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RESEARCH

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Enhancing sugar beet quality and productivity under the effects of co-application of urea and herbicides on weed control and crop performance

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Abstract

Background Sugar beet (*Beta vulgaris* var. saccharifera, L.) is the main source of sugar in many countries and ranks 2nd after sugarcane worldwide. Being poor competitor, weeds are a major obstacle against healthy growth and sustainable production in sugar beets. The current study was conducted during two successive seasons (2019/2021) with the aim of assessing the response of weed growth and sugar beet yield to certain herbicides that are commonly used in different cropping systems. In conjunction with unweeded check and hand hoeing twice, Goltix® 70 SC, Tegro® 27% EG and Betanal® MaxxPro herbicides were applied alone (at the recommended rates) or in combination (50 and 75%) with urea (2%) in a randomized complete block design.

Results The results indicated that weed competition significantly reduced plant growth, as well as root and sugar yields by 50.21% to 68.68%. Overall, all herbicidal treatments provided significant weed control with positive changes in sugar beet yield and quality. While the reduction in total weed biomass remained relatively consistent across the various treatments, broad-leaved and narrow-leaved weeds exhibited marked differences in their responses to the herbicide treatments. Obviously, no much significant differences were observed between the individual application of the herbicides and their combined use, particularly at the 75% dilution level with urea, in terms of either weed suppression or crop enhancement. The maximum root yield and better weed control were proportionally achieved with Tegro and Betanal at the recommended concentrations followed by hand hoeing twice, and their use significantly contributed to further improvement in quality characteristics compared to those recorded with the other treatments.

Conclusions Using such herbicides at reduced doses in combination with urea proved to be a feasible approach for improving application efficacy without compromising root yield or affecting sugar quality. This strategy may also contribute to reducing herbicide resistance while promoting more sustainable, environmentally friendly weed management in sugar beet production in the foreseeable future.

Keywords Weed control, Sugar beet, Herbicides, Combined application, Urea

Background

Sugar beet is one of the two most economically important sugar-yielding crops globally. It ranks 2nd after sugarcane in world sugar production (Brar et al. 2015; Wimmer and Sauer 2020). The industrial sugar beet market contributes 30–40% of the world's human consumption (Mall et al. 2021), which is valued at approximately $ 11.29–15.05

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billion with an expected annual growth rate of increase of 2.7% into the foreseeable future (2024–2029).

According to the statistics of 2021, the plant is grown in more than 51 countries with a total area of 4.565 million ha and annual production of 229.2 million metric tons in 2018 (Tayyab et al. 2023). The world's leading producing countries are Russian Federation, yielding approximately 55 million metric tons, followed by France, USA, Germany and Turkey (Statista 2023). Yet, their contributions in the global market are inconsistent and affected by several considerations related to local and economic policies (Bezhin et al. 2015). France has the highest yield productivity per unit area with an average of 83,926 kg ha^{-1}. Egypt comes eighth with 10.5 million metric tons yearly production (FAO 2023).

Sugar beets belong to *Chenopodiaceae* family and are grown primarily in regions with a temperate and subtropical climate. Given their specific soil and climate requirements, sugar beets are a strong candidate for successful cultivation in Egypt. Their unique ability to tolerate salinity stress and harsh desert conditions makes them the second most viable option for addressing the gap between sugar production and local demand in Egypt. For decades, the crop has been widely grown in Egypt under irrigated systems. In contrast to sugarcane, which occupies a vast area in southern Egypt, sugar beet is primarily grown in the more limited areas of the Nile Delta region. About 1.05 million ton of sugar is produced from sugar beet, which constitutes 45.55% of the total domestic sugar production in the country. To keep pace with the rising demand revival, the Egyptian government has adapted several strategies to raise sugar's productivity, both quantitatively and qualitatively (Elbeih 2021).

The traditional agricultural practices including irrigation, fertilization, combating pests and post-harvest processing have a good impact on sugar beet production, with the emphasize that the output of such crop depends mainly on yield quality rather than quantity (El-zayat 2022). Ever since the beginnings of the agricultural revolution in which pest management science played a role (Shaw 1964), weed-related issues have aroused worldwide concern (Chen et al. 2024). As a major yield-suppressive factor adapted significantly to evade human removal (Clements and Jones 2021; Vercellino et al. 2023; Westbrook and DiTommaso 2023), weeds have been documented as among the most dangerous biological constraints that cause serious damage to the entire agricultural process (Sardana et al. 2017). Weed penalizes crop yields by competing for most abiotic resources essential for plant growth (Singh et al. 2022). Apart from increasing production costs because of the persistent control interference and depleting limited resources essential for crop growth, weeds adversely affect agricultural productivity causing heavy yield losses, reducing the quality of produce, as well as making harvest and post-harvest processing difficult (Bhadra et al. 2020). In addition to an annual crop loss amounting to more than US $100 billion worldwide due to weed infestation, the use of modern, highly efficacious and fast-acting herbicides for weed control incurred additional expenditure of about US $25 billion (Agrow 2003 *cited in* Sardana et al. 2017).

Like many other crops, sugar beets are sensitive to stresses associated with weed growth as they have been deliberately selected for high yields, rather than for competitiveness against weeds (Liliane and Charles 2020). Unlike economic crops, the ability of weeds to evolve is the key that may potentiate stress-related motivation, making weed management a challenging task. Sugar beets are generally more susceptible to weed competition, especially under conditions that promote high yields. Studies revealed that competition under uncontrolled annual weeds could be responsible for a 25% – 100% reduction in sugar yield production (Soltani et al. 2018; Hamed et al. 2021; MacCollough et al. 2024). Researchers have argued that sugar beet's poor competitiveness against weeds stems from its slow early-season growth, which continues until canopy closure (Mahmood and Murdoch 2017). This extended period of vulnerability underscores the critical need for effective and sustainable weed management strategies in sugar beet production, to a greater extent than is typically required for most other field crops (Bhadra et al. 2020). Furthermore, the crop's long growing season presents an additional challenge, as maintaining season-long weed control is essential, with early-season measures alone often proving insufficient to ensure effective control.

Several herbicides are recommended for the selective control of weeds in sugar beets. Frequently, more than one herbicide may need to be combined sequentially (Robinson et al. 2013; Bergiers et al. 2022) or as tank mixtures (Deveikyte et al. 2015; Grzanka et al. 2023) to achieve broad-spectrum weed control. However, the specific sequences and timing of application vary based on weed species, geographic region, and planting and harvest schedule. In this context, accurate identification of weed species is critical for the design and implementation of effective weed management strategies. Postemergence herbicides such as paraquat (Gramoxone SL 2.0) and glyphosate are greatly effective in combating sugar beet weeds by providing mainly contact and systematic actions, respectively. Betasana-Trio and Tegro precluded mischievous growth of broad-leaved weeds when applied twice at 0.9 and 1.0 l fed^{-1}, respectively; meanwhile, Select Super (0.375 l fed^{-1}) and Betanal Maxx-Pro (0.5 l fed^{-1}) provided convenient control of grassy

weeds (Abd El Lateef et al. 2021). The use of adjuvants such as urea is an effective and safe tool to enhance herbicides efficiency. Much information is available for the field benefits of using urea and urea–ammonium nitrate in increasing herbicides efficacy and reducing weed control costs (Mookodi et al. 2023; Sarkar et al. 2023; Soltani et al. 2023). Adding nitrogen-based fertilizers to spray solutions can enhance herbicides toxicity by further increasing herbicides uptake and/or penetration into plant tissue (Pacanoski 2015; Berestetskiy 2023).

Relying solely on synthetic herbicides to control weed growth and improve the quality and yield of sugar beets is not a sustainable approach to weed management. Recently, various alternative control measures have been adopted to reduce dependence on synthetic herbicides, driven by concerns regarding environmental and public health. The widespread and unrestrained use of synthetic herbicides is one of the most severe driving forces of environmental health problems. The intensification of herbicides application can trigger loss of biodiversity, making ecosystems more vulnerable to pollution and climate change. Published research indicated that re-evaluation of agronomic techniques such as timing of sowing, intercropping, crop rotation and diversification, competitive plant materials, the amount and method of herbicides applied, the rational use of irrigation and fertilization may influence sugar beet's competition against undesirable vegetation (Winkler et al. 2015; Bhadra et al. 2020; Sarkar et al. 2020; Sharma et al. 2021; Kotlánová et al. 2024). Soil tillage intensity and straw coverage also play a substantial role in the integrated management of weeds and ensure crop protection in this regard (Wenninger et al. 2019; Hamed et al. 2021). Concomitantly, inclusion life cover crops such as wheat, sunflower, corn and/or barley into sugar beet rotation can reduce the intensity of weed proliferation and increase the scope of weed control (Larney et al. 2016; Kunz et al. 2017) by dominating water, space, light and nutrients (Chitband et al. 2017) or releasing allelopathic chemicals into the environment (Scavo and Mauromicale 2021; Khamare et al. 2022; Janusauskaite 2023). Plant-based extracts and residues are an under-investigation approach that has received considerable attention in recent years as a safe and cost-effective mean to suppress weed growth and enhance sugar beet productivity (El-Metwally et al. 2022). However, further research is needed to expand and refine bioherbicide-based applications in the global market.

Although financially costly, hand weeding performed twice, either alone or in combination with selective herbicide applications, contributes significantly to satisfactory weed management in sugar beet (Gouda 2019). Overall, identifying the critical period of weed control is essential to achieve optimal results and minimize potential yield losses (Martinez et al. 2015). For instance, maintaining weed-free conditions as early as the first week after beet emergence and up to 8 – 9 weeks (4 weeks of the crop attainment the 2-leaf phase) thereafter is critically significant to parry severe competition during this period (Hamed et al. 2021), thus avoiding more than a 5% loss in sugar beet root yield (Isika and Akca 2018). Gerhards et al. (2017) indicated that weeding is essential up to the 8-leaf stage in order to sustain sugar beet production.

The objective of the current study is to evaluate the impact of certain selective herbicide treatments, either applied alone or in combination with urea, and hand hoeing twice on weed control, yield productivity and the technological quality of sugar beet.

Methods

Site Description:

Two field experiments were conducted during the winter seasons of 2019/2020 and 2020/2021, at the Experimental Station of the National Research Centre, El-Nubaria District, El-Buhayra Governorate. The station is located at a latitude of 30°30″N and a longitude of 30°18″E, with an altitude of 21 m above sea level (Fig. 1). According to the local weather monitoring station inside the farm, this represents arid climate with a mean annual temperature exceeds 23.3 °C, high relative humidity (60.5% in minimum) and scarce rainfall, but has typical monsoon conditions (wind speed 5.7 m sc^{-1} in maximum). The physical and chemical properties of the soil, shown in Table 1, were determined using standard methods as described by the IUSS Working Group WRB, (2015) and Moreno-Maroto and Alonso-Azcárate (2022).

The previous crop at the experimental site was maize (*Zea mays* L.), which is part of the typical crop rotation system practiced in the region. The predominant weed species included wild radish (*Raphanus raphanistrum* L.), sweet clover (*Melilotus indica* L.), wild beet (*Beta vulgaris* L.), greater ammi (*Ammi majus* L.), wild oat (*Avena fatua* L.) and ryegrass (*Lolium temulentum* L.). These species persisted throughout the subsequent two seasons of investigation.

Crop Establishment and Management

The soil was prepared at a tillage depth of 30 cm with ordinary calcium superphosphate (15% P_2O_5) incorporated at a rate of 74.0 kg P ha^{-1}. Nitrogen fertilizer was applied as ammonium nitrate (33.5% N) at a rate of 240.0 kg N ha^{-1}, while potassium fertilizer was added in the form of potassium sulfate (48% K_2O) at a rate of 60.0 kg K ha^{-1}. To ensure the continuous fulfillment of the growth requirements of the nitrogen and potassium

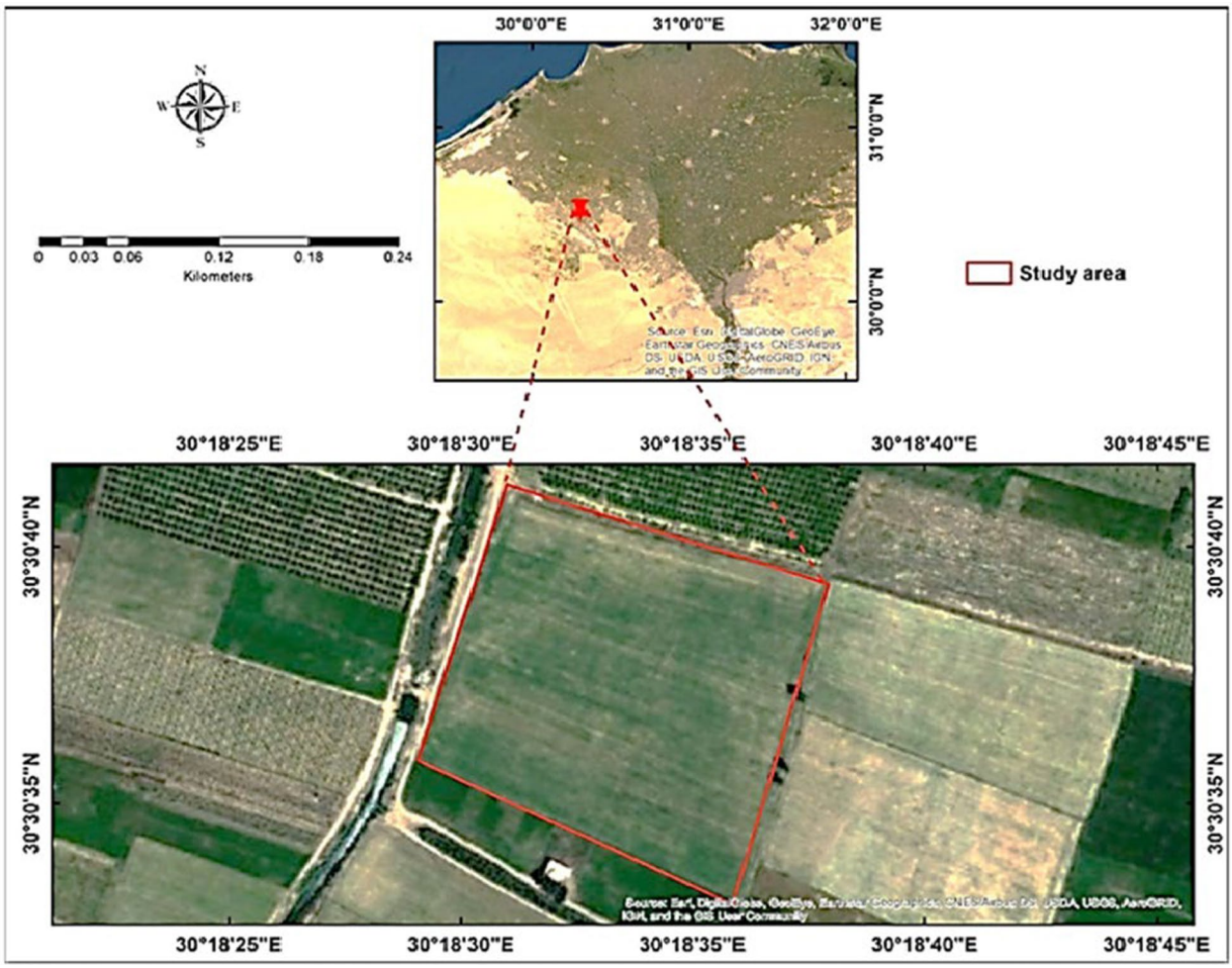


Fig. 1 An approximate schematic map of the study area at El-Nubaria District, El-Buhayra Governorate, Egypt (Quoted from one of our previously published articles, El-Metwally et al. 2022)

elements throughout the growing season, the ammonium nitrate fertilizer was added to the soil in seven equal batches at 30, 45, 60, 75, 90, 105 and 120 days after sowing (DAS). Meanwhile, the potassium sulfate was applied three times mainly at 60, 80 and 100 DAS.

Traditionally, sugar beet seeds (Baraka multi-germ variety) were manually sown on one side of 70-cm-wide ridges, with 20 cm between hills, using a seeding rate of 4.8 kg ha^{-1} and 3 – 4 seeds per hill. Sowing took place on 21 and 29 October in the 1st and 2nd season, respectively. After complete germination and emergence, the plants were specifically hand-thinned twice (30 and 50 DAS) to one vigorous plant per hill. Drip irrigation was the irrigated system used to deliver water and sometimes nutrients. Time and number of irrigations were determined weekly based on local weather conditions and the specific requirements of the plant.

Experimental Design:

A complete randomized block design with three replicates per treatment (*i.e.*, 33 plots in total) was employed in this regard. Plot area was 21 m^2, consisting of 6 ridges, each 70 cm wide and 5 m long.

The experimental design comprised eleven treatments (Table 2). Hand hoeing was performed twice: once at 30 DAS and again 20 days following the initial hoeing and unweeded check (control), where weeds were allowed to grow freely throughout the growing season without interference. The hand-hoeing and untreated control treatments were used to evaluate the comparative effectiveness of herbicides in controlling weeds and enhancing sugar beet growth. The remaining treatments involved the post-emergent herbicides Goltix, Tegro and Betanal, applied either alone or in combination with urea. Urea was added at a concentration of 2% (w/v) of the carrier volume, resulting in an application rate of 9.6 kg ha^{-1} in

Table 1 Physiochemical properties of the experimental soil at El-Nubaria District, El-Buhayra Governorate

Physical characteristics						Chemical characteristics										
Sand (%)	Silt (%)	Clay (%)	Bulk density (g m^{-3})	Water-holding capacity (%)	Organic matter (%)	pH*	EC** (dS m^{-1})	Ion composition: (meq L^{-1})								
								Nitrogen, N	Phosphor, P	Potassium, K^+	Calcium, Ca^{++}	Magnesium, Mg^{++}	Sodium, Na^+	Chloride, Cl^-	Carbonate, $CO_3^=$	Bicarbonate, HCO_3^-	Sulfate, $SO_4^=$
70.12 ± 0.32	10.70 ± 1.12	19.15 ± 0.95	11.30 ± 0.58	23.71 ± 1.54	0.35 ± 0.01	8.31 ± 0.25	0.93 ± 0.13	7.25 ± 0.02	4.30 ± 0.03	0.31 ± 0.01	2.24 ± 0.02	0.75 ± 0.02	4.22 ± 0.21	1.36 ± 0.06	Nile	4.14 ± 0.45	0.92 ± 0.01

* pH, Soil acidity; ** EC, Soil electrical conductivity. Nitrogen and phosphorous exist in either of the two bioavailable forms: nitrate (NO_3^-)/ammonium (NH_4^+) or orthophosphates ($H_2PO_4^-$/HPO_4^{2-}). The data were recorded as an average of three replications ± standard error

Table 2 Description of the experimental treatments applied in the study

No	Herbicidal treatments			Treatment's details
	Trade name	Active ingredient/IUPAC nomenclature	Mode of action	
1	Goltix® 70 SC	Metamitron 70%, 4-Amino-3-methyl-6-phenyl-1,2,4-triazixin-5(4H)-one	- *Metamitron* is a triazinone herbicide disrupts photosynthetic activities (PS II) in susceptible plants. Based on selectivity, it works as both a pre- and postemergence product and is absorbed effectively through leaves and roots. It provides reliable broad-spectrum weed control and a safe approach in beets crop (Janaki et al. 2013; Chitband et al. 2014)	- One application of 3.6 l ha^{-1}Goltix at three to six true leaf stage (25 DAS)
2	Goltix 75% + urea 2%		–	- One application of 2.7 l ha^{-1} Goltix plus 2% urea at three to six true leaf stage (25 DAS)
3	Goltix 50% + urea 2%		–	- One application of 1.8 l ha^{-1} Goltix plus 2% urea at three to six true leaf stage (25 DAS)
4	Tegro® 27.4% EG	- Phenmedipham 7.1%, [3-(methoxycarbonylamino) phenyl] *N*-(3-methylphenyl)carbamate—Desmedipham 9.1%, [3-(ethoxycarbonylamino)phenyl] *N*-phenylcarbamate—Ethofumesate 11.2%, (RS)−2-ethoxy-2,3-dihydro-3,3-dimethylbenzofuran-5-yl methanesulfonate	- *Phenmedipham* is a selective carbamate herbicide commonly used for the control of broad-leaved weeds in young sugar beet. It is a systemic, postemergence herbicide that is absorbed through the leaves. It inhibits photosynthetic electron transport (PS II) and acts by disrupting carbon dioxide.—*Desmedipham* is the demethylated version of Phenmedipham. Its uses, structure and mode of action on plants are similar to those of Phenmedipham.—*Ethofumesate* is a selective, systemic pre- and postemergence, herbicide for grasses and broad-leaved weed control that is absorbed through the root and emerging shoots. It inhibits the growth of meristems, retards cell division, limits the formation of waxy cuticle and functions as inhibitor of lipid synthesis (Velkoska-Markovska et al. 2008; Lewis et al. 2016; Tandon and Pal 2021)	- One application of 4.81 l ha^{-1}Goltix at two to three true leaf stage (15 DAS)
5	Tegro 75% + urea 2%		–	- One application of 3.60 l ha^{-1} Tegro plus 2% urea at two to three true leaf stage (15 DAS)
6	Tegro 50% + urea 2%		–	- One application of 2.40 l ha^{-1} Tegro plus 2% urea at two to three true leaf stage (15 DAS)
7	Betanal® MaxxPro	- Phenmedipham 6%,—Desmedipham 4.7%,—Ethofumesate 7.5%,—Lenacil 2.7%, 3-cyclohexyl-1,5,6,7-tetrahydrocyclopentapyrimidine-2,4(3H)-dione	- *Lenacil* is an uracil product widely applied as pre- and post-emergency herbicide for the selective weed control (annual grasses and broad-leaved) in beet crops, especially sugar beet. It is a systemic herbicide that is absorbed by roots, and acts via inhibiting photosynthesis at photosystem II (Lewis et al. 2016)	- One application of 1.20 ha^{-1} Betanal at three to six true leaf stage (25 DAS)
8	Betanal 75% + urea 2%		–	- One application of 0.90 l ha^{-1} Betanal plus 2% urea at three to six true leaf stage (25 DAS)
9	Betanal 50% + urea 2%		–	- One application of 0.60 l ha^{-1} Betanal plus 2% urea at three to six true leaf stage (25 DAS)
10	Hand hoeing		–	- Repeated hand hoeing; one 30 DAS followed by another treatment 20 days later
11	Unweeded (control)		–	- Weeds were free to grow without any interference

the spray solution. The tested herbicides were applied once as postemergence treatments using a knapsack sprayer equipped with a single-nozzle boom, delivering a spray volume of 480 L ha^{-1}. The timing and rates of herbicide application varied according to the recommended guidelines.

Data Collection

Weed growth

Weeds grown in four randomly selected quadrats (1 m × 1 m) of each plot were manually collected at 60 and 100 DAS, except for Tegros treatments, where sampling was conducted at 50 and 90 DAS. Weeds were identified and classified into two groups: broad-leaved and narrow-leaved. Thereafter, they were separately subjected to dehydration in a forced-air oven at 70 °C for 48 h until a constant weight was achieved. Weed dry weights (g m^{-2}) were determined using a digital balance with a precision of 0.001 g. The mean biomass data were calculated, and analysis of variance (ANOVA) was performed.

Agronomic traits

At 100 DAS and the harvest date, a sample of ten representative sugar beet plants was randomly taken from each plot to assess the growth responses to changes in weed growth as influenced by herbicidal and hand-hoeing treatments. Growth efficiency was evaluated using various metrics, including dry weight of leaves and roots (g $plant^{-1}$), root length and root diameter (cm $plant^{-1}$). At the harvest stage (on 15 May and 20 May for the 1st and 2nd season, successively), the whole plants in each plot were uprooted to estimate root yield and total sugar yield (t ha^{-1}).

Sugar yield and quality traits

At harvest, root quality characteristics were estimated using random samples of ten plants per replicate. Analysis were conducted at the Quality Control Laboratory, El-Nubaria Sugar Factory, El-Buhayra Governorate, Egypt. Sucrose content (%) was determined using a saccharometer, following the method described by the AOAC (2012). Impurities, namely potassium, sodium and α-amino N, were measured according to the procedures of Cooke and Scott (1993). Sugar losses to molasses (%) [I] and the alkalinity coefficient [II] were calculated as described by Deviller (1988). Extractable sugar (%) [III] was estimated using the method of Dexter et al. (1967), while juice purity was calculated using equation [IV] from Cooke and Scott (1993). Finally, sugar yield (t ha^{-1}) [V] was calculated according to the method outlined by Deviller (1988).

[I] Sugar losses to molasses (%) = 0.14 (Na + K) + 0.25 (α − amino N) + 0.5

[II] Alkalinity coefficient = (2) (K% + Na %) / α-amino N (%)

[III] Extractable sugar (%) = Sucrose (%) − sugar losses to molasses (%) − 0.6

[IV] Juice purity (%) = [Extractable sugar (%)/sucrose (%)] × 100.

[V] Sugar yield (t ha^{-1}) = Root yield (t ha^{-1}) × extractable sugar (%).

Statistical Analysis

The data collected over the two successive seasons were separately subjected to analysis of variance (ANOVA) as described by Casella (2008), using the Costat software program, version 6.303 (2004), CoHort Software, Monterey. Years and weed control treatments were considered fixed effects, while replications (blocks) were treated as random effects. Means separation was performed only when the F-test indicated significant differences ($P \leq 0.05$) among treatments, using Duncan's multiple range test. The inhibition percentage [A] (for weeds) or the increase percentage [B] (for crop traits) was calculated from the analyzed data using the following equations: A = 100 − (Treatment/Control × 100); B = (Treatment/Control × 100) − 100.

Results

Data presented in Tables (3 and 4) show the effect of the studied weed control treatments on the growth and development of weeds associated with sugar beet plants at 35 and 75 days of the herbicidal treatments. According to the analyzed data at 35 days of the herbicidal treatments, the sole application of Goltix, Tegro and Betanal herbicides at the recommended concentrations led to a prominent impact on reducing dry matter content and total weights of both broad- and narrow-leaved weeds in the two successive seasons as compared with the untreated control (Table 3). The results exhibited a highly significant reduction percentage amounted to 72.24% – 89.26%, in response to the various herbicide treatments (Fig. 2). Notably, no much significant differences were observed between the individual application of the three herbicides and their uses at 75% of the recommended concentration, along with urea at 2% of the carrier volume. The least significant differences was recorded with applying 50% of the herbicides in combination with urea as compared with the control. Goltix and Betanal were, to some extent, more effective against narrow-leaved weeds. In contrast, Tegro had a good impact against broad-leaved weeds, whether applied alone or in combination with urea. Hand hoeing twice achieved the best results in suppressing weed growth, resulting in an overall reduction rate of 90.83% – 94.20% (Fig. 2). Obviously,

Table 3 Weed growth as affected by the different control treatments at 50/60 DAS during the two successive seasons (2019/2020 and 2020/2021)

Treatments	Broad leaves (g m^{-2})		Narrow leaves (g m^{-2})		Total weeds (g m^{-2})	
	2019/2020	2020/2021	2019/2020	2020/2021	2019/2020	2020/2021
Goltix	85.23c	90.07cd	53.67ef	83.07fg	138.90e	173.17d
Goltix 75% + Urea*	91.30c	96.37bc	61.77e	90.37ef	153.10d	186.77d
Goltix 50% + Urea	105.10b	105.36b	73.17d	98.27de	178.30c	203.67c
Tegro	62.30f	75.67e	96.67c	106.70cd	159.00d	182.37d
Tegro 75% + Urea	69.40f	83.47de	103.47c	114.47bc	172.90c	198.00c
Tegro 50% + Urea	78.20e	95.67bc	115.27b	120.27b	193.50b	216.00b
Betanal	75.30e	85.27cde	45.67f	54.37h	121.00f	139.67f
Betanal 75% + Urea	83.70d	96.50bc	52.77f	60.07h	136.55e	157.27e
Betanal 50% + Urea	95.30c	103.47b	60.06e	75.27g	155.40d	178.80d
Two hand hoeing	41.70g	35.70f	35.67g	41.27i	77.40g	77.00g
Unweeded control	580.47a	615.07a	415.30a	450.27a	955.80a	1065.40a

* At a rate of 2% (v/v) of the carrier volume. Weed growth was expressed as dry matter content (Dr. Wt.). Data of Tegro-based herbicidal treatments were exceptionally taken at 50 DAS. Means followed by the same letter within a column are not significantly different according to Duncan's multiple range test at 0.05 probability (namely the values that do not share a letter are significantly different)

