height of wheat plants was possibly due to better weed suppression at proper time, resulting in maximum utilization of water and nutrients by the crop during both seasons[35]. The observed reduction could be attributed to the negative effect of weeds competition on the growth and/or development of wheat plants[36]. The tallest plants were realized in the plots sprayed with pallas herbicide (111 and 113 cm in two seasons) which was statistically similar with that sprayed with derby ($P > 0.05$), while shortest plants were found in the weedy plots. Moreover, the findings show that the spike length increased in the both season over the un-weeded group after herbicides treatment ($P > 0.05$). Maximum value was obtained by spraying of derby herbicide (13.6 cm) and there was no significant variation between all weed control treatments in the first season, however, sulfo-s herbicide caused a notable increase of spike length (15.96 cm) in the second year over other treatments ($P > 0.05$). Observably, the shortest spikes were found (12.6 and 13.0 cm) in un-weeded plots in both seasons. Implicit from this is that, herbicides application improved spike length as a result of timely and efficiency of weeds control which resulted in higher nutrients accessibility to crop plants[37]. Also, Zakariyya et al.[38] reported that the integrated weed control strategies such as herbicides treatment significantly affected growth and yield attributes (including spike length) of wheat.

Table 7 exhibits the influence of various herbicidal treatments on the No. of spikelet's/spike of wheat plants. Reference to control, the results showed non-significant ($P > 0.05$) effect of three herbicides on the No. of spikelet's/spikes of wheat in both seasons. The highest values (23.2 and 21.9) were documented under pallas herbicide, followed by sulfo-s, derby, and control over the two seasons. These investigations were mostly linked to the removal of weeds, which maximized the uptake of mineral nutrients by wheat plants, and consequently formed more spikelet's/spike. Also, no significant variations were noticed between all weed control treatments on spike weight (Table 7). The heaviest spikes (7.64 and 7.17 g) were recorded after the use of derby herbicide, whereas the slightest spikes (5.44 and 5.22 g) were observed for control in both growing seasons. Further, the highest No. of grains/spike was recorded in plots treated with derby herbicide (Table 7). Un-weeded plants, however, possessed a lowest No. of grains/spike. This was probably due to better weed control in treated plots with various herbicides which provided a favorable environment for plants to effectively utilize natural resources and thereafter produced a large No. of grains/spike. Also, the significantly increased No. of grains might be associated with simply available growth factors (nutrient, water, and light) for plants that retained higher net assimilation rate without competition of weeds. This result was in agreement with the observations of Alvi et al.[39] and Hameed et al.[40], who found that the herbicidal application significantly enhanced No. of grains/spike of wheat reference to control. Weight of 1000-grain is an important factor that can directly affect grain yield. Table 7 illustrated that the herbicidal treatments had considerable effects on weight of 1000-grain of wheat. However, among treatments, the heavier grains (56.0 and 55.1 g) were recorded in plots sprayed with pallas herbicide, whilst weedy check produced lighter (43.6 and 44.2 g) weight in two growing seasons. Similarly, previous reports displayed that the application of herbicides (with pallas and sulfo-s) substantially augmented the weight of 1000-grain of wheat over control[41,42]. Besides, plots sprayed with derby herbicide was statistically at par with those treated by sulfo-s herbicide. The heavier grains observed in herbicides treated plots were mainly due to accessibility of more resources including nutrients as a result of suppressed weeds.

Moreover, statistical analysis shows that the mean wheat grain yield was substantially affected by diverse weed management treatments. The greatest grain yield (6359 and 5921 kg/ha) was noted in pallas herbicide (Fig. 4a). The significant increase in wheat grain yield under the application of herbicides was reasonable because wheat plants were free from weeds, which augmented the yield traits including No. of grains/spike and 1000-grain weight and thus improved grain yield. The observed outcomes were buttressed by the results of WCE and dry weight of *Avena fatua* L. and broad-leaved weeds in this study. These results were in accordance with the finding of Bharat et al.[43] who noticed that maximum wheat yield was documented in weed-free treatment. Also, Shaban et al.[44] recorded a decrease in wheat yield due to the competition of grassy, broad-leaved, and total weeds. Different weed control treatments in respect to straw yield showed significant difference at $P < 0.05$ (Fig. 4b). The straw yield observed under pallas application (7573 and 8075 kg/ha) was notably higher than that

	Plant height (cm)		Spike length (cm)		No. of spikelet's/spike		Spike weight (g)		No. of grains/spike		Weight of 1000-grain (g)	
Treatment	1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season
Control	103b	105b	12.6a	13.0a	20.2b	16.1b	5.44b	5.22b	45.7c	41.5c	43.6c	44.2c
Derby	110a	111a	13.6a	14.6a	22.2a	19.9a	7.64a	7.17a	62.0a	58.8a	55.7a	54.8ab
Sulfo-s	107ab	109ab	13.0a	16.0a	22.2a	21.2a	7.60a	6.89a	55.4b	48.8b	52.1b	51.2b
Pallas	111a	113a	12.8a	14.3a	23.2a	21.9a	7.44a	6.83a	59.9ab	55.7a	56.0a	55.1a

Table 7. Effect of weed control treatments on yield components of wheat.

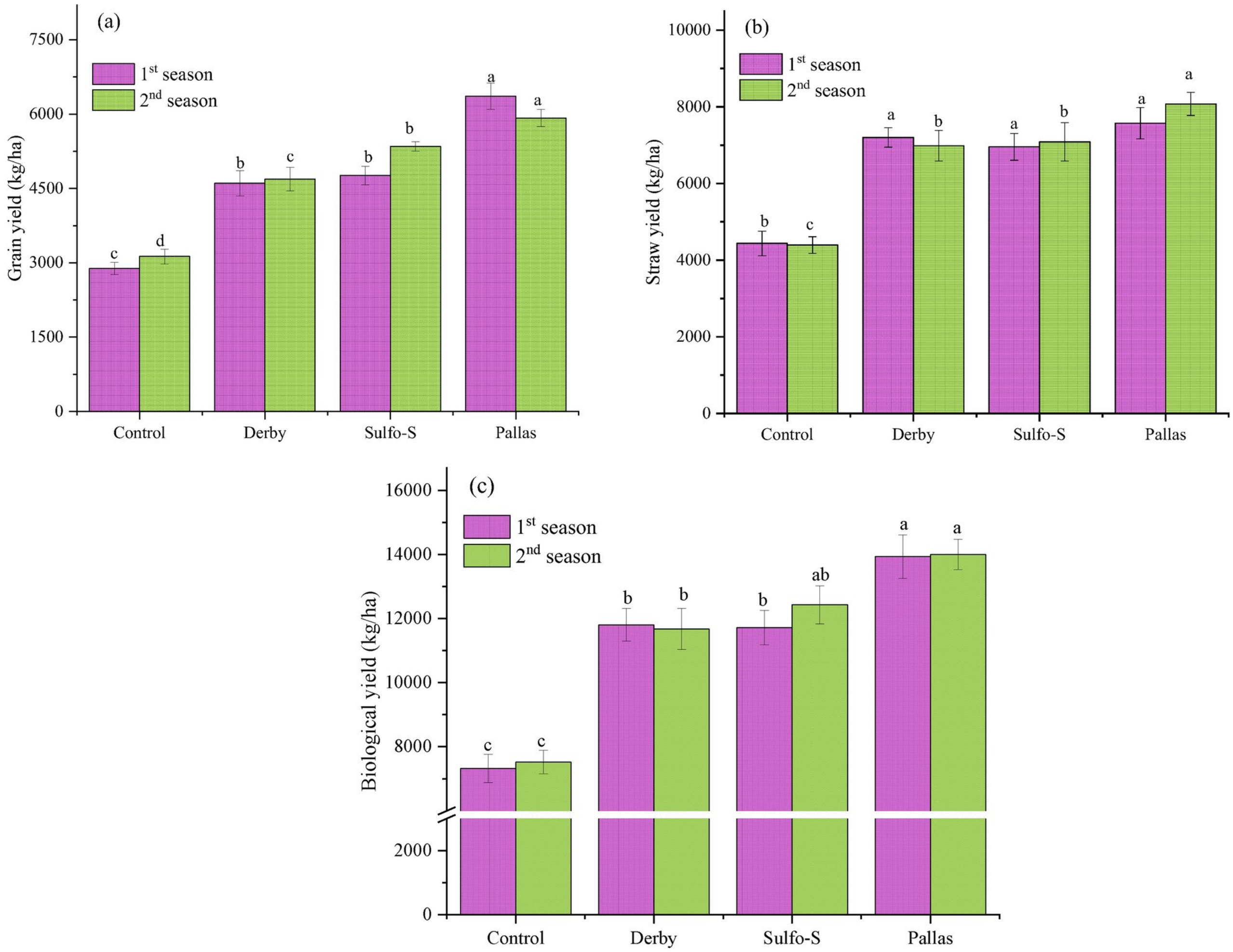

Fig. 4. Effect of weed control treatments on grain (**a**), straw (**b**), and biological (**c**) yield of wheat.

of sulfo-s (6957 and 7085 kg/ha), derby (7202 and 6983 kg/ha), and control (4436 and 4394 kg/ha) during two seasons. Such increase was probably associated with the reduction in weed-wheat competition following the application of pallas (over other herbicides and control), providing more space for wheat plants to grew45, and thus increased straw yield. Furthermore, biological yield increased respectively by 38.0, 37.5, and 47.4% (in the 1st season) and 35.6, 39.5, and 46.3% (in the 2st season) after the use of derby, sulfo-s, and pallas herbicides relative to control (Fig. 4c). Deducing from this is that, the utilization of herbicides may have provided a plenty chance to use available resources from the environment which eventually increased the biological yield[25]. However, there were no significance differences between derby and sulfo-s herbicides ($P > 0.05$). Spraying pallas herbicide achieved highest biological yields (13,933 and 13,997 kg/ha) in the 1st and 2nd season, respectively. However, the lowest biological yield (7323 and 7521 kg/ha—in both seasons) was accomplished from weedy check plots, mainly due to the severe weed spread in control plots which impaired the growth and development of plants, resulting in minimum dry matter accumulation in wheat crop and thus minimized the biological yield. This finding was in agreement with the investigation of Pisal and Sagarka[46] who noticed a substantial reduction in grain and straw yield for un-weeded plots of wheat.

Effect of gibberellin treatment

Table 8 illustrated that plant height was remarkably influenced by GA_3 ($P < 0.05$). The foliar use of GA_3 (at 100 and 200 mg/L) led to taller plants in first and second season than control group. Specifically, plant height decreased significantly under control treatment (103 and 104 cm in both seasons, respectively). Results also demonstrated that the tallest plants were obtained after spraying of GA_3 at 200 mg/L which was statistically similar with that sprayed at 100 mg/L. The increase was principally due to the improvement in flexibility of cellular matrix followed by the hydrolysis of starch to sugars, causing the reduction in the water potential of the cells, which facilitated the movement of cellular water into intercellular spaces[15,47]. Such osmotic-driven responses after the spraying of GA_3 may have boosted photosynthesis activity and intensified the translocation and effectiveness of using photosynthesis products, leading to the rapid cell division and thus augmented the cell elongation[47]. This resulted in the enhancement in plant growth (observably the internode length of stem) and consequently augmented plant height[48]. As shown in Table 8, no significant effects were found in spike length

GA$_3$ (mg/L)	Plant height (cm)		Spike length (cm)		No. of spikelet's/spike		Spike weight (g)		No. of grains/spike		Weight of 1000-grain (g)	
	1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season
0	103b	104b	12.9a	13.6a	21.9a	18.4b	6.73a	5.87b	54.0b	49.6b	47.4b	46.5c
100	109a	111a	12.8a	14.3a	21.8a	20.3a	6.78a	6.43ab	55.1ab	47.1b	52.3a	51.8b
200	112a	114a	13.3a	15.5a	22.1a	20.7a	7.58a	7.28a	58.2a	56.8a	55.4a	55.7a

Table 8. Effect of gibberellic acid on yield components of wheat.

due to the foliar spraying of GA$_3$ at varied concentrations in the both seasons of study ($P > 0.05$). Plants treated with GA$_3$ at 200 mg/L had the tallest spikes (13.3 and 15.5 cm) in the first and second season, respectively, which significantly contributed to the increase of No. of spikelet's/spikes. Similarly, Islam et al.[15] and Iftikhar et al.[49] studied the effect of GA$_3$ at varied concentrations (0–200 ppm) on the yield characteristics of wheat, and they found that the foliar use of GA$_3$ at 200 ppm augmented spike length and No. of spikelet's/spikes over compared with control. Spraying GA$_3$ at 200 mg/L induced a notable increase in No. of spikelet's/spike (22.1 and 20.7, respectively) in the 1st and 2nd seasons compared with control (distilled water). The increase in the No. of spikes/plants and No. of spikelet's /spikes was consistent with the findings of weight of grains per spike and the weight of 1000-grain (Table 8), which in turn contributed to the enhancement in the grain yield/ha. Furthermore, plants sprayed with 200 mg/L GA$_3$ possessed significantly higher No. of grains/spike (58.2 and 56.8) in the first and second season over than that of plants treated with distilled water only (control) and GA$_3$ at 100 mg/L. Notably, the lowest No. of grains/spike (54.0) was observed for the plots sprayed with distilled water and GA$_3$ at 100 mg/L (47.1) in the 1st and 2nd season, respectively. Such investigations were in well line with the findings of Attiy et al.[50], who noticed an increase in No. of grains/spike when the wheat plants (cv. Ipa99 and Rasheed) were sprayed with GA$_3$ under varying concentrations (from 30 to 90 ppm) over untreated plots (control). The production of organic matter/spike and spike weight were associated directly with a No. and weight of grain per spike. Spike weight is important constituent of yield. Changes in spike weight considerably impacts the final yield. In this study, the highest spike weight was achieved from high concentration of GA$_3$ (7.58 and 7.28 g) then 100 mg/L, whereas the untreated plots had the minimal spike weight (6.73 and 5.87 g) in both seasons. The results of both seasons showed significant effect of GA$_3$ on weight of 1000-grain ($P < 0.05$). In the 1st and 2nd season, spraying of GA$_3$ at 200 mg/L maximized the weight of 1000-gain (55.4 and 55.7 g, respectively) (Table 8). Further, the weight of 1000-grain increased remarkably with increased doses of GA$_3$ from 0 to 200 mg/L. This superiority may be due to the physiological effect of GA$_3$ on improving the carbon assimilation efficiency and dry matter accumulation in the grains[50].

Maximum grain yield was found following the application of GA$_3$ at 200 mg/L (5209.8 and 5845 kg/ha, respectively), followed by 100 mg/L (4905 and 4720 kg/ha), while plants sprayed with distilled water only produced the minimal yield (3841 and 3746 kg/ha, correspondingly) in the 1st and 2nd season (Fig. 5a). Such investigations were consistent with the outcomes of weight of 1000-grain, spike length, spike weight, No. of grain/spike, and No. of spikelet's/spike. This suggests that GA$_3$ may enhance the mobilization of reserve food matrices to the developing source-sink of wheat plants through the increase in hydrolysis and oxidation of enzyme activities, which improved translocation/accumulation of sugars and other metabolites[15], which eventually augmented grain yield. This improvement was also correlated with the augmentation of total fertile blooms after heading stage of wheat plants following the application of bio-growth regulators (e.g., GA$_3$)[21], causing an increment in spike weight and weight of 1000-grain, and subsequently contributed to the increased grain yield. Protich et al.[51] also found a strong positive interrelationship between weight of 1000-grain and grain yield.

Furthermore, straw yield was significantly affected by GA$_3$ treatments compared with spraying of distilled water only. Wheat plants considerably produced more straw yield (7273 and 6971 kg/ha, respectively) when sprayed with GA$_3$ at 100 and 200 mg/L in the first and second season (Fig. 5b). Besides, the lowest values (5412 and 6005 kg/ha) were documented in untreated plants during two growing seasons. The observed results were mostly attributable to the vigorous vegetative growth of wheat plants following the application of GA$_3$, which ultimately augmented the leaf area and intensified the photosynthesis process[15,52], thereby maximizing the straw yield. Moreover, the foliar spraying of GA$_3$ at 100 mg/L recorded the highest biological yield (12,178 kg/ha) in the first season and 200 mg/L in the second season gave the maximal yield (12,816 kg/ha) (Fig. 5c). However, the lowest yield was achieved following the spraying of distilled water (9253 and 9751 kg/ha) in both seasons. These results were in accordance with straw yield in the current study. The observed increase was mainly due to the enhancement of plant height, weight of 1000-grain, straw yield, and grain yield.

Effect of the interaction between weed control and gibberellin treatments

It was noticed that the influence of combined weed control treatments and gibberellin at varying concentrations was not significant on spike length (in both seasons) and No. of spikelet's /spike (in the first season only) (Table 9). Plots sprayed with pallas herbicide and GA$_3$ at 200 mg/L had the tallest plants (117 and 118 cm, respectively) in the first and second season. Contrarily, the shortest plants were found from no weeding (control) and untreated plants with GA$_3$ (99.0 and 100 cm) in two seasons. However, the interaction of T4G3 (pallas and 200 mg/L GA$_3$) recorded the maximal No. of spikelet's/spike in both seasons (22.7 and 23.0). Results also revealed that spike weight was significantly affected by weed control treatments and gibberellin (Table 9). The highest spike weight (8.33 and 8.24 g, respectively) was realized subsequent to the spraying of pallas herbicide with gibberellin at 200 mg/L, whilst minimum weight (5.00 and 4.68) was observed from control plots. Regarding No. of grains /spike,

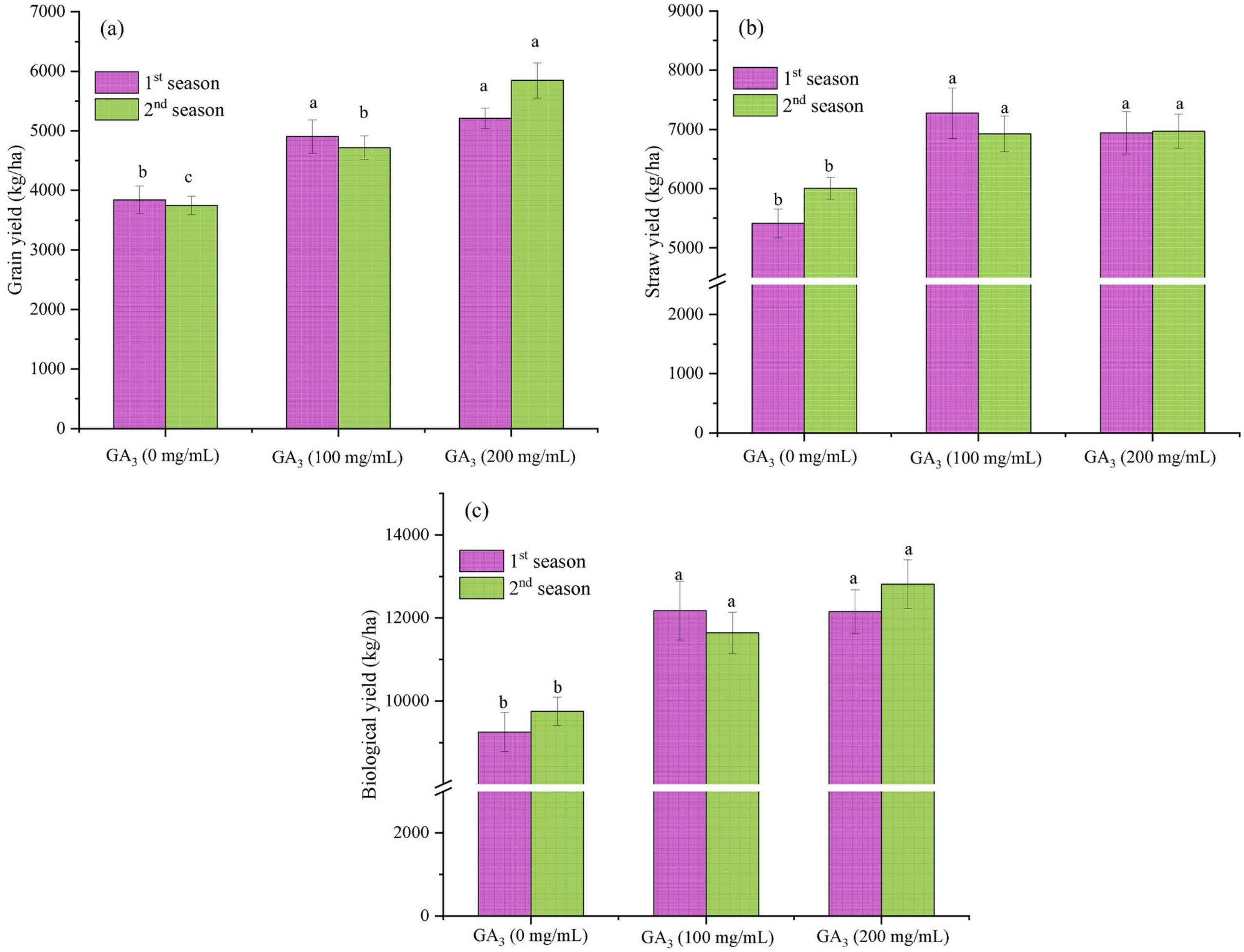

Fig. 5. Effect of gibberellic acid on grain (**a**), straw (**b**), and biological (**c**) yield of wheat.

the effect of the interaction between weed control treatments and three concentrations of GA_3 was statistically significant. Importantly, the synergistic application of pallas herbicide and gibberellin at 200 mg/L produced the highest No. of grains/spike (67.0 and 65.7, correspondingly) in both growing seasons. Whilst, the lowest No. of grains/spike was resulted from T1G3 (un-weeded and 200 mg/L GA_3) and T1G1 (un-weeded and without GA_3) in 1st and 2nd season, respectively. Abouziena et al.[53] also realized that the un-weeded plots produced the minimal No. of grains/spike. Further, synergetic application of herbicides and GA_3 had significant effect on weight of 1000-grain (Table 9). Nonetheless, among treatments, the heaviest grains (61.3 and 62.1 g) were noted after pallas and GA_3 (200 mg/L) treatment, whereas untreated plots produced the lightest grain weight (41.5 and 41.8 g) in the 1st and 2nd season. Such outcomes might be due to the availability of more resources of nutrients and favorable soil environment[37].

Moreover, the interactions between four weed control treatments and gibberellic acid affected the grain yield of wheat plants (Fig. 6a). The synergistic effects of herbicides and GA_3 at varied concentrations notably augmented the grain yield relative to the untreated group (2451 and 2674 kg/ha), especially under the combined application of T4G3 (pallas herbicide and GA3 at 200 mg/L) and T3G3 (sulfo-s and 200 mg/L) (7278 and 6935 kg/ha, in 1st and 2nd season, respectively). Nevertheless, the variations between pallas herbicide and sulfo-s under the same concentration of GA3 did not reach to significance in the 2nd season. The observed increase was due to the efficient weed control and the uptake of all the available nutrients by wheat plants. These results are in well accordance with the results of Tunio et al.[54]. Regarding straw yield, results displayed significant differences among herbicides and among gibberellic acid treatments relative to control plots (Fig. 6b). The interaction of pallas herbicide and GA_3 (200 mg/L) observably maximized the straw yield in both growing seasons. This was associated with the improved activities of various biochemical and physiological processes such as photosynthesis, which enhanced the growth/ development of wheat plants[55], and consequently improved straw yield. This was buttressed with the observation of plant height in this study. Similarly, Muhammad et al.[56] reported that the utilization of post-emergence herbicides significantly enhanced the grain and straw yield of wheat. Furthermore, results in Fig. 6c exhibit observable variations among the combined application of weed control and gibberellic acid treatments on biological yield. Importantly, plots treated T3G3 (pallas herbicide and 200 mg/L GA_3) produced substantially higher biological yield (17,186 and 15,285 kg/ha) over other treatments

Treatment		Plant height (cm)		Spike length (cm)		No. of spikelet's/spike		Spike weight (g)		No. of grains /spike		Weight of 1000-grain (g)	
Weed control	GA3 (mg/L)	1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season
Control	0	99.0f	100g	13.5a	12.6a	20.3ab	14.5c	5.00b	4.68e	46.4f	40.0d	41.5f	41.8f
	100	104de	106ef	11.7a	13.0a	19.3b	15.9bc	5.00b	4.96de	46.5f	40.5cd	44.5ef	45.3ef
	200	106de	109def	12.7a	13.5a	21.0ab	17.7abc	6.33ab	6.00cde	44.3f	44.0cd	44.8def	45.5def
Derby	0	104de	106ef	12.5a	13.6a	22.0ab	19.3abc	7.27ab	6.17cde	59.7bcd	56.4ab	52.7bcd	51.3cd
	100	111bc	113bcd	13.6a	15.6a	22.3ab	20.1ab	7.33ab	7.10abc	61.7bc	57.5ab	55.5abc	54.7bc
	200	114ab	115ab	14.7a	14.7a	22.1ab	20.4ab	8.33a	8.24a	64.7ab	62.4a	59.0ab	58.4ab
Sulfo-s	0	102ef	105f	13.2a	15.1a	22.3ab	19.6abc	7.67a	6.23bcd	55.7de	50.9bcd	45.8def	45.7def
	100	108cd	110cde	12.8a	15.3a	22.3ab	22.4a	7.47a	7.26abc	53.7e	40.3cd	52.3bcde	51.2cde
	200	111bc	112bcd	13.1a	17.4a	22.0ab	21.5a	7.66a	7.19abc	56.8cde	55.1ab	58.0ab	56.8abc
Pallas	0	105de	106ef	12.4a	13.0a	22.9ab	20.1ab	7.00ab	6.38bcd	54.3e	51.2bc	49.7cde	47.1def
	100	112bc	114abc	13.3a	13.3a	23.3a	22.7a	7.33ab	6.40bcd	58.3cde	50.3bcd	57.0abc	56.0bc
	200	117a	118a	12.8a	16.5a	23.4a	23.0a	8.00a	7.70ab	67.0a	65.7a	61.3a	62.1a

Table 9. Effect of weed control treatments and gibberellic acid on yield components of wheat.

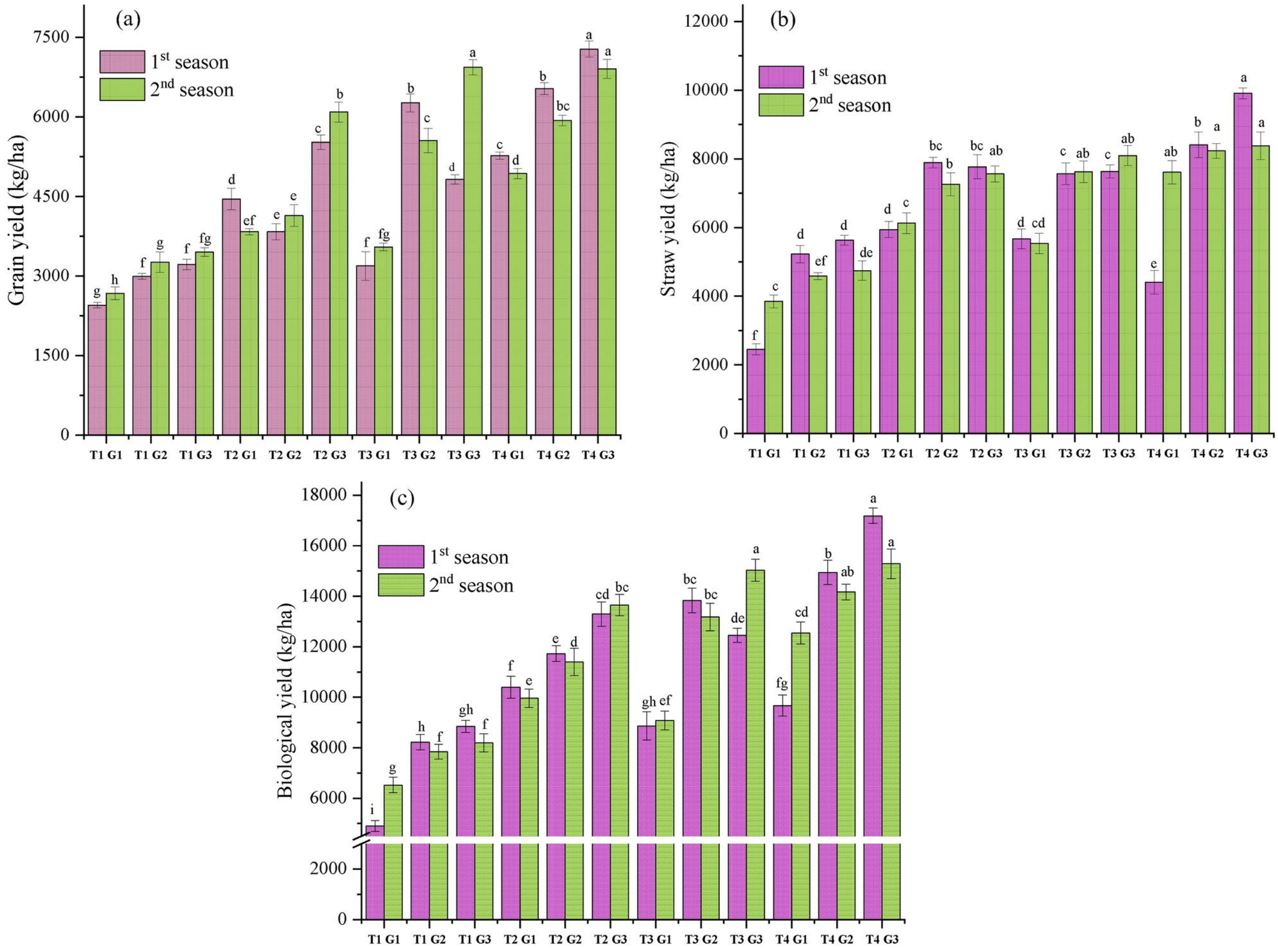

Fig. 6. Effect of weed control treatments and gibberellic acid on grain (**a**), straw (**b**), and biological (**c**) yield of wheat. T_1 = un-weed group, T_2 = derby, T_3 = sulfo-s, T_4 = pallas, G_1 = 0 mg/L GA_3, G_2 = 100 mg/L GA_3, and G_3 = 200 mg/L GA_3.

in the 1st and 2nd season, respectively. Besides, the minimal biological yield (4900 and 6525 kg/ha) was noticed for plots sprayed with T1G1 (without herbicides and zero-GA_3) in the 1st and 2nd season.

Chemical composition analysis

Effect of weed control treatments

Figure 7 portrays the impact of herbicides treatment on chemical attributes of wheat grains. Findings indicated that there were significant effects on nitrogen, potassium, and protein content ($P < 0.05$). Un-weeded plots displayed a significant reduction in nitrogen content of grains by around 30.9, 28.7, and 29.2% (in the 1st season) and 31.1, 31.2, and 36.2% (in the 2nd season) relative to various herbicidal treatments (i.e., derby, sulfo-s, and pallas, respectively) (Fig. 7a). The highest nitrogen content (2.46%) was obtained after derby treatment and when plants were treated with pallas herbicide (2.46%) in 1st and 2nd season, respectively, however, lowest nitrogen content (1.70 and 1.57%) was documented for control, which was consistent with the findings of Abouziena et al.[53]. These results may be due to the less competition for nutrients, water, and light through limiting weeds infestation under herbicidal treatments. Therefore, the impaired weed competition for nutrients favored the crop against weeds resulting in increased N-uptake[57]. Additionally, spraying wheat plants with post-emergence herbicides significantly increased potassium content of grains in both seasons (Fig. 7b). In the 1st season, the highest potassium content was recorded in plants sprayed with derby herbicide, followed by sulfo-s and pallas herbicides, whereas the lowest uptake by wheat (44.05) was realized in weedy check. However, in the 2nd season, potassium content of wheat grain followed the order T_4 (pallas) > T_3 (sulfo-s) > T_2 (derby) > T_1 (control). Inferring from this is that, weed management practices influenced significantly K-uptake (positively) by wheat plants. The differences between all herbicides were not significant in the first season ($P > 0.05$), whereas substantial variation ($P < 0.05$) among pallas and other herbicides (i.e., sulfo-s and derby) treatment was noticed in the second season. Concerning protein content (Fig. 7c), the outcomes illustrated that the use of derby herbicide was statistically similar with pallas and sulfo-s herbicide during both seasons ($P > 0.05$). Further, the herbicidal treatments significantly augmented protein content of wheat grains in two growing seasons over the control ($P < 0.05$). Also, El-Rokiek et al.[58] observed an increase in protein content of wheat grains due to the utilization of

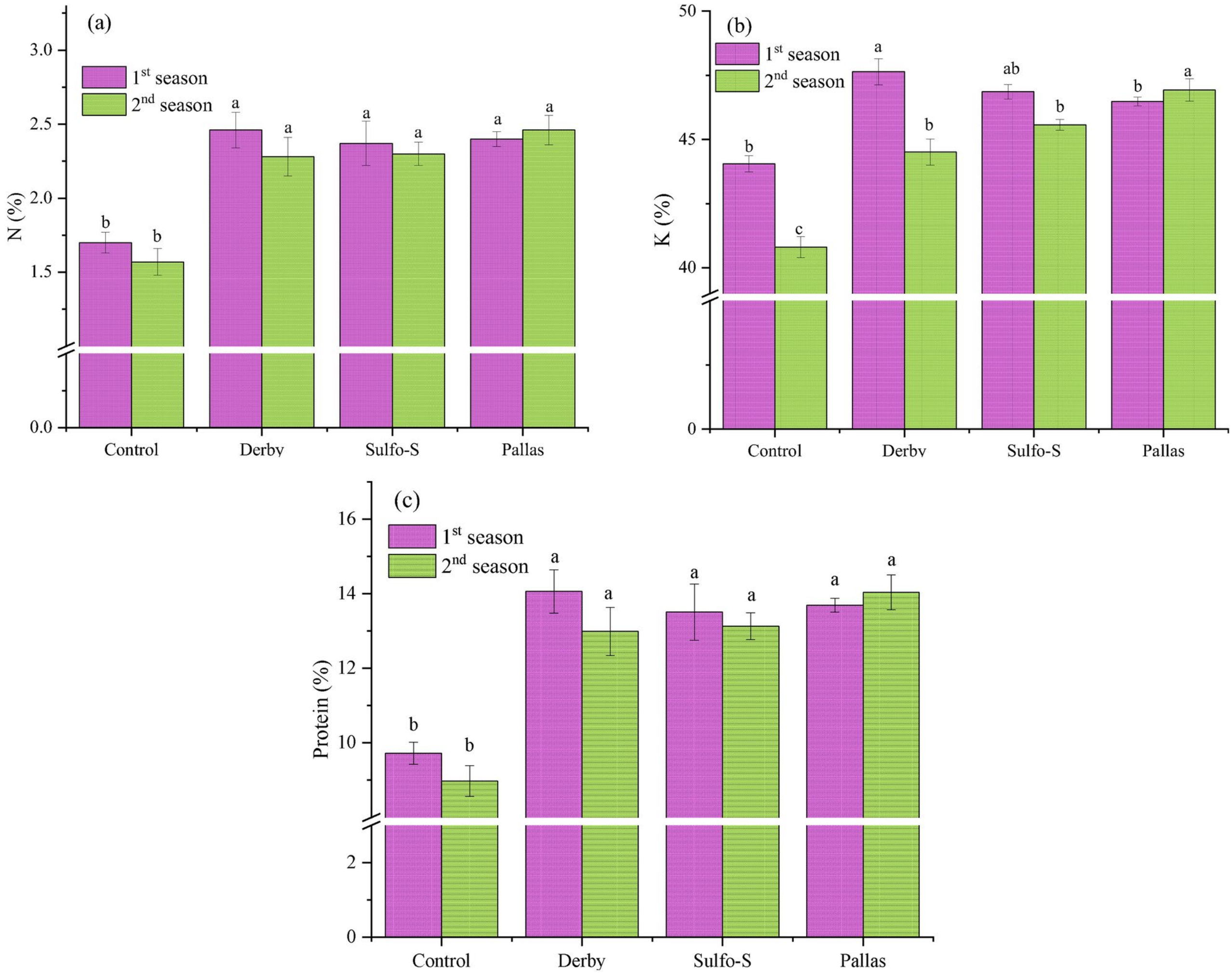

Fig. 7. Effect of weed control treatments on chemical composition of wheat grains.

derby (flumetsulam + florasulam) herbicide compared to the un-weeded plots. In that sense, the aforementioned results confirmed that the application of herbicidal treatments remarkably enhanced the quality of wheat grains by increasing their nitrogen, potassium, and protein content.

Effect of gibberellin treatment

Application of GA_3 at 100 and 200 mg/L had no considerable action on chemical attributes (i.e., nitrogen, potassium, and protein content) in two seasons as presented in Fig. 8. Following the utilization of GA_3, particularly at 200 mg/L, nitrogen content was higher than that of control in the first and second season. Potassium content in the plant tissue is crucial to the proper functioning of several important biochemical and physiological processes that directly affect crop productivity[59]. Plants sprayed with GA_3 at 200 mg/L possessed higher of K value (47.0 and 45.0%) reference to other concentrations (i.e., 0 and 100 mg/L) in the both seasons. The effective role of GA_3 in enhancing the growth and development of plants may intensify the uptake of nutrient elements[60]. Also, protein content was enhanced when plants subjected to the application of GA_3 at 200 mg/L concentration (13.5 and 13.1%, correspondingly), whereas the lowest content was observed from plants sprayed with distilled water only (12.0 and 11.8, respectively) in the two growing seasons. This was probably ascribed to the enhancement in physiological efficiency after GA_3 treatment which increased the translocation of nitrogen compounds to the grains and thereafter improved protein content[61].

Effect of the interaction between weed control and gibberellin treatments

Figure 9 exhibits the mutual action of weed control and gibberellin on chemical attributes of wheat grains. The outcome in this work inferred that there were significant effects on all chemical attributes (i.e., nitrogen, potassium, and protein content) of wheat grains ($P < 0.05$) due the sequential application of post-emergence herbicides and GA_3. The highest nitrogen content was documented after the use of derby herbicide (2.77 and 2.77%, correspondingly) and gibberellic acid applied at 200 mg/L in the 2021/2022 and 2022/2023 seasons (Fig. 9a). Meanwhile, the lowest contents were noticed for untreated plots (1.47 and 1.37%, respectively) during the two growing seasons. Similar findings were also indicated by Zhang et al.[62]. These superiorities are credited to

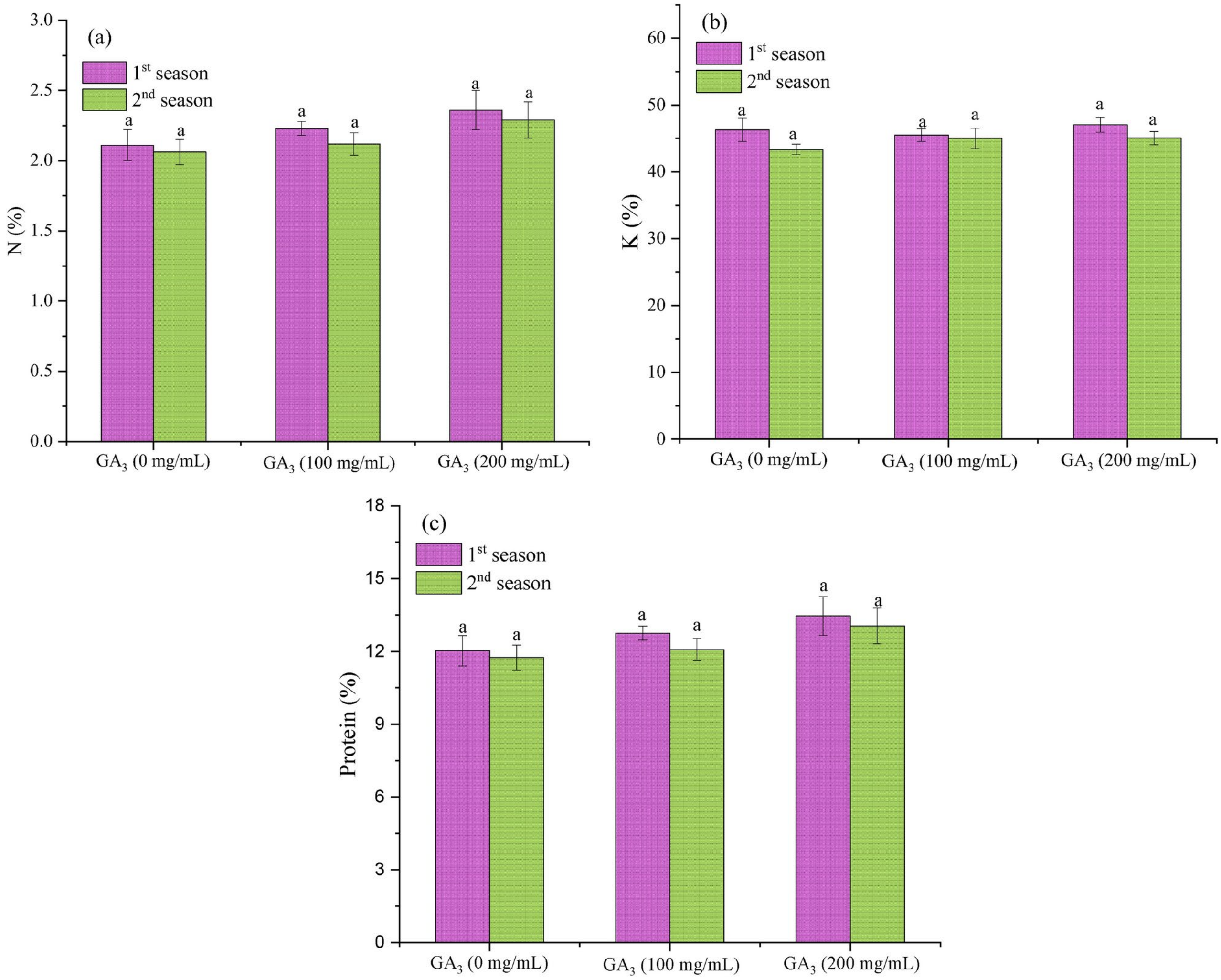

Fig. 8. Effect of GA_3 concentration on chemical composition of wheat grains.

minimizing weed competition which in turn increased the accessibility of nutrients to wheat plants as compared to control that accompanied with weeds[63]. Additionally, it can be observed that spraying of derby herbicide and high concentration of GA_3 resulted in the maximal protein content (15.8%) in 1st and 2nd season, consistent with what was indicated previously[58]. Also, El-Metwally et al.[64] found that the use of pyroxsulam herbicide led to an increase of crude protein (10.6 and 10.5%) in wheat grains compared to the control (9.19 and 9.28%) in two seasons.

Correlational analysis

Pearson's correlation was used to highlight the intrinsic relationship between the dry weight of *Avena fatua* L. and broad-leaved weeds as well as yield and chemical traits of wheat following GA_3 and weed control treatments (Fig. 10a). Depending on the levels of the computed correlation coefficient (*r*), Dias et al.[65] indicated that the correlation could be categorized as strong ($1 < |r| > 0.7$), moderate ($0.5 < |r| < 0.7$), and weak ($|r| < 0.5$). Broad-leaved weeds (i.e., *Chenopodium album L., Euphorbia hirta* L., *Malva parviflora* L., *Anagallis arvensis* L., *Sonchus oleraceus* L., and *Convolvulus arvensis* L.) displayed strong negative correlation with plant height, spike length, No. of spikelet's/spike, spike weight, No. of grains/spike, weight of 1000-grain, as well as grain, straw, and biological yield. Similarly, the reduction in *Avena fatua* L. was respectively responsible for 92%, 96%, 91% 81%, 76%, 84%, 76% and 84% of the increase in plant height, No. of spikelet's/spike, spike weight, No. of grain/spike, weight of 1000-grain, grain yield, straw yield, and biological yield. Deducing from this is that, *Avena fatua* L. and broad-leaved weeds may have influenced (inversely) the yield attributes of wheat. Such outcomes were mostly attributable to the reduction in wheat-weed competition subsequent to the synergetic utilization of post-emergence herbicides and GA_3, which augmented the availability of nutrients, and water for wheat plants as well as photosynthesis during the growth/development stages, resulting in a substantial increase in the grain yield. Most remarkably, the increase in *Avena fatua* L. and broad-leaved weeds, especially *Avena fatua* L., *Sonchus oleraceus* L., and *Convolvulus arvensis* L., contributed negatively to grain quality (i.e., N, K, and protein), indicating that weed control and GA_3 treatments played a crucial role in enhancing the quality of wheat grains due to the significant reduction in the density of total weeds. Importantly, the analysis portrayed

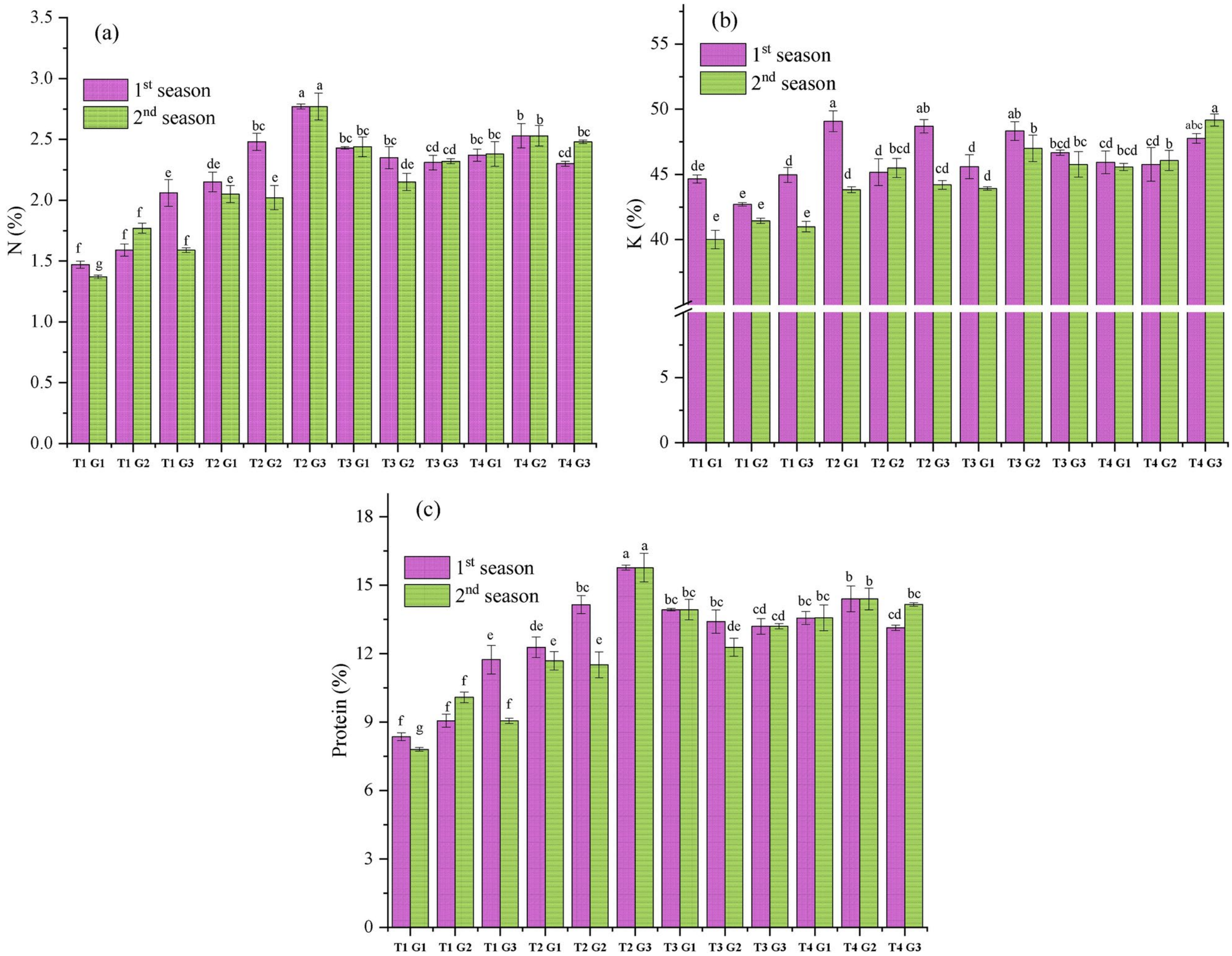

Fig. 9. Effect of weed control treatments and gibberellic acid on chemical composition of wheat grains. T_1 = un-weed group, T_2 = derby, T_3 = sulfo-s, T_4 = pallas, G_1 = 0 mg/L GA_3, G_2 = 100 mg/L GA_3, and G_3 = 200 mg/L GA_3.

strong positive correlation between grain yield and spike length (r = 0.83), No. of spikelet's/spike (r = 0.89), spike weight (r = 0.87), and weight of 1000-grain (r = 0.76). Further, plant height was interrelated with straw (r = 0.75) and biological yield (r = 0.83), providing good evidence for the intrinsic relationship amongst plant height and the mentioned parameters. To end with, correlational analysis demonstrated that *Avena fatua* L. and broad-leaved weeds were strongly associated with the yield and chemical attributes of wheat under the application of herbicides and GA_3 treatments.

To simplify the complexity of influence of weed control and GA_3 treatments on the dry weight of *Avena fatua* L. and broad-leaved weeds, as well as yield and chemical attributes of wheat, PCA was performed and the analysis is portrayed in Fig. 10b. The overall variance (92.20%) computed from two components (86.8% and 5.4%) was enough to highpoint the variation and similarity between components. Weed control and GA_3 treatments were categorized into 4 groups. T2G2, T4G2, and T4G3 are respectively positioned on positive and negative side of PC1 and PC2 with No. of grain/spike, weight of 1000-grain, plant height, No. of spikelet's/spike, N, and protein. These investigations confirmed that the combined application of pallas and GA_3 under varied concentrations considerably affected the mentioned parameters. The 2nd cluster (containing T2G3, T3G1, T3G2, T3G3, and T4G1), located on upper right-hand quadrant (i.e., positive side of both components), was characterized by spike length, spike weight, K, and grain, straw, and biological yield, implying that the said parameters were linked strongly to the synergistic actions of sulfo-s herbicide and GA_3 treatments.

The 3rd group (T1G1 and T1G2), associated with *Avena fatua* L. and all broad-leaved weeds (i.e., *Chenopodium album* L., *Euphorbia hirta* L., *Malva parviflora* L., *Anagallis arvensis* L., *Sonchus oleraceus* L., and *Convolvulus arvensis* L.), is respectively situated on negative and positive side of PC1 and PC2. This illustrated that the foliar spraying of GA_3 (at 0 and 100 mg/L) and un-weeded plots substantially contributed to the increase in the density of total weeds, which maximized the competition between wheat plants and weeds, thereby reducing grain yield and quality. The remaining treatments (T1G3 and T2G1) did not display interrelation with any measured parameter. Inferring from this is that, the sequential use of post emergence herbicides and GA_3 at varying

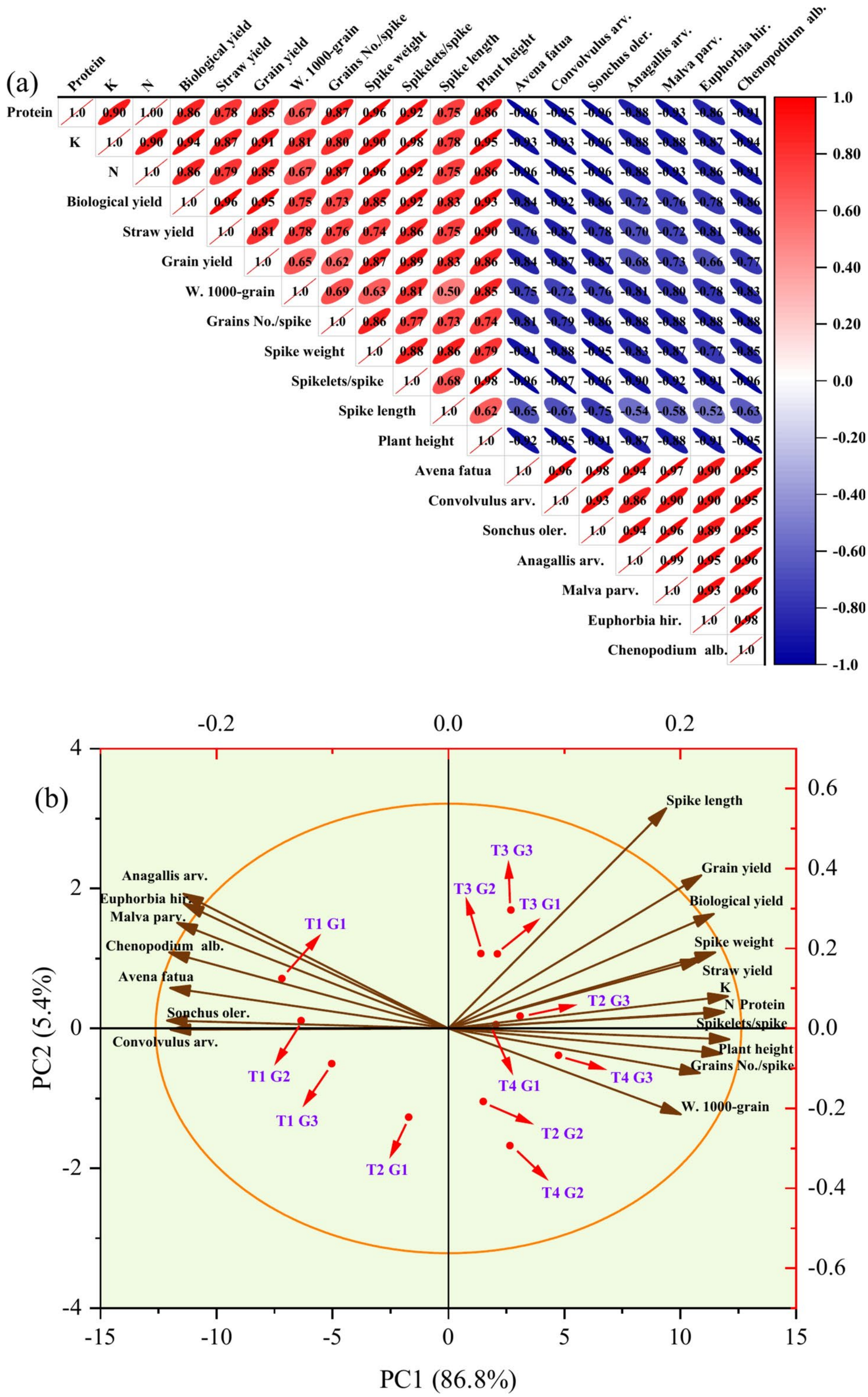

Fig. 10. Pearson's correlation (**a**) and PCA (**b**) of *Avena fatua* L. and broad-leaved weeds, as well as yield and chemical characteristics of wheat treated with post-emergence herbicides and GA_3.

concentrations had various influences on the dry weight of total weeds as well as the yield and chemical traits of wheat.

Conclusions

The influence of weed control treatments (untreated check, sulfosulfuron, florasulam 7.5% + flumetsulam 10%, and pyroxsulam) and GA_3 (at varied concentrations) on *Avena fatua* L. and broad-leaved weeds as well as yield and chemical attributes of wheat was investigated. All herbicidal treatments led to a reduction in a dry weight of *Avena fatua* L. and broad-leaved weeds, especially pallas herbicide. Importantly, sequential pallas herbicide and foliar use of GA_3 at 200 mg/L at booting stage is recommended to effectively minimize the dry weight of *Avena fatua* L. and broad-leaved weeds. Furthermore, the combined utilization of pallas herbicide at (30 DAS) and GA_3 at 200 mg/L remarkably enhanced plant height, No. of spikelet's /spike, No. of grains/spike, weight of 1000-grain, and grain yield. However, the synergistic application of derby herbicides and 200 mg/L GA_3 maximized the spike weight. In that sense, the sequential use of herbicidal treatments and GA_3 seems to be useful in enhancing the yield and its components as well as chemical properties of wheat. By this, the revenue of wheat farmers could increase, contributing to sustainable wheat production which would consequently guarantee regular supply of wheat grains for food application all-year-round despite the expected increases in the global population. Further studies, however, may be required in the future to investigate the synergistic effect of other post-emergence herbicides and growth regulators on the yield and quality of wheat.

Data availability

All data are included in this article, and any further information will be made available from the corresponding author on reasonable request.

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Experimental design, Methodology, Data analysis, Writing—review & editing, A.H. Validation, Software, Data analysis, Funding acquisition, E.Y.K. and K.S.R. All authors have read and agreed to the published version of the manuscript.

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Declarations

Competing interests
The authors declare no competing interests.

Additional information
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