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Effects of seed treatment and foliar fertilisation by chelated fertilisers on the productivity of sugar beets (*Beta vulgaris* L.)

Abstract. Sugar beets are a highly productive crop that requires a significant amount of micronutrients and trace elements. They are sensitive to a lack of micronutrients in the early stages of development, which can affect the morphological changes in the root crop and, consequently, reduce yield. The purpose of this study was to determine the effects of seed treatment with a complex of chelated fertilisers and the effects of foliar feeding on the biometric indicators of sugar beets, photosynthetic productivity, and technological qualities. The study was conducted on typical low-humus chernozems in the Right-Bank Forest-Steppe zone of Ukraine. To determine the mass of roots and leaves, leaf area, and photosynthetic productivity, samples were taken during the row closure phase, the mid-phase of intensive root growth, and the row reopening phase. Technological

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qualities, root yield, and sugar content were determined in plants selected at the physiological maturity phase. The study found that foliar feeding significantly increased root mass during the row reopening phase and physiological maturity. The highest root mass was formed in the seed treatment variant with a high content of trace elements and foliar feeding. The root mass reached 692 g with a yield of 59.6 t/ha and a sugar content of 16.6%. Technological indicators, particularly sugar yield for this variant, were also maximal at 9.86 t/ha. Nanofertilisers for foliar feeding enabled an increase in leaf area until the row reopening phase without reducing net photosynthetic productivity, which allowed the crops to accumulate more dry matter. Seed treatment with chelated fertilisers increased the accumulation of dry mass in the early stages, leading to a larger photosynthetic apparatus, which collectively resulted in increased productivity

Keywords: nanofertilisers; net photosynthesis; leaf area; dry matter; mass of the root crop; productivity; sugar content

INTRODUCTION

The creation and implementation of new environmentally safe and technological preparations designed to increase the efficiency of plant nutrient use of mineral fertilisers and soil is relevant for the global agricultural sector. According to D. Kour *et al.* (2020), biofertilisers, consisting of beneficial microorganisms, offer a sustainable and eco-friendly alternative to chemical fertilisers by enhancing soil nutrient availability and promoting plant growth through various direct and indirect mechanisms, ultimately improving crop yields without harming the environment. In their research on soybeans, S. Kalenska *et al.* (2022) highlighted the potential for advanced fertiliser technologies, including nanofertilisers, to offer targeted nutrient delivery, minimising environmental impact while maximising crop yield. As mentioned by N. Ahirwar *et al.* (2020), this helps to increase crop yields and product quality while increasing the overall efficiency of crop cultivation. The development of innovative technologies for growing plants in crops, such as nanofertilisers, growth-stimulating complexes, etc., are starting to play a significant role in increasing the efficiencies and quality of crops (Marchiol *et al.*, 2020). T. Farooq *et al.* (2023) highlighted the shift from conventional chemical fertilisers, which have a negative environmental impact, towards the use of nanofertilisers in sustainable agriculture. Nanofertilisers, utilising nanomaterials, offer controlled nutrient release and enhanced plant growth while minimising ecological harm.

The long-term availability of all nutrients to the plant during the full growing period is crucial to promote germination, growth, flowering, and fruiting (Koch *et al.*, 2020). The undoubted prospects for the development and widespread use of nanotechnology are that nanoparticles of biogenic metals have extremely high activity and sizes corresponding to the size of living cells, contribute to an increase in yields, gross harvests of crops, and product quality; increase the efficiency of nutrient use and their intended use, and reduce the toxicological burden on the environment due to a significant reduction in the gross volume of fertiliser and pesticide application (Gowda *et al.*, 2022).

According to J. Wang *et al.* (2022), the controlled release of nanofertilisers (nanoparticles) enhances plant growth and development while contributing to increased yields and overall productivity. The targeted delivery of nutrients using nanoparticles is employed to optimise the production process by directing their movement through specific areas of functional efficiency (Helal *et al.*, 2023). N. Konappa *et al.* (2021) explored how nanotechnology, specifically through nanopesticides and nanofertilisers, can revolutionise agriculture in developing countries by providing controlled release of agrochemicals, enhancing nutrient efficiency, and minimising environmental risks associated with conventional farming practices. The encapsulation of fertilisers and pesticides within nanoparticles, enabling a “slow release” mechanism, offers the potential

for precise dosage delivery to plants. This not only significantly reduces chemical waste and environmental contamination but also optimises nutrient uptake, thereby improving crop yields and promoting sustainable agricultural practices. A. Elnahal *et al.* (2022) highlighted that incorporating nanomaterials into crop cultivation technologies ensures consistently high yields while reducing the environmental impact of agricultural practices. Specifically, M. Rizwan *et al.* (2019) found that the effects of these changes depend on varietal characteristics, the phase of plant development, and the intensity and duration of stress factors. The researchers found that foliar applications of titanium dioxide and silicon nanoparticles can effectively mitigate cadmium toxicity in rice plants, enhancing photosynthesis, and improving the antioxidant defence system.

The purpose of the present study was to determine the effect of chelate nanofertilisers for seed treatment and foliar fertilisation on the formation of photosynthetic parameters (leaf area, dry biomass accumulation, net productivity of photosynthesis), plant biometric indicators, and the productivity of yield and sugar content. Since microelements improve the course of physiological cycles and help counteract stress, they assist in realising the yield potential under existing conditions. Therefore, their effectiveness in field conditions should be considered.

MATERIALS AND METHODS

The field study was conducted at the farm enterprise "Rasavske", located in the Right-Bank Forest-Steppe zone of Ukraine (49°46' N, 30°44' E) in 2021-2022. The weather conditions are presented in Table 1.

Table 1. Weather conditions in 2021-2022 in the Right-Bank Forest-Steppe zone of Ukraine

Month	Air temperature, °C			Precipitation, mm		
	2021	2022	MA	2021	2022	MA
IV	10.5	13.3	8.6	55.7	23.1	45
V	15.4	18.4	15.0	38.0	42.1	44
VI	20.6	20.2	18.0	27.7	162.6	77
VII	20.9	21.1	19.4	18.5	103.8	88
VIII	22.4	22.0	18.7	22.7	21.2	61
IX	17	16.7	14.2	18.5	123.5	41
Average/sum	17.8	18.6	15.7	291.1	476.3	356

Note: MA – multi-annual average/sum based on data from 1990 to 2010

Source: developed by the authors

The weather conditions during the years of the study varied significantly from each other and from the long-term average. Notably, the beet growing season (late April to late September) in 2021 was characterised by high temperatures (+17.8°C) and lower moisture availability compared to the long-term average. The total precipitation was 291.1 mm, with a small amount in the summer months. In contrast, the conditions in 2022 were more favourable, with higher precipitation and an average temperature of +18.6°C. The total precipitation for that year was 476.3 mm during the beet growing season, with a peak in June (162.6 mm). These conditions are conducive to the development of a robust leaf apparatus, and consequently, increased root biomass and sugar content. Considering the contrasting weather

conditions of the years under study, the research on the effects of foliar application and seed treatment was comprehensive and addressed abiotic stresses caused by weather factors.

Soil of research plot was a typical low-humic chernozem, with the arable layer characterised by the following agrochemical and agrophysical indices: pH_{KOH} – 6.8; humus content – 4.9%; nitrogen content (alkaline-hydrolysed) – 145.5 mg per 1 kg of soil; labile phosphorus – 38.5 mg per 1 kg of soil; exchangeable potassium – 117.5 mg per 1 kg of soil. Micronutrient content of soil was as follows: Fe – 0.26 mg kg⁻¹; Mn – 5.21 mg kg⁻¹; Cu – 0.08 mg kg⁻¹; Zn – 0.11 mg kg⁻¹. The research design for investigating the effects of nanofertilisers on sugar beets of cultivar Nastya is presented in Table 2.

Table 2. Research design

Factor A: seed-treatment composition, g L ⁻¹ of solution				Factor B: Fertilisation system
Option	NCF SMP	NCF Zn	NCF P	
Control	–	–	–	B1. N ₁₂₀ P ₈₀ K ₂₀₀ + foliar fertilisation with Boron
T1	7	11	13	
T2	9	8	8	B2. N ₁₂₀ P ₈₀ K ₂₀₀ + foliar fertilisation with NCF
T3	8	12	7	

Note: NCF SMP – Nano Chelate Fertiliser Super Micro plus

Source: developed by the authors

The fertilisation system factor included two options: a background with spraying of Boron (500 g of Boron acid) and foliar fertilisation. The baseline option involved the application of NPK in autumn at 120:80:200 kg/ha. The alternative option involved the application of preparations according to the scheme

presented in Table 3 (Boron was applied at same stages). Aqueous solutions of fertilisers were prepared before spraying, which was conducted in the evening after 18 hours with a sprayer with a working fluid consumption rate of 300 l/ha. Sprayer OP-2000, volume 2000 l, working solution rate – 300 l/ha.

Table 3. Scheme of foliar fertilisation with nanochelate fertilisers

#	Application stage	Fertilisation	Rate, kg ha ⁻¹
1	8-10 leaves	Nano Chelate fertiliser Potassium 23% (P)	1.0
		Nano Chelate fertiliser Nitrogen 20%	0.2
		Nano Chelate enriched fertiliser Iron 10%	1.0
2	12-14 leaves	Nano Chelate Fertiliser Super Micro plus (SMP)	1.0
		Nano Chelate fertiliser Magnesium 25%	1.0
3	16-18 leaves	Nano Chelate fertiliser Potassium 23% (P)	2.0
		Nano Chelate fertiliser Calcium 25%	0.5

Note: fertiliser developer information

Source: developed by the authors

Nanopreparations for seed treatment contain micronutrients and macronutrients in a rapidly accessible form. Since certain micronutrients can exhibit phytotoxicity on seedlings,

their concentration in the treatment solution is maintained within permissible ranges. Nutrient content of applied fertilisers upon seed treatment is presented in Table 4.

Table 4. Nanofertiliser characteristics

Variant	Nutrient content in fertiliser, %											
	Fe	Zn	Mn	K	Mg	Cu	N	P	P ₂ O ₅	Mo	Ca	B
SMP	4.5	8	0.8	3	6	0.65	5	3	7.8	0.1	6	0.65
Zn		20					5					
P								25	65			
Nutrient content in seed treatment composition, mg L ⁻¹ of solution												
T1	315	2,760	56	210	420	45.5	900	3,460	9,000	7	420	45.5
T2	405	2,320	72	270	540	58.5	850	2,270	5,900	9	540	58.5
T3	360	3,040	64	240	480	52	1,000	1,990	5,170	8	450	52.0

Note: fertiliser developer information

Source: developed by the authors

The area of the individual plot was 40 m² (2.7 m × 15 m, 8 rows). The row spacing was 45 cm. Sowing was carried out in the third decade of April (22 April 2021 and 25 April 2022). The repetition of the experiment was threefold. Seed rate was 100 thsd seeds/ha. Field seed germination was 89.3-90.4%. The study was conducted using bioadaptive technology of sugar beet cultivation. The main soil tillage was semi-steam tillage. It included the following operations: stubble was peeled 5-6 days after harvesting the predecessor (winter wheat) with a universal disk stubble harvester UDA-2.4-20, which was aggregated with a tractor MTZ-82 to a depth of 8-10 cm. Under the predecessor (winter wheat), the following fertilisers were applied: potassium chloride – 120 kg/ha (potassium content 60%), phosphorus fertilisers – 80 kg/ha (ammonium phosphate with a phosphorus content of 50% and nitrogen content of 12%), nitrogen fertilisers – 200 kg/ha (ammonium phosphate in autumn and urea with a nitrogen content of 34% in spring).

Ploughing was carried out until August 15 after applying mineral fertilisers to a depth of 30-32 cm with a Lemken EuroDiamant 100-F 7 plow in combination with a CLAAS-Axion 840 tractor. In the first decade of October, the area was levelled, and weeds were destroyed with a USMK-5.4 cultivator, the working bodies of which were arranged for continuous tillage. In spring, the moisture was closed and pre-sowing tillage was conducted with the USMK-5.4 working razors for continuous tillage to a depth of 4 cm. Sugar beet was sown with a Kleine Multicorn precision beet seeder to a seeding depth of 4 cm. The seeds were treated with Cruiser, Force, Tachigaren, TMTD with a fraction of 3.5-4.5 mm. Sowing was carried out with KZK-6P rollers, which were aggregated with an MTZ-82 tractor.

The crop management system was aimed at controlling the number of weeds – spraying (first application) was performed when the weeds were in the cotyledon to two-leaf stage with Betanal Expert herbicides at 1 L/ha, Kariibu – 30 g/ha with Trend 90 adhesive at 0.3 l/ha, the second application was performed when new weed shoots appeared, from the cotyledon to the stage of 2 leaves, according to the same scheme. Against annual cereals in the phase of 2-4 leaves in weeds, the herbicide Fusilade

Forte 150 ES, e.e. was used at 1-2 l/ha. To protect plants from pests, the insecticide Nurel-D was used at 0.8 l/ha. Herbicides and insecticides were applied with an OP-2000 sprayer, which was aggregated with an MTZ-82 tractor. To protect against diseases of the leaf apparatus, if necessary, the fungicide Alto-Super 330 ES, c.e. with a consumption rate of 0.5 l/ha was used, spraying was performed with a knapsack sprayer. Sugar beet was harvested in late terms (1 October).

The research programme included the selection of plant samples across three stages of development: Stage 1 – leaf canopy cover interrows (Date 10.07), Stage 2 – intensive root growth (Date 10.08), and Stage 3 – pre-harvest (leaves discovered interrows, 10 September). At each growth phase, a minimum of 10 plants were sampled to determine the mass of roots and leaves. Leaf area was assessed by scanning the leaf surface of each plant, calculating the average and extrapolating to density per hectare.

The dry matter content was determined using a thermogravimetric method in a two-phase scheme. Samples were dried at 60°C for 12 hours, followed by further drying at 105°C until a stable weight was achieved. Accumulation of dry mass was calculated as the difference between the actual weight and the weight in the previous phase. Additional samples were taken during the Emergency phase (“E” in the table) to determine dry matter content and leaf area.

Net photosynthetic productivity (NPP) was calculated using the following formula (1):

$$NPP = \frac{DMA_n - DMA_{n-1}}{LA \times T_v}, \quad (1)$$

where DMA is the accumulation of dry biomass (n is a current stage, $n-1$ is a previous stage), g/m^2 ; LA is the average leaf area between two stages, m^2/m^2 ; T_v is the duration of the recording period, days.

Root mass for yield determination, sugar content, and sugar yield were assessed from samples obtained during the technological ripeness phase of beetroot as of 30 September. Plant density per hectare for individual plant metrics was calculated separately for each variant. Sugar content was determined by digesting the juice in a saccharimeter. Statistical calculations

were performed using Statistica 10.0. Two-way ANOVA and post-hoc analysis based on Tukey's HSD were conducted to determine differences between variants. The study followed the ethical standards outlined in the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1973) and the Convention on Biological Diversity (1992).

RESULTS

The positive effects of using nanofertilisers for seed treatment are manifested in an increase

in root mass during the phase of row closure (Table 5, Stage 1). The study found that foliar application significantly increased root mass in the row closure phase compared to similar seed treatment options without foliar application. Seed treatment with the T3 formulation led to a significant increase in root mass even without foliar application (182 g), and therefore the gain from foliar application was negligible. This fact indicates the effectiveness of foliar fertilisation, as on average, root weight gains were greater than the effect of this factor at this stage.

Table 5. Root, shoot, and plant weight of sugar beet during vegetation (average in 2021-2022), g

Factors		Stage 1			Stage 2			Stage 3		
F1	F2	R	L	Plant	R	L	Plant	R	L	Plant
C	B	171 ^a	276 ^{bc}	446 ^a	319 ^a	289 ^a	608 ^a	479 ^a	211 ^a	690 ^a
	B+FF	187 ^c	289 ^d	476 ^b	347 ^c	309 ^{ab}	656 ^c	506 ^c	220 ^{abc}	726 ^{cde}
T1	B	175 ^{ab}	266 ^{ab}	442 ^a	328 ^a	304 ^{ab}	632 ^{abc}	502 ^{bc}	215 ^{ab}	717 ^{bcd}
	B+FF	190 ^c	282 ^{cd}	471 ^b	341 ^{bc}	310 ^b	651 ^{bc}	518 ^c	230 ^c	747 ^e
T2	B	176 ^{ab}	264 ^a	440 ^a	327 ^a	308 ^{ab}	635 ^{abc}	487 ^{ab}	221 ^{abc}	708 ^{abc}
	B+FF	185 ^c	280 ^{cd}	465 ^b	341 ^{bc}	296 ^{ab}	636 ^{abc}	509 ^c	227 ^{bc}	736 ^{de}
T3	B	182 ^{bc}	266 ^{ab}	448 ^a	330 ^{ab}	298 ^{ab}	627 ^{ab}	479 ^a	221 ^{abc}	697 ^{ab}
	B+FF	185 ^c	282 ^{cd}	467 ^b	341 ^{bc}	303 ^{ab}	643 ^{bc}	513 ^c	226 ^{bc}	735 ^{de}
Average		181.3	275.5	456.8	334.0	302.2	636.2	498.8	221.3	720
CV, %		4.2	4.0	3.5	8.5	4.3	5.9	7.1	4.1	5.8

Note: R – root weight, g; L – leaves weight, g; Stage 1 – leaf canopy cover interrow; Stage 2 – intensive root growth; Stage 3 – pre-harvest (leaves discovered interrows); B – background; B+FF – background + foliar fertilisation. Same letters in column show no significant differences between variants by Tukey's HSD

Source: developed by the authors

The weight of the leaf surface in Stage 1 was the highest in the control variants of treated seeds (276 g and 289 g, respectively, in the system without and with foliar fertilisation), but was significantly lower in the nanopreparation treatment. At the same time, the total mass of the plant indicated that as early as at this stage, the processes of assimilation of dry matter and biomass in the root were dominant. The largest weight was formed by variants with foliar fertilisation (465-476 g), without a significant difference in the factor "seed treatment", while the plant weight was within 440-448 g without foliar fertilisation.

The root weight in Stage 2 repeated the trend of the previous stage, as foliar treatments gave significant increases compared to options without foliar application, considering the same seed treatments. Notably, the greatest effect of foliar

application was observed in the control variant, which resulted in a 28 g increase (+8.8%), while the others had a lower effect. Leaf mass in this stage varied little among the treatments and averaged 302.2 g. Most variants did not differ significantly from each other, with only the "T1 with foliar fertilisation" combination showing a significant difference from the untreated control. Foliar application significantly increased plant mass compared to the variant without its use, but for the T2 seed treatment, the difference was negligible (including the control variant).

In Stage 3, the root weight increased to 479-518 g, while the stem and leaves decreased to 211-230 g. The fertiliser system factor (presence or absence of foliar fertilisation) significantly influenced any variant of seed treatment with nanopreparations. The effectiveness of nanopreparations for seed treatment was manifested

only in the formulation T1, which significantly increased the root weight compared to the control and other variants – up to 502 g without foliar fertilisation and up to 418 g with their application. The total weight of the plant when applying nanopreparations for seed treatment was significantly greater both in the fertiliser system with and without foliar application, so seed treatment can be considered as a factor in increasing crop productivity with a long-term effect. Notably, the T3 seed treatment formulation without foliar application did not provide a significant increase compared to the control in terms of root growth and overall plant growth.

Trace elements in nanofertilisers play a vital role in the functioning of the enzymatic and photosynthetic systems of plants, and therefore their effects on dry matter accumulation are indirect. Since an increase in the concentration of

trace elements in a plant does not directly affect the dry matter growth, as with macrofertilisers, only the indirect effects on biometric parameters can be assessed or a nutrient deficiency can be stated. The study found that the investigated factors significantly affected the leaf area index in all the studied periods, but with different effects in the combination of factors (see Table 6). On the control variant without seed treatment in stage 1, the crops formed 27.6 thsd m²/ha of leaves in the variant without foliar fertilisation and 29.6 thsd m²/ha with their application (this variant also significantly differed from all others). The use of nanopreparations for seed treatment positively influenced the leaf area in the variants T2 and T3 in the system with foliar fertilisation, but when they were applied, it had the opposite effect – the leaf area was insignificantly lower than without seed treatment.

Table 6. Leaf area and photosynthetic parameters of sugar beet

Factors		LA, thou. m ² ha ⁻¹			DM accumulation, g m ⁻²			NPP, g DM per m ² ×day		
F1	F2	S1	S2	S3	E-S1	S1-S2	S2-S3	E-S1	S1-S2	S2-S3
C	B	27.6 ^a	37.7 ^a	27.6 ^a	469 ^a	312 ^a	180 ^{ab}	7.5 ^a	3.2 ^a	1.8 ^{bc}
	B+FF	29.6 ^d	41.4 ^{cd}	30.8	519 ^c	318 ^a	165 ^a	7.7 ^{ab}	3.0 ^a	1.5 ^a
T1	B	27.8 ^{ab}	40.7 ^{bcd}	28.6 ^b	480 ^{ab}	330 ^a	190 ^{bc}	7.6 ^{ab}	3.2 ^a	1.8 ^{bc}
	B+FF	28.8 ^{bcd}	42.5 ^d	32.2 ^{cd}	511 ^c	318 ^a	208 ^{cd}	7.8 ^b	3.0 ^a	1.8 ^{bc}
T2	B	28.2 ^{abc}	41.6 ^{cd}	28.2 ^{ab}	480 ^{ab}	338 ^a	166 ^a	7.5 ^a	3.2 ^a	1.6 ^{ab}
	B+FF	28.9 ^{cd}	39.7 ^{abc}	31.7 ^c	507 ^c	305 ^a	216 ^d	7.7 ^{ab}	3.0 ^a	1.9 ^c
T3	B	28.4 ^{abc}	38.2 ^a	28.8 ^b	489 ^b	314 ^a	164 ^a	7.6 ^{ab}	3.1 ^a	1.6 ^{ab}
	B+FF	29.3 ^{cd}	38.6 ^{ab}	32.7 ^d	509 ^c	316 ^a	208 ^{cd}	7.6 ^{ab}	3.1 ^a	1.9 ^c
Average		28.6	40.1	30.1	495.5	319.0	187.2	7.6	3.1	1.7
CV, %		3.4	5.2	6.6	5.4	13.6	13.2	2.6	11.9	12.2

Note: Stage 1 – leaf canopy cover interrow; Stage 2 – intensive root growth; Stage 3 – pre-harvest (leaves discovered interrows); B – background; B+FF – background + foliar fertilisation. Same letters in column show no significant differences between variants by Tukey's HSD

Source: developed by the authors

An analogous trend was observed in the next period is the maximum growth of the leaf surface. In the variant without seed treatment with nanopreparations, the leaf area was 37.7 thsd m²/ha under the fertiliser system without foliar fertilisation and increased to 41.4 thsd m²/ha with their implementation. At the same time, the T1 formulation was effective in both systems, as the leaf area increased by 3.0 thsd m²/ha (8.0%) and 1.1 thsd m²/ha (2.7%), respectively. When treating the seeds with the T2 formulation, the effect was different: the leaf area increased

significantly in the system without foliar fertilisation by +3.9 thsd m²/ha (10.3%), and in the system with foliar fertilisation, conversely, it decreased by 1.7 thsd m²/ha (-4.1%). Formulation of T3 was generally ineffective in the variant without foliar fertilisation and led to a decrease in leaf area when they were performed.

Since the activity of the photosynthetic apparatus depends on the leaf area and its viability during the growing season, it is advisable to evaluate this indicator at the time of harvesting (Stage 3). The study found that the effect of seed

treatment and foliar fertilisation was positive in terms of preserving a viable leaf surface. In the control variant of seed treatment (no treatment) under the fertiliser system without foliar application, the leaf area was 27.6 thsd m²/ha, while with fertilisation it was 30.8 thsd m²/ha. Under the fertilisation system without fertilisation, seed treatment allowed preserving more leaf surface – 28.6 thsd m²/ha and 28.8 thousand m²/ha (T1 and T3, respectively), which is significantly more than in the control. During foliar fertilisation, different formulations of nanopreparations for seed treatment showed differing effects. The most effective was the T3 formulation, where the leaf area in Stage 3 was 32.7 thsd m²/ha, which is 1.9 thsd m²/ha (+6.2%) more than in the control variant, while in T1 and T2 the increase was 1.4 thsd m²/ha (4.5%) and 0.9 thsd m²/ha (2.9%), respectively.

The net photosynthesis productivity (NPP) in the period from emergence to closure of rows varied insignificantly within the fertilisation system, i.e., did not depend on seed treatment. NPP during this period averaged 7.6 g DM/m² of leaves per day, with no significant difference between treatments except for the “T1 with foliar fertilisation” combination (7.8 g DM/m² × day). The dry mass accumulated by the crops varied more significantly. Under the basic fertilisation system, the crops accumulated 469 g/m² of dry matter, and when the seeds were treated with the T1 and T2 formulation, this indicator increased slightly (+11 g/m²), while T3 had a more significant effect (+20 g; +4.3%). Seed treatment with nanopreparations with foliar application increased biomass significantly compared to variant without foliar treatment, but in context of seed treatment difference between variant is absent). In the period from row closure to intensive root growth, the NPP did not differ significantly depending on the fertiliser or seed treatment and amounted to 3.0-3.2 g DM/m² per day. This is

explained by the variation in the accumulation of dry biomass during this period (CV 13.6%), and therefore the variants did not differ significantly from each other, although this indicator increased with foliar treatment. In the future (from intensive growth to the opening of the rows), the NPP decreased and ranged within 1.5-1.9 g of DM/m² per day. In the variant with foliar fertilisation without seed treatment, a significant decrease in NPP was observed, whereas in the other variants, this indicator did not change significantly. At the same time, foliar fertilisation positively influenced the accumulation of dry matter. When treated with the T1 and T3 formulation, the amount of dry matter increased by 15.6% (208 g), while in T2 it increased by 20.0%.

Since after the phase of intensive growth of root crops and opening of rows the redistribution of dry matter between the root and leaves occurs and trace elements play a vital role in these processes, the direct influence of these factors on the yield of root crops, their sugar content, and sugar yield per area should be considered. Indicators of root weight and root yield in the authors' studies have an almost linear relationship because the plantation density in all plots was within the same range with minor fluctuations in some variants. The study found that foliar application of fertilisers significantly increased root mass in all variants compared to control without foliar fertilisation (Table 7). The largest root mass was observed in the “T2-foliar fertilisation” combination at 692 g, while in T2 and T3 variants this value was slightly lower (672-684 g). This allowed achieving a yield level of 59.6 t/ha in the best variant, which is 14.4% greater than the control variant. The average sugar content in the study was 16.2%. There was a significant difference in sugar content between the control variant without foliar treatment (15.8%) and the T2 and T3 seed treatments with foliar fertilisation (16.6%).

Table 7. Root weight, root yield, and sugar yield as of 30 September

Factors		Root weight, g	Root yield, t ha ⁻¹	Sugar content, %	Sugar yield, t ha ⁻¹
F1	F2				
C	B	608	52.1	15.8 ^a	8.25 ^a
	B+FF	652 ^{ab}	55.9 ^{ab}	16.2 ^{ab}	9.06 ^{bc}
T1	B	637 ^a	54.7 ^a	16.0 ^{ab}	8.76 ^{ab}
	B+FF	644 ^a	55.1 ^a	16.4 ^{ab}	9.05 ^{bc}

Table 7, Continued

Factors		Root weight, g	Root yield, t ha ⁻¹	Sugar content, %	Sugar yield, t ha ⁻¹
F1	F2				
T2	B	672 ^{bc}	57.6 ^{bc}	16.2 ^{ab}	9.29 ^{cd}
	B+FF	692 ^c	59.6 ^c	16.6 ^b	9.86 ^e
T3	B	677 ^{bc}	58.1 ^{bc}	16.2 ^{ab}	9.36 ^{cde}
	B+FF	684 ^c	58.8 ^c	16.6 ^b	9.74 ^{de}
Average		658.2	56.5	16.2	9.17
CV, %		6.8	13.9	2.5	9.3

Note: B – background; B+FF – background + foliar fertilisation. Same letters in column show no significant differences between variants by Tukey's HSD

Source: developed by the authors

All research variants significantly increased sugar yield compared to the absolute control (without seed treatment and foliar fertilisation). The highest sugar yield (9.86 t/ha) was observed in variant T2 with seed treatment and foliar fertilisation. However, in variants with treatment T3, there was only a non-significant decrease in this indicator (9.36-9.74 t/ha).

The sugar content and yield correlate with the factory sugar yield, but there may be differences due to sugar losses through excess molasses formation. The main elements contributing to molasses formation are potassium and sodium, which are present in the soil and additionally supplied through fertilisers. Additionally, alpha-amino nitrogen, an intermediate product in plant nitrogen metabolism, can also contribute to molasses formation. Managing nitrogen nutrition is crucial from this perspective because increasing yields through nitrogen fertilisation can potentially reduce sugar yield. Therefore, microelements influencing metabolic cycles can mitigate high sugar content.

DISCUSSION

The effects of chelated fertilisers on plant growth and development are stimulating, as the gross indicators of macroelements they contain are insufficient for a significant biomass increase (Honchar et al., 2021). Certain micronutrients help overcome abiotic stresses, complicating the isolation of their real impact on growth factors. Root crops accumulate significantly more microelements in the leaf mass than in the roots, making foliar fertilisation an effective means to prevent or overcome

deficiencies (Trembitska & Bohdan, 2023). There is sufficient research on sugar beets that examines the effects of individual elements on yield formation, but the application of complex fertilisers is still difficult to predict (Kalenska et al., 2024). According to E. Kandil et al. (2020), the combination of nanopreparations with boron increases plant biomass and root mass, but without a clear dependency.

Complex chelated fertilisers help maintain the necessary concentration of micronutrients in the plant, enabling the full utilisation of available resources. To reduce macro- and micronutrient deficiencies and address the problem of eutrophication, nanofertilisers are effective in releasing nutrients in a controlled manner according to plant needs (Shukla et al., 2019; Bielashov et al., 2022). Unlike conventional nitrogen fertilisers, where losses due to evaporation or leaching can reach 50-70% (Ramos-Ulate et al., 2022; Firmanda et al., 2023). Nano-formulations of nitrogen fertilisers synchronise the release of nitrogen with crop needs, minimising nutrient losses and reducing nutrient interactions with soil, water, air, and micro-organisms (Kalia & Sharma, 2019; Mejias et al., 2021; Pavlichenko et al., 2023). The use of porous nanomaterials such as zeolites, clay, or chitosan helps to regulate release on demand and increase nitrogen uptake by plants (Dimkpa et al., 2020; Thambiliyagodage et al., 2023). According to S. Jafarzadeh et al. (2023) and A. Yadav et al. (2023), ammonium zeolites can also increase the solubility of phosphate minerals.

The best options for seed treatment had higher contents of most micronutrients

compared to alternative options, which, even at relatively low rates, increased the plants' biometric indicators. According to H. Aktaş *et al.* (2006), the main micronutrients with such effects are zinc and boron, which are effective even in small doses. R. Zewail *et al.* (2020) indicated that doubling the concentration resulted in an increase in root dry mass from 8 to 35%, depending on the year's conditions. Increasing the fertiliser rate also positively affected the leaf area of individual plants and the leaf area index. These elements also increased photosynthetic productivity, pigment content in leaves, overall sugar content, and reducing sugar content. The overall increase in photosynthetic productivity may be related to the increase in zinc (Abdel-Motagally & Attia, 2009). The complex application of nanopreparations in several treatments positively affects leaf growth at distinct levels and the photosynthetic parameters of beets, including the efficiency of various photosystems (Artyszak *et al.*, 2018).

According to A. Artyszak & D. Gozdowski (2021), the use of preparations containing silicon and iron also affects root weight, the content of molasses-forming substances, and sugar loss during processing. However, unlike boron and zinc, it almost does not affect leaf mass growth. Pre-sowing application of preparations containing copper, manganese, and iron also enables a significant increase in yield and sugar content (Prośba-Białczyk *et al.*, 2017). Increasing the concentration during treatment also leads to an increase in ash elements and nitrogen in the roots. The results show some differences, manifested in a weaker change in potassium content in the roots compared to previous studies (Zewail *et al.*, 2020). Boron, which is present in the preparations for foliar feeding, may balance the content of alpha-amino nitrogen and potassium and sodium content (Nemeat-Alla *et al.*, 2021). The results on sugar losses in molasses indicate that balanced micronutrient application does not lead to negative consequences, as is the case with the unilateral application of individual micronutrients (Zewail *et al.*, 2020). The application of individual micronutrients in combination with NPK can increase root yield without deteriorating quality across a wide range of conditions (Draycott & Christenson, 2003; Varga *et al.*, 2022).

Nanopreparations, due to their high bio-availability, enhance sugar beet productivity by supplying young plants with a balanced complex of essential micro- and macronutrients. This supports the process of root moulting and positively influences the productivity potential of the root. Foliar fertilisation plays a stimulating role during growth stages when nutrient uptake is high, but the demand for microelements stays at a level that can be effectively supplemented. These measures can increase the productivity of sugar beets and sugar yield while maintaining the same nutrient supply level in the crop.

CONCLUSIONS

The analysis of the photosynthetic activity of the crop and the features of sugar accumulation and extraction at factories suggested the significant effectiveness of nanopreparations for seed treatment and foliar spraying. The application of these preparations enabled a reliable increase in plant mass as early as in the intensive root growth phase, which was reflected in the root mass at early harvesting maturity (10 September, Stage 3) and technological maturity of the tubers (30 September). Root mass was primarily influenced by seed treatment, leading to an increase of 9.5% compared to the control with the T2 formulation and 10.2% with the T3 formulation at the technological maturity phase. Root weight increased by 64-69 g in untreated plots, but foliar fertilisation resulted in a smaller increase in root mass (5.8% and 4.7%, respectively).

The net photosynthesis productivity significantly increased at the beginning of vegetation with foliar treatments, while in the subsequent stages after row closure, further growth did not significantly differ. On the other hand, foliar treatments helped maintain a larger leaf area until harvest (30.8-32.7 thsd m²/ha vs. 27.6-28.8 thsd m²/ha in plots without foliar treatment), increasing the overall productivity of the crop. The sugar content under the proposed treatment schemes did not differ significantly from the control (15.8%) in most cases. However, the T2 and T3 seed treatment variants in combination with foliar fertilisation significantly increased the sugar content in the root to 16.6%. This is promising in the context of increasing sugar yield per unit area, while also positively

influencing other yield parameters. The application of T2 and T3 schemes for seed treatment with high microelement content (compared to T1) enabled the formation of a more robust plant, which, combined with foliar fertilisation, resulted in a beetroot yield of 57.6-59.6 t/ha with a potential sugar yield of 9.29-9.86 t/ha.

The application of nanoproducts for seed treatment and the selection of optimised complexes for foliar application enabled the fulfilment of genetic potential under limited resource

conditions. Future studies should explore the long-term effects of these treatments on soil health and the sustainability of sugar beet production in varying agroecological zones.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Вплив обробки насіння та позакореневого підживлення хелатними добривами на продуктивність буряків цукрових (*Beta vulgaris* L.)

Анотація. Буряки цукрові є високопродуктивною культурою, яка потребує значної кількості мікроелементів та поживних речовин. Вони чутливі до нестачі мікроелементів на ранніх етапах розвитку, що може вплинути на морфологічні зміни коренеплоду і, як наслідок, знизити врожайність. Метою дослідження було визначення впливу обробки насіння комплексом хелатних добрив та позакореневого підживлення на біометричні показники буряків цукрових, їх фотосинтетичну продуктивність та технологічні якості. Дослідження проводили на чорноземах типових малогумусних Правобережного Лісостепу України. Для визначення маси коренеплодів і листків, площі листової поверхні та фотосинтетичної продуктивності відбирали зразки у фазі змикання рядків, у середині фази інтенсивного росту коренеплодів та у фазі розмикання листків у міжряддях. У рослин, відібраних у фазі фізіологічної стиглості, визначали технологічні якості, урожайність коренів і цукристість. Встановлено, що позакоренево підживлення значно збільшувало масу коренів у фазі розкриття рядків і фізіологічної стиглості. Найбільша коренева маса формувалася у варіанті з обробкою насіння з високим вмістом мікроелементів і позакореневим підживленням. Маса коренеплоду досягала 692 г, урожайність – 59,6 т/га, цукристість – 16,6 %. Технологічні показники, зокрема урожайність цукру, для цього варіанту також були максимальні – 9,86 т/га. Нанодобрива для позакореневого підживлення дозволила збільшити площу листя до фази розкриття рядків без зниження чистої продуктивності фотосинтезу, що, у свою чергу, дозволило посівам накопичувати більше сухої речовини. Обробка насіння хелатними добривами збільшила накопичення сухої маси на ранніх стадіях, сприяла збільшенню фотосинтетичного апарату, що в сукупності призвело до підвищення продуктивності

Ключові слова: нанодобрива; чиста продуктивність фотосинтезу; площа листової поверхні; суха речовина; маса коренеплоду; урожайність; цукристість