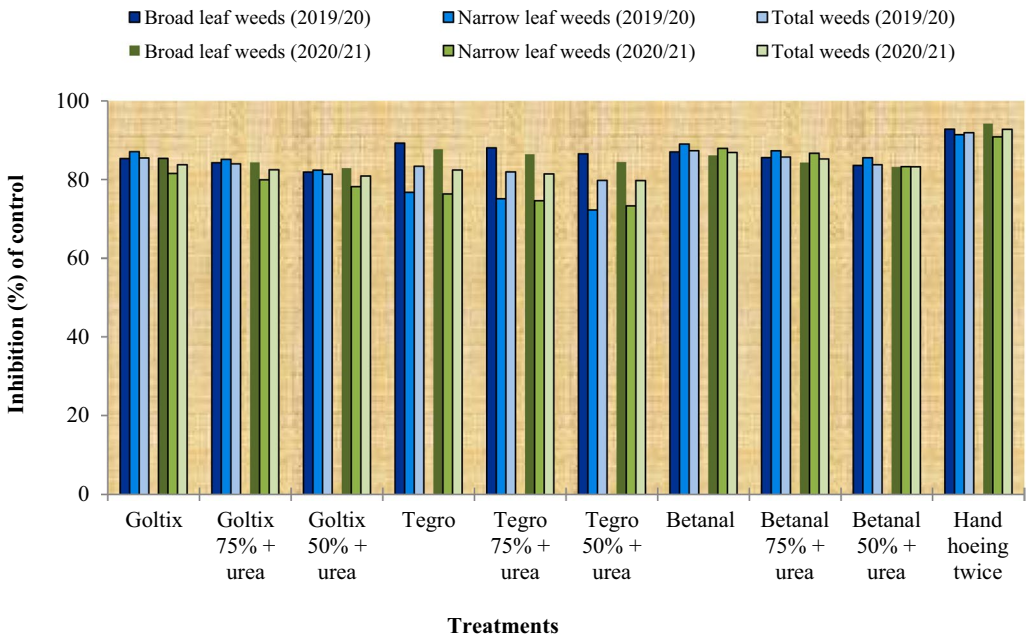


Fig. 2 Weed growth in response to the different control treatments at (50/60 DAS, based on the herbicidal treatment) during the two successive seasons (2019/2020 and 2020/2021). Data were derived from statistically analyzed measurements

the data obtained were, to a large extent, congruent in both seasons at the level of all studied criteria (Table 3).

Similar significant results were found concerning suppressing weed growth at 75 days of the herbicidal treatments, where weed growth was quite differentially affected by the tested treatments compared to the control (Table 4). Goltix, Tegro and Betanal demonstrated a consistent approach in controlling weeds. In this connection, there were no significant differences between Goltix treatments, whether applied alone or in combination with urea in effecting broad- or narrow-leaved weeds, with only slight significant differences noted in total weed growth. A similar pattern was noted with Betanal herbicide and its combinations. Broad- and narrow-leaved weeds responded differently to Tegro treatments, but ensured equivalent total weed losses compared to the

Table 4 Weed growth as affected by the different control treatments at 90/100 DAS during the two successive seasons (2019/2020 and 2020/2021)

Treatments	Broad leaves (g m^{-2})		Narrow leaves (g m^{-2})		Total weeds (g m^{-2})	
	2019/2020	2020/2021	2019/2020	2020/2021	2019/2020	2020/2021
Goltix	121.00bcd	130.10bcd	102.23def	103.73ef	223.23cde	233.83de
Goltix 75% + Urea*	126.70bc	137.50bc	110.17cde	113.50ef	236.87bc	251.00bc
Goltix 50% + Urea	131.90b	145.30b	115.17cde	120.13cde	247.07b	265.43b
Tegro	75.30d	86.30e	126.00bcd	135.33bcd	201.30e	221.63e
Tegro 75% + Urea	81.60cd	93.50de	131.10bc	141.30bc	212.70de	234.80de
Tegro 50% + Urea	87.30bcd	101.20cde	139.90b	150.13b	227.20bcd	251.33bc
Betanal	115.70bcd	126.10bcd	90.47ef	96.70ef	206.17de	222.80e
Betanal 75% + Urea	125.30bc	133.20bc	96.50ef	105.170ef	223.23cde	238.37cd
Betanal 50% + Urea	130.50b	139.10bc	105.17de	112.70ef	235.67bc	251.80bc
Two hand hoeing	79.10cd	85.30e	79.63f	89.97f	158.73f	175.27f
Unweeded control	1260.10a	1310.50a	703.10a	745.17a	1963.23a	2055.67a

* At a rate of 2% (v/v) of the carrier volume. Weed growth was expressed as dry matter content (Dr. Wt.). Data of Tegro-based herbicidal treatments were exceptionally taken at 90 DAS. Means followed by the same letter within a column are not significantly different according to Duncan's multiple range test at 0.05 probability (namely the values that do not share a letter are significantly different)

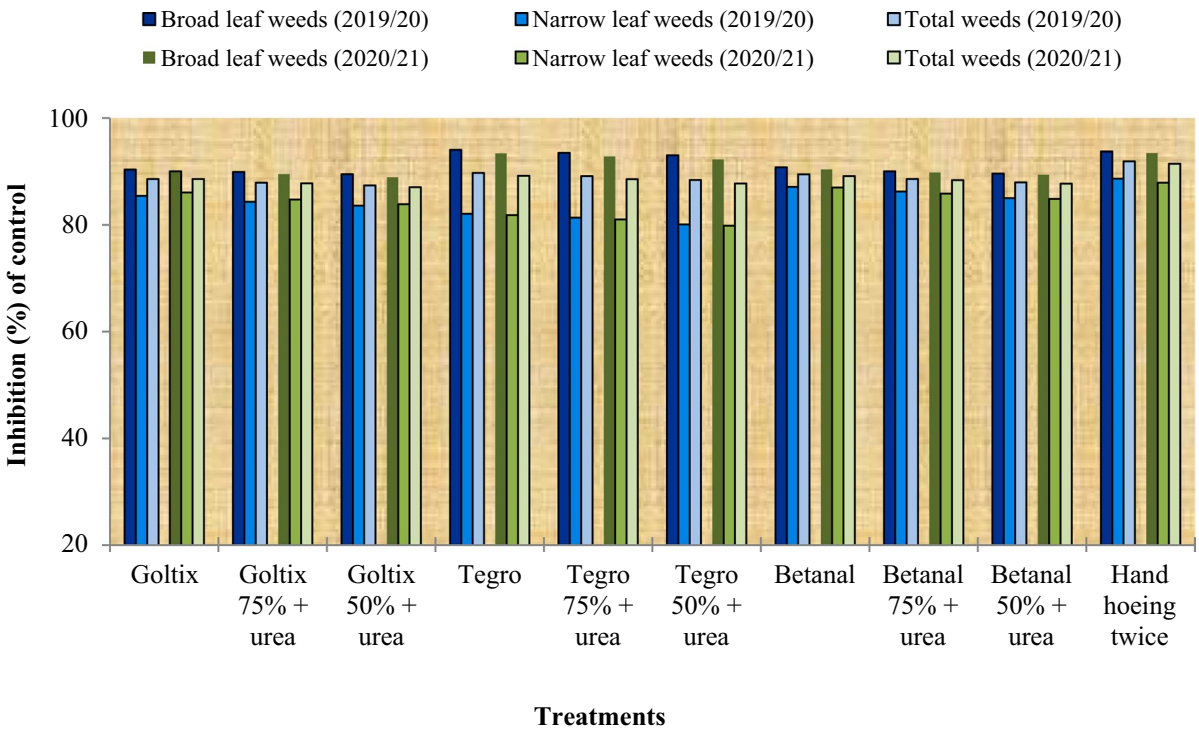


Fig. 3 Weed growth in response to the different control treatments at (90/100 DAS, based on the herbicidal treatment) during the two successive seasons (2019/2020 and 2020/2021). Data were derived from statistically analyzed measurements

untreated plots (Table 4 and Fig. 3). In general, the data showed a reduction range of 88.91 – 94.02% for broad-leaved weeds, with a lesser impact on narrow-leaved weeds (79.85 – 88.67%) in response to the different herbicidal treatments. Total weed yields decreased by 87.42 to 89.75%. The best results were observed with Tegro, whether applied alone or as a spray solution with urea compared with the other two herbicides; 79.85 – 94.02% inhibition was recorded for broad- and narrow-leaved weeds, with an overall reduction of 87.77% – 89.22% for

total weed growth. Obviously, hand hoeing twice outperformed all chemical weed control treatments, achieving up to a 93.72% reduction in both broad- and narrow-leaved weeds and 91.47% in total weed growth (Fig. 3).

On the other hand, the different weed control treatments had a remarkable significant effect on enhancing the shoot growth (leaf weight) and root development (*i.e.*, root weight, root length and root diameter) of sugar beet plants compared to the unweeded control treatment (Table 5). It is noteworthy that weeds caused a substantial decline in sugar beet development, affecting both root and shoot characteristics, with reductions ranging from 19.25% to 66.02% (data not reported). No much significant differences in efficacy were observed between the different chemical weed control treatments throughout the two successive seasons, with the most significant effect attributed to the full dose of the herbicides and those applications comprising 75% of the herbicides plus 2% urea. Comparison of differences between the herbicide treatments pointed to an increase of up to 154.29% in shoot and root weights, with a less significant increment in root length (up to 40.10%) and root diameter (up to 63.25%) compared to the unweeded control. The 50% reduced doses of herbicides in association with urea were not as effective as the other treatments, demonstrating lower overall efficiency. Hand hoeing twice recorded the highest values in promoting shoot weight, root weight, root length and root diameter (up to 179.07%, 171.11%, 43.40% and 67.72%, respectively), followed by Betanal, regardless of whether applied alone or in combination with urea (Fig. 4). The results were largely convergent in both seasons for approximately all estimated criteria.

The study recorded a clear effect on crop productivity by the end of the growing season. The lowest growth and yields were achieved when weeds were not controlled. In this context, weed growth coincided with a significant decrease in sugar beet growth and root yield (up to 52.17% each), alongside a reduction in sugar yield of up to 68.68% (data not reported). Similar trend of results was noted regarding the effect of the various treatments on promoting vegetative growth and yield characteristics including white sugar yields (Table 6). Mostly, there were no significant differences between the full-dose applications of herbicides and those applied as a 75% spray solution with urea, regardless of the trait evaluated. Excluding root length in the first season, the average percentage increase in crop growth and yield from the unweeding treatment (control) reached about 47.27% – 233.23% for herbicides applied alone and 36.36% – 209.60% for those applied as 75% herbicide solutions with urea. The least significant increment was obtained from using half of the recommended concentration of the herbicides in combination with urea (27.27% – 154.38% increase), compared with the other treatments (Fig. 5). Hand-hoeing treatment demonstrated a superior impact, largely equivalent to the use of Goltix, Tegro and Betanal herbicides alone in promoting sugar yield, which was estimated at 10.57–11.03 t ha^{-1}, compared to the weedy check plots (3.31 t ha^{-1}). A parallel trend was recorded for sugar beet root yield and root characteristics (length and diameter), in response to these treatments (Table 6).

Table 5 Sugar beet growth characteristics as affected by the different weed control treatments at 100 DAS during the two successive seasons (2019/2020 and 2020/2021)

Treatments	Shoot growth (kg $plant^{-1}$)		Root growth (kg $plant^{-1}$)		Root length (cm $plant^{-1}$)		Root diameter (cm $plant^{-1}$)	
	2019/2020	2020/2021	2019/2020	2020/2021	2019/2020	2020/2021	2019/2020	2020/2021
Goltix	0.87bcd	0.85bcd	1.08abc	0.95c	25.47abc	24.03a	8.51abc	8.32ab
Goltix 75% + Urea*	0.82cd	0.80bcde	0.94abc	0.90c	24.3cd	22.93a	8.02c	8.02ab
Goltix 50% + Urea	0.78d	0.75e	0.90abc	0.87c	22.1d	21.23b	7.13d	7.05bc
Tegro	0.90bc	0.87bc	1.06abc	1.01b	26.03abc	25.03a	8.75ab	8.61a
Tegro 75% + Urea	0.87bcd	0.84bcd	0.67bc	0.95c	25.00bc	24.03a	8.2bc	7.69ab
Tegro 50% + Urea	0.80cd	0.78de	0.93abc	0.92c	24.60 cd	22.17a	7.30d	7.01bc
Betanal	0.96b	0.89b	1.19ab	1.13ab	27.60ab	22.17b	9.00a	8.95a
Betanal 75% + Urea	0.90bc	0.85bcd	1.06abc	1.01ab	26.27abc	24.20a	8.30bc	7.99ab
Betanal 50% + Urea	0.86bcd	0.81cde	0.65bc	0.92c	24.33 cd	23.07a	7.50d	7.20bc
Two hand hoeing	1.20a	1.03a	1.35a	1.22a	28.10a	26.20a	8.99a	8.75a
Unweeded control	0.43e	0.35f	0.52c	0.45d	19.70e	18.27b	5.36e	6.02c

* At a rate of 2% (v/v) of the carrier volume. Shoot and root growth was expressed as dry matter content (Dr. Wt.). Means followed by the same letter within a column are not significantly different according to Duncan's multiple range test at 0.05 probability (namely the values that do not share a letter are significantly different)

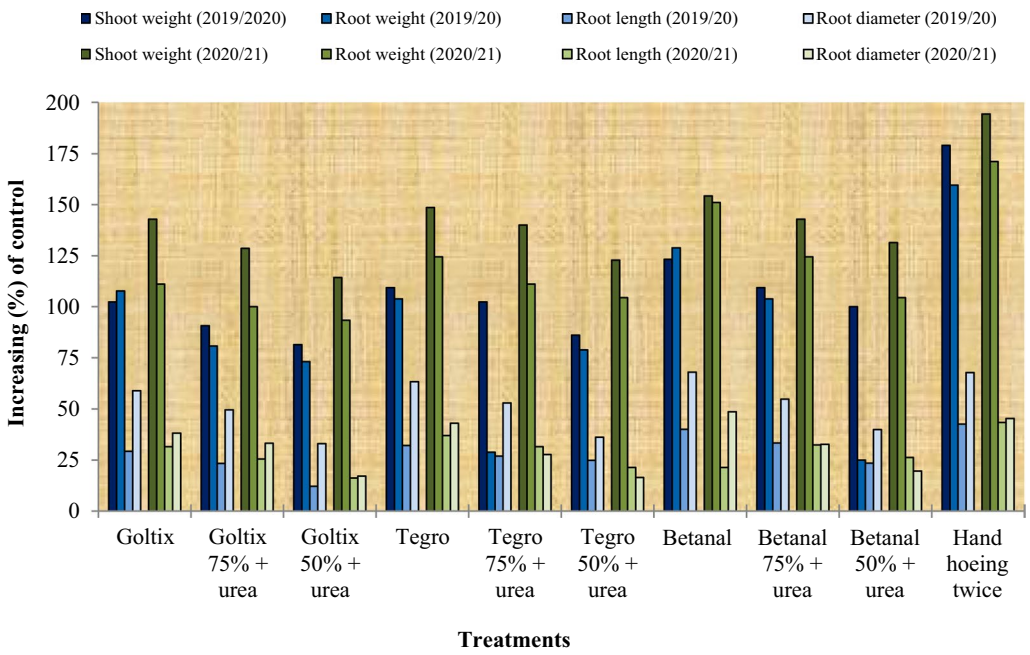


Fig. 4 Beet growth in response to the different weed control treatments at 100 DAS during the two successive seasons (2019/2020 and 2020/2021). Data were derived from statistically analyzed measurements

The data illustrated in Table 7 and Fig. 6 refer to the potential impact of weed control treatments on sugar beet quality. The treatments exhibited clear differences in affecting sugar beet quality parameters, which reflected positively on sucrose content and sugar losses to molasses. Regardless of treatment modality, sucrose content, extractable sugar and juice purity percentages were markedly increased compared to the untreated control. The maximum results were obtained with the sole application of the herbicides, accompanied by minimal sugar losses to molasses. While Goltx, Tegro and Betanal alone had a significant role on increasing sucrose content and extractable sugar (28.06% – 47.50%), using these herbicides at 75% concentration with urea was, to some extent, less efficient (11.16 – 44.53%, Fig. 6). Lower activity was recorded for the mixtures containing half doses of herbicides combined with urea. Juice purity was fairly increased, with the best results observed with the herbicides applied alone (up to 18.20%) and 75% diluted herbicide treatments (up to 17.48%). Similar results were attained with regard to sugar losses to molasses. Most likely, hand hoeing twice had a statistically significant effect comparable to that of the herbicides applied alone for all the studied parameters. Minimal results were recorded with the untreated control treatment (Table 7). In uncontrolled conditions, weeds significantly reduced sugar beet quality, including sucrose content, extractable sugar and juice purity percentages (12.36% – 34.86%), while also leading to increased sugar loss to molasses [up to 38.60% (data not reported)].

As undesirable contents affecting the quality of extracted white sugar, weed control treatments significantly decreased juice impurities in terms of potassium, sodium, α-amino N and alkalinity coefficient (Table 8 and Fig. 7). Regardless of whether applied alone or in combination with urea, herbicides-based weed control treatments resulted in fluctuated results in affecting potassium, sodium and α-amino N elements in sugar juice as compared with unweeded control. At the same time that, sodium content was significantly declined by herbicidal treatments (12.82% – 61.74%), and potassium and α-amino N composition were consistently increased (up to 53.62%). However, an improvement in alkalinity coefficient was recorded with all weed control treatments. Overall, the lowest values of impurities were detected with hand hoeing twice, indicating it as the most effective treatment in this regard, with reductions in content ranging from 14.57% to 55.86% (Fig. 7). In contrast, higher values of purported impurities (19.12% – 126.56% increments) and alkalinity coefficient (up to 28.38% increment) were recorded under uncontrolled conditions (data not reported).

Table 6 Growth, productivity and yield characteristics of sugar beet at harvest stage as affected by the different weed control treatments during the two successive seasons (2019/2020 and 2020/2021)

Treatments	Shoot growth (kg plant^{-1})		Root length (cm plant^{-1})		Root diameter (cm plant^{-1})		Root yield (t ha^{-1})		Sugar yield (t ha^{-1})	
	2019/2020	2020/2021	2019/2020	2020/2021	2019/2020	2020/2021	2019/2020	2020/2021	2019/2020	2020/2021
Goltix	20.70bc	82.03ab	33.00abc	32.40abc	12.50ab	12.00ab	79.70d	82.03ab	9.62b	10.18b
Goltix 75% + Urea	19.00bc	77.03d	30.57bcd	30.00bcd	12.00ab	11.70ab	77.20f	77.03d	8.09de	9.06c
Goltix 50% + Urea	18.20c	73.03e	28.10d	28.00d	11.00b	10.30b	73.50h	73.03e	7.75e	7.80d
Tegro	21.00bc	80.30bc	34.00ab	33.50ab	13.00ab	13.00a	81.03c	80.30bc	11.25a	11.03a
Tegro 75% + Urea	20.00bc	77.53cd	31.90abc	31.00abcd	11.57ab	11.50ab	78.47e	77.53cd	10.69a	10.23b
Tegro 50% + Urea	19.03bc	72.73e	29.50cd	29.00cd	11.03b	10.90ab	73.70h	72.73e	8.91bc	8.42d
Betanal	21.70ab	81.03ab	34.03ab	33.70ab	13.50ab	13.10a	82.40b	81.03ab	11.19a	10.78a
Betanal 75% + Urea	20.30bc	78.10 cd	32.00abc	31.20abcd	13.00ab	12.50ab	79.57d	78.10cd	9.66b	9.37c
Betanal 50% + Urea	19.30bc	73.10e	30.70bcd	29.00 cd	12.40ab	12.00ab	75.20g	73.10e	8.64cd	8.11d
Two hand hoeing	23.50a	83.70a	35.40a	34.03a	14.10a	13.50a	85.50a	83.70a	11.09a	10.57a
Unweeded control	11.70d	40.03f	33.00abc	22.00e	8.30c	8.00c	42.30i	40.03f	3.98f	3.31e

* At a rate of 2% (v/v) of the carrier volume. Shoot growth was expressed as dry matter content (Dr. Wt.). Means followed by the same letter within a column are not significantly different according to Duncan's multiple range test at 0.05 probability (namely the values that do not share a letter are significantly different)

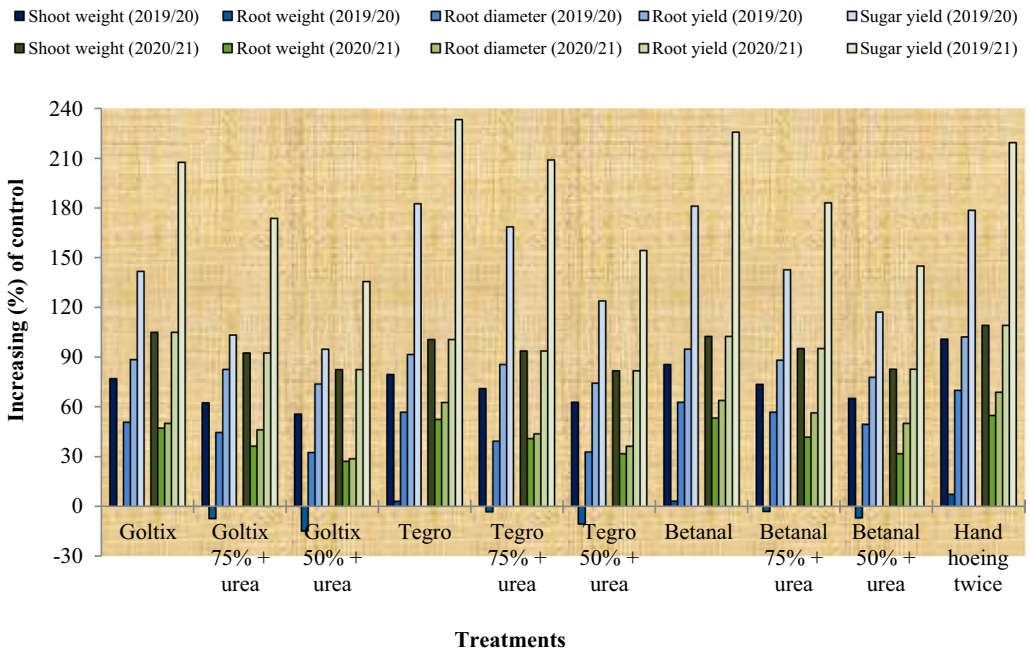


Fig. 5 Beet growth in response to the different weed control treatments at harvest stage during the two successive seasons (2019/2020 and 2020/2021). Data were derived from statistically analyzed measurements. Values in minus indicate to a decrease in estimation

Table 7 Qualitative characteristics of sugar beet harvested product as affected by the different weed control treatments during the two successive seasons (2019/2020 and 2020/2021)

Treatments	Sucrose (%)		Extractable sugar (%)		Juice purity (%)		Sugar lost to molasses (%)	
	2019/2020	2020/2021	2019/2020	2020/2021	2019/2020	2020/2021	2019/2020	2020/2021
Goltix	16.00ab	16.26ab	12.05d	12.73c	75.64b	78.34abc	3.35b	2.92d
Goltix 75% + Urea*	14.83abc	15.21b	10.46f	11.76e	70.39c	77.83bc	3.80a	2.75e
Goltix 50% + Urea	14.06bcd	14.40b	10.58f	10.68h	75.14b	74.17d	2.90de	3.12c
Tegro	17.20a	17.65a	13.88a	13.79a	80.76a	81.36a	2.70f	2.56f
Tegro 75% + Urea	16.70ab	16.25ab	13.60b	13.18b	81.44a	80.86	2.52g	2.52f
Tegro 50% + Urea	15.19abc	15.00b	12.10d	11.57f	79.71a	77.13bc	2.85e	2.83e
Betanal	16.96a	16.71ab	13.58b	13.31b	79.78a	79.70ab	2.80e	2.79e
Betanal 75% + Urea	16.02ab	15.81ab	12.15d	12.00d	75.78b	75.95cd	3.28bc	3.21b
Betanal 50% + Urea	12.22d	14.98b	11.49e	11.10g	75.16b	74.00d	3.20c	3.30a
Two hand hoeing	15.73ab	15.25b	12.97c	12.68c	82.72a	81.54a	2.15h	2.27g
Unweeded control	13.00cd	12.00c	9.41g	8.26i	72.50bc	68.83e	2.98d	3.14bc

* At a rate of 2% (v/v) of the carrier volume. Means followed by the same letter within a column are not significantly different according to Duncan's multiple range test at 0.05 probability (namely the values that do not share a letter are significantly different)

Discussion

Sugar beet is one of the most economically significant crops globally, yet it faces considerable challenges that impact its growth and yield. Among the key factors influencing sugar beet productivity, weeds emerge as one of the most destructive threats. Effective weed control, therefore, stands as one of the most crucial agronomic practices for enhancing sugar beet productivity, in terms of both quantity and quality. Despite the high adaptation of weeds to herbicides and the associated environmental and public health concerns resulting frequent herbicide use, herbicides are still widely perceived as the most convenient and effective mean in weed management strategies.

The field data from the present study demonstrated satisfactory results in controlling noxious weeds that

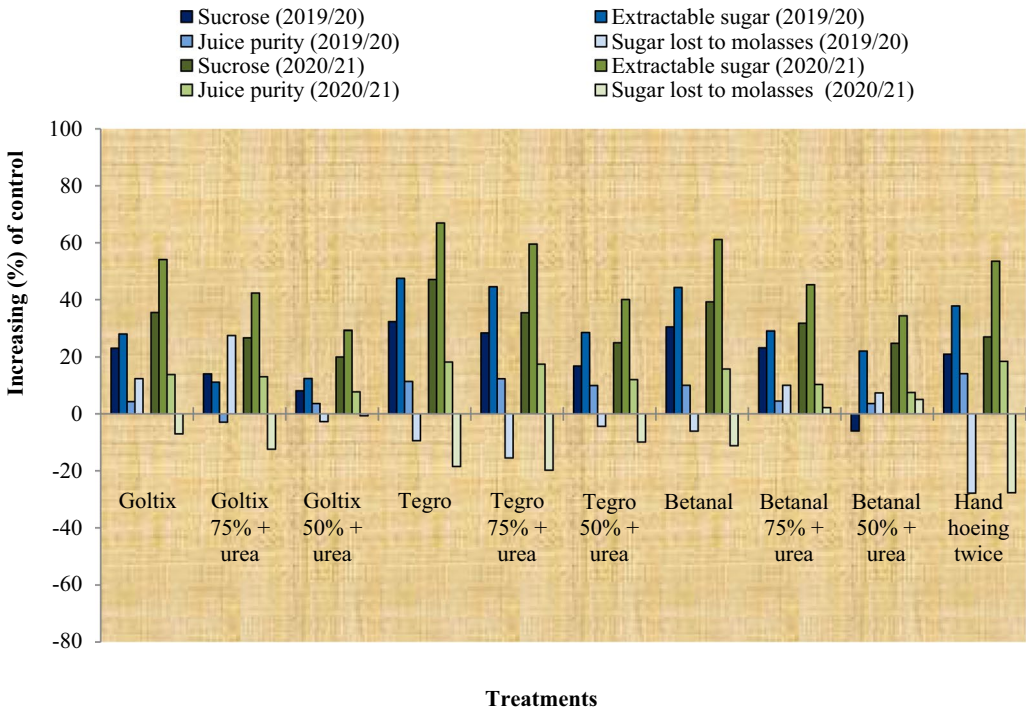


Fig. 6 Influence of different weed control treatments on sucrose, extractable sugar, juice purity and sugar losses to molasses (%) during the two successive seasons (2019/2020 and 2020/2021). Data were derived from statistically analyzed measurements. Values in minus indicate to a decrease in estimation

Table 8 Sugar impurities as affected by the different weed control treatments during the two successive seasons (2019/2020 and 2020/2021)

Treatments	Potassium (mg 100 g beet^{-1})		Sodium (mg 100 g beet^{-1})		α-amino N (mg 100 g beet^{-1})		Alkalinity coefficient	
	2019/2020	2020/2021	2019/2020	2020/2021	2019/2020	2020/2021	2019/2020	2020/2021
Goltix	3.77gh	3.60 fg	3.11e	3.21e	5.97b	7.85a	1.16g	1.16f
Goltix 75% + Urea*	3.91f	3.80ef	3.06e	3.10e	5.26c	5.16cd	1.32f	1.35de
Goltix 50% + Urea	3.65i	3.48g	4.76b	4.50b	6.70a	6.00bc	1.26f	1.33de
Tegro	4.67c	4.46c	2.39f	2.20h	4.88d	4.50cd	1.44e	1.48cd
Tegro 75% + Urea	4.16e	4.10d	3.03e	3.15e	4.05e	4.00d	1.79b	1.81a
Tegro 50% + Urea	3.72hi	3.95de	2.55f	2.85f	5.84b	5.50bc	1.07h	1.25ef
Betanal	5.30b	5.20b	2.66f	2.75f	4.77d	4.70cd	1.68c	1.69b
Betanal 75% + Urea	5.80a	5.70a	3.39d	3.50d	5.95b	5.70bc	1.55d	1.61bc
Betanal 50% + Urea	4.48d	4.20d	4.12c	4.00c	6.54a	6.60b	1.26f	1.24ef
Two hand hoeing	3.19j	3.17h	2.41f	2.55g	3.29f	3.93d	1.70c	1.48cd
Unweeded control	3.80cfg	3.95de	5.46a	5.75a	4.68d	5.11cd	1.99a	1.90a

* At a rate of 2% (v/v) of the carrier volume. Means followed by the same letter within a column are not significantly different according to Duncan's multiple range test at 0.05 probability (namely the values that do not share a letter are significantly different)

pose problems in sugar beet cultivation in this area of the newly reclaimed soils of the Egyptian deserts. Broad- and narrow-leaved weeds exhibited slight variations in their responses to the different herbicide treatments. However, all treatments contributed to a substantial and relatively equivalent reduction in overall weed growth. The highest biomass of broad-leaved, narrow-leaved and total weeds was recorded in the untreated (weedy check) plots, whereas the lowest values were observed with the hand-hoeing treatment, followed by the herbicides applied at the recommended dose, and then by the treatments at 75% of the recommended dose combined with urea.

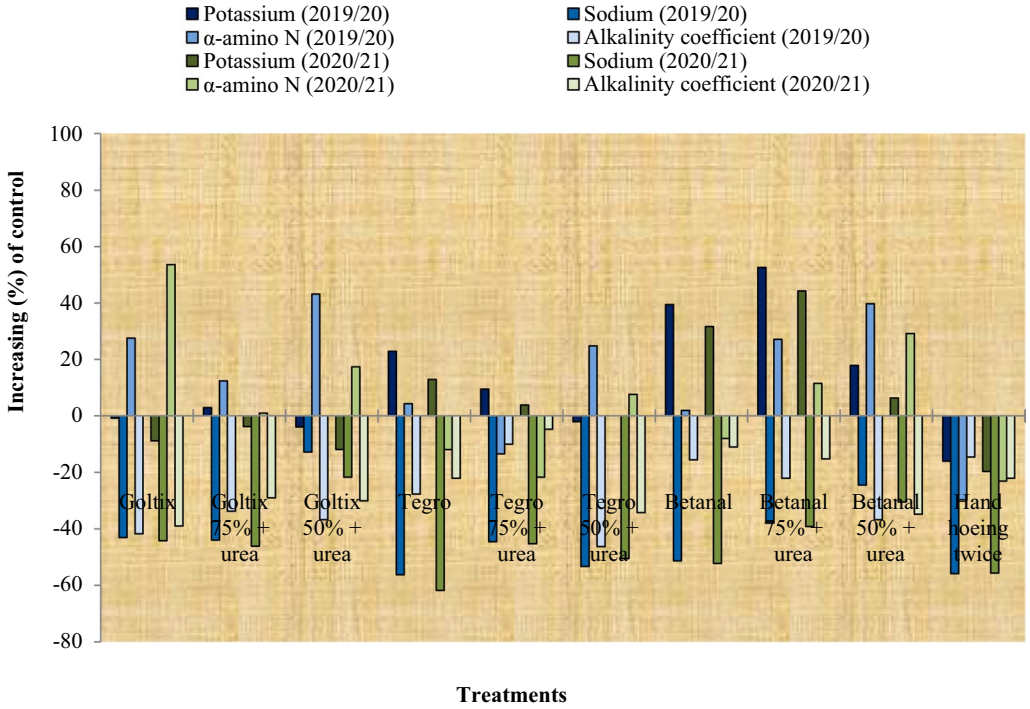


Fig. 7 Sugar quality, as indicated by impurity levels, in response to various control treatments at harvest stage during the two successive seasons (2019/2020 and 2020/2021). Data were derived from statistically analyzed measurements. Values in minus indicate to a decrease in estimation

Herbicides applied at 50% of the recommended dose plus urea were the least effective.

The separate application of Goltix, Tegro and Betanal herbicides at the recommended rates showed remarkable results in controlling both broad-leaved and grassy weeds by significantly reducing dray matter accumulation. Undoubtedly, the use of these high herbicide doses is associated with increased production costs and may have far-reaching implications for public health and environmental sustainability. In contrast, the use of low doses of herbicides (*i.e.*, 75% of the recommended rate) in combination with urea at 2% in volume caused, to a great extent, similar effects to using the full recommended rates of herbicides alone, leading to significant reduction in weed biomass and growth inhibition over the two growing seasons. Furthermore, this approach contributed to broadening the spectrum of controlled weed species. Paradoxically, weed control resulting from herbicide combinations at half the recommended doses with urea was the lowest across all evaluated criteria.

Published research has reported various weed control methods and dispersed empirical findings, in some cases obtaining similar significant results that are consistent with the current study. Most studies have highlighted the effectiveness of Goltix, Tegro and Betanal herbicides in suppressing weeds in sugar beet cultivation. For instance, Tegro has been reported as a potent herbicide for managing grassy weeds in sugar beet, while Betanal MaxxPro has demonstrated excellent efficacy as a broad-leaved weed suppressant (Abd El Lateef et al. 2021). The preemergence application of 1.0 L ha^{-1} Goltix, followed by two to four post-emergent applications of 1.0 L ha^{-1} Goltix plus 1.5 L ha^{-1} Betanal as a tank mix, was found to provide weed control efficacy equal to that of two or three glyphosate applications in sugar beet field (Bezhin et al. 2015).

According to the literature, herbicides are applied at higher single doses than required to achieve maximum results in controlling weeds and enhancing sugar beet growth (Lystad and Peters 2023). The overarching purpose of using urea in this study is to minimize the applied dose of herbicides while maintaining their effectiveness. Decreasing production cost, avoiding purported ecological and health risks, as well as preventing the development of resistant weeds are also valuable targets to be considered in this regard. Reducing the recommended dose of herbicides is one of the important strategies in weed management systems and has more than line of work (Deveikyte and Seibutis 2015). Traditionally, two main strategies are common to reduce herbicide application while maximizing economic return and minimizing herbicide load on the environment: reducing herbicide use toward the absolute minimum lethal dose or the number of treatments (Lauk 2004; Zargar et al. 2014;

Deveikyte et al. 2015). Today, synthetic herbicides are often applied at relatively low doses with increased frequency (up to four times) to ensure optimal efficacy and selectivity (Cioni and Maines 2010; Kraehmer et al. 2014), although this practice may inadvertently contribute to nontarget resistance in weeds (Tafoya-Razo et al. 2019). Early control is crucial in this connection as combating weeds become more challenging when plants reach more advanced development stages (Chitband et al. 2014). Additionally, two or more herbicides can be combined in low quantities to achieve broader activity against problematic weeds (Bezhin et al. 2015; Chitband et al. 2017; Lobmann and Petersen 2018), considering various reference models of herbicide interactions including additive, synergistic or antagonistic effects (Barbieri et al. 2022). While such procedure is both cost-efficient and reliable, its success is contingent upon certain factors such as the type of herbicides used, the optimal dosage for the mixture and the specific weed and crop species targeted (Abdollahi and Ghadiri 2004). Indeed, reducing herbicide application rates helps prevent crop stress and the potential symptoms of phytotoxicity. However, the potential impact of herbicide interactions when applied in mixtures on soil processes of sorption, desorption, half-life and leaching in the soil should be meticulously evaluated, as these interactions may alter the conception of their environmental impact and guide future strategies for herbicide use and control (Silva et al. 2022; Alehashem et al. 2024). According to Bezhin et al. (2015), using two to four post-emergent applications, as needed, of 1 L ha^{-1} Goltix Gold combined with 1.5 L ha^{-1} Betanal Expert significantly enhances the potential for achieving thorough weed management in sugar beet. This finding aligns with that reported by Lauk's (2004).

In parallel, nitrogen-based adjuvants, such as urea and urea–ammonium nitrate, are also widely used to promote the performance of low dose of foliar-applied herbicides in various cropping systems, including sugar beet (Koger et al. 2007; Deveikyte et al. 2105; Idziak et al. 2023; Soltani et al. 2023). Samai and Muhidin (2021) reported that using urea with glyphosate to control weeds under minimum tillage conditions was as effective as applying glyphosate alone at the high recommended dose, while offering two key advantages: reduced control costs and minimized crop toxicity. Similarly, co-application of ammonium nitrate, ammonium chloride, urea–ammonium nitrate or ammonium sulfate in a tank mixture with herbicides has showing promising results in optimizing weed control efficiency (Izadi-Darbandi et al. 2019; Reddy et al. 2021; Mookodi et al. 2023). Additionally, the use of low molecular weight dioxolanes (1% v/v) as adjuvants with glyphosate significantly reduced the herbicide dose required to achieve 100% weed control in *Chenopodium album* L.: by 40% when combined with 2,2-dimethyl-1,3-dioxolane, 50% with 2,2,4-trimethyl-1,3-dioxolane and 40% with (2,2-dimethyl-1,3-dioxan-4-yl)methanol (Szwajczak et al. 2023).

Limited information is available regarding the underlying mechanisms by which nitrogen fertilizers enhance herbicide efficacy. Despite numerous studies documenting their performance, few have provided clear interpretations of the possible interactions in this regard. In general, incorporating common nitrogen sources such as urea, urea–ammonium nitrate or ammonium sulfate along with reduced herbicide doses accelerates plant death and increases the control level (Soliman et al. 2011; Soltani et al. 2023). This effect is largely attributed to enhance herbicide absorption into plant tissues (Bunting et al. 2004; Pacanoski 2105), as well as to the role of nitrogen fertilizers as carrier solutions that exert synergistic effects (Soltani et al. 2012; Mookodi et al. 2023). Palma-Bautista (2020) linked the effectiveness of such adjuvants with their capacity to increase the retention time and decrease the contact angle of herbicide droplets on the leaf surface. Prolonged surface contact allows for extended uptake, enabling greater accumulation of active compounds in sensitive plant tissues and thereby improving herbicidal efficacy. On a physiological level, the rapid dissolution of urea into plant tissues creates a porous structure that facilitates deeper penetration of water-soluble substances such as herbicides (Sopeña et al. 2009). Furthermore, urea itself possesses weak to moderate phytotoxic activity and has traditionally been employed as a means to eradicate undesirable vegetation (Samai and Muhidin 2021). This supports the notion that urea may contribute independently to weed control when applied in combination with herbicides. The nature of this interaction, whether synergistic (greater than the sum of effects) or additive (equal to the sum of individual effects), has been explored in previous studies (Zhang et al. 1995; Barbieri et al. 2022). Without strictly adhering to conventional theories, foliar application of urea at high rates has demonstrated contact herbicidal activity, mainly due to the ammonium ions. These ions can also disrupt cytosolic pH and interfere with photophosphorylation processes in plant cells (Shilpha et al. 2023).

Similar to post-treatment weed growth monitoring, sugar beet growth data were collected sequentially over time (100 DAS and at harvest) to track trends and changes throughout the growing period. The root and shoot development of sugar beet plants responded similarly and consistently to weed suppression, with effective weed control resulting in substantial increases in both leaf and root characteristics. Evidently, there were no much significant differences in beet growth resulting from herbicide treatments applied individually at their

recommended rates. When herbicide doses were reduced by 25% and applied in combination with urea, the resulting efficacy was comparable to that of the full-dose treatments. Both the full-dose and the 75% rate herbicide plus urea applications exhibited similarly superior effects on enhancing sugar beet growth, improving overall biomass and dimensional traits of leaves and roots more effectively than the half-rate plus urea treatments. At both growth stages, leaf and root biomass, along with other morphological characteristics, was generally higher in the hand-hoeing treatment compared to herbicide-treated plots. A notable consistency between weed suppression and crop performance data was observed, suggesting several hypothetical explanations.

The results clearly point to the fact that poor weed growth supports crop competitiveness, thereby promoting healthier growth trajectories throughout the plant life cycle. The damage caused by weed growth is pervasive and causally linked to inferior crop growth outcomes. In fact, sugar beets are inherently vulnerable to weed competition due to their slow canopy closure and low plant height (Isika and Akca 2018). Moreover, factor such as lack of synchronization between peak solar radiation and full canopy development can further intensify weed competition, limiting the crop's ability to achieve its potential growth (Hoffmann and Kenter 2018). Effective weed control, therefore, helps rebalance competition for key growth elements, including light, water, nutrients and physical space within crop environment, thus nurturing a more consistent growth trajectory throughout the crop's development (Wenninger et al. 2019). Research indicates that once sugar beet plants overcome early weed competition, they grow more vigorously and aggressively combating later-emerging weeds (Kotlánová et al. 2024). All modern and conventional weed control strategies are built upon a core premise that sugar beet plants need to gain an initial competitive advantage over weeds early in the season (Isika and Akca 2018).

Apparently, the application of various control treatments significantly reduced yield losses or, rather, increased productivity by mitigating weed-related damage. According to our calculation-based conclusions, every 1000 kg ha^{-1} of oven-dried weeds present in sugar beet fields led to a substantial drop in sugar beet root yield ranging from 2,308.3 to 2,393.5 kg ha^{-1}, with corresponding declines in white sugar yield between 394.1 and 386.2 kg ha^{-1} (data not reported). These losses are considerably lower than earlier estimates; for instance, Wicks and Wilson (1983) reported root yield reductions of 10,000 to 11,500 kg ha^{-1} for every 1,120 kg ha^{-1} of oven-dried weeds.

The robust vegetative growth of crop plants, driven by effective weed control, had a significant positive impact on both root and sugar yields. Indeed, observed productivity trends were closely associated with enhanced vegetative development, as increases in shoot biomass consistently reflected corresponding gains in both root and sugar yields. Root and white sugar yields were higher in the weed control treatments, particularly with herbicides applied alone or those diluted with urea at 75% compared to the untreated plots. Notably, the two hand-hoeing treatment achieved the highest values in beet productivity.

As a valuable agricultural practice, the impact of hand hoeing extends beyond preventing the development of potentially serious weed infestations to enhance positively soil health. By breaking soil encrustations, hand hoeing promotes soil ventilation, improves water and nutrients retention, and strengthens root growth. The relative abundance of O_2 levels in aerated soil positively influences the microbial community, drives differences in C and N contents, and promotes root zone respiration (Zhang et al. 2021). According to well-documented research, no herbicide treatments have been as effective as sequential hand hoeing/weeding for achieving season-long weed control and enhancing productivity in sugar beet fields (El-Metwally et al. 2022).

In general, our results align closely with previous studies that have emphasized the significant role of weed management in enhancing sugar beet root and sugar yields. Majidi et al. (2017) and Abd El Lateef et al. (2021) reported that effective control of weeds infesting sugar beet fields resulted in a favorable return by enhancing both root yield and white sugar production. Tekleselassie and Yirefu (2013) indicated that removing weeds, particularly in the early stages of sugar beet growth, resulted in maximum root and sugar yield: 99% higher than in untreated (weedy) plots. Similarly, Mousa et al. (2015) confirmed that eliminating weeds using herbicides such as Goltix resulted in the highest recorded root yield. Taken together, weed control aids in creating a healthy environment with adequate moisture, nutrients and light, which in turn lead to increased sugar beet yield.

The results of this study showed significant advantages associated with weed control treatments in enhancing the quality of sugar yield. However, no substantial statistically significant differences were observed among the various treatment methods—whether herbicides applied alone, reduced herbicide doses (by 25%) combined with urea, or hand hoeing performed twice—with respect to improvements in key sugar beet quality attributes, including sucrose content, extractable sugar, and purity percentages. Consistent with well-established findings in the literature, hand weeding twice and specific herbicide treatments, notably Betanal and Tegro, have been identified as highly effective methods for promoting extractable

sugar, root quality and biological yields in sugar beet (Abd El Lateef et al. 2021). Concurrently, the chemical analysis revealed appreciable reductions in root impurities (potassium, sodium, α-amino N contents), as well as alkalinity coefficient and sugar lost to molasses across the studied weed control treatments. The highest values of these parameters were observed in the untreated control (weedy check) and treatments involving 50% herbicide plus urea. Empirical research has demonstrated an inverse relationship between alkalinity (defined as the ratio of sodium and potassium to nitrogen in the root) and the amount of sugar losses to molasses (Abd El-Rahman and El-Geddawy 2019). Additionally, Bocianowski et al. (2022) highlighted the detrimental effects of high potassium and α-amino N content on sugar beet quality. These elements, along with sodium, have been found to exert an inversely proportional effect on the amount of extractable white sugar (Enan 2016). Ultimately, any factor or conditions that elevate these impurities, such as heavy weed infections, salinity and drought stress or delayed harvesting, can reduce sugar beet quality and increase sugar lost to molasses (El-Geddawy et al. 2023; Abdou et al. 2024).

Conclusions

This two-year investigation demonstrated that urea can function effectively as an adjuvant to enhance the performance of the selected postemergence herbicides. At the recommended application rates, all herbicides (Goltix, Tegro and Betanal), achieved superior weed control and contributed to substantial improvements in both the quantitative and qualitative aspects of sugar beet yield. Notably, urea effectively compensated for the anticipated reduction in efficacy when herbicide dosages were reduced to 75% of the recommended rate. These improvements were unequivocally an indirect result of reduced weed competition, which enhances resource availability and creates a more favorable environment for crop growth. However, it was evident that none of the herbicide treatments was as effective as hand hoeing twice in ensuring season-long weed control and optimizing yield productivity. Although hand hoeing twice may excel in specific aspects of weed control and contribute to environmental sustainability, its labor-intensive, costly and time-consuming nature limits its practicality and desirability compared to herbicide treatments. Ultimately, co-applying herbicides at 75% of the recommended rate with 2% urea is recommended as an effective and cost-efficient approach for weed control in sugar beet, particularly during the early stages of crop development.

Abbreviations

DAS Day after sowing

EC Soil electrical conductivity

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Author contributions

Both authors contributed to the study conception, design, methodology, formal analysis and administrating the project. E.M.E. was responsible for resources, sampling, investigation and data collection. T.A.E. was involved in data curation, data interpretation, visualization, writing—original draft preparation and writing—reviewing and editing. The authors have read and agreed to the published version of the article.

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Data availability

All analyzed data supporting the findings of this study are included in this published article. Source data will be made available upon reasonable request from the corresponding author.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

There are no known competing interests to declare or personal financial relationships that could appear to influence the work reported in this manuscript.

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