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# Sugar beet fertilisation for sustainable yield under climate change conditions

Vadym IVANINA[1], Roman SHAPOVALENKO[1], Oksana STRILETS[1], Svitlana SENCHUK[2]

[1]Institute of Bioenergy Crops and Sugar Beet (NAAS)
Klinichna 25, 03141 Kiev, Ukraine
E-mail: v_ivanina@meta.ua

[2]Bila Tserkva Research and Breeding Station of the Institute of Bioenergy Crops and Sugar Beet
Kiev Region, Ukraine

## Abstract

The aim of this study was to determine how different fertiliser systems affect sugar beet (*Beta vulgaris* L.) productivity, water-use efficiency (WUE) index, nutrient uptake and balance and establish the efficient fertilisation of the plant. A randomized experimental design with four replications as factorial arrangement with four treatments: (1) without fertilisers (control), (2) mineral fertilisation (MF), (3) alternative organic-mineral fertilisation (OMF) and (4) organic-mineral fertilisation supplemented with boron (B) (OMF+B), was used. The results showed that sugar beet root yield, gross and white sugar yield were significantly affected ($P < 0.05$) by all fertilisation treatments. The highest average of the aforementioned parameters was obtained in OMF+B treatment: 63.5, 10.73 and 8.86 t ha$^{-1}$, respectively, that included combined application of the mineral fertilisers and winter wheat straw plus B twice foliar applied. OMF+B had a more pronounced effect on sugar beet productivity in the year of hot and moderately humid growing season (2018) than in dry (2017) and moderate (2019) years. OMF+B resulted in a positive nutrient balance in the soil and the highest WUE index (44.7 kg ha$^{-1}$ mm$^{-1}$), provided efficient use of water and the sustainability of sugar beet cultivation under climate change conditions, while mineral fertilisation led to nutrient imbalance and low stability. The accumulation of sugar in the roots mainly depended on the dry weather in September. The driest September of 2019 contributed to the highest sugar content in the roots – 18.2–18.5%, while moderately and too humid weather in September 2017 and 2018 caused a significant decrease ($P < 0.05$) in sugar content to 17.0–17.5% and 14.9–15.2%, respectively.

Key words: *Beta vulgaris*, fertilisation, yield, sustainability.

## Introduction

Sugar beet (*Beta vulgaris* L.) is widely cultivated in Ukraine. Its production is concentrated in the forest-steppe zone, the area of productive black soils. In recent decades, the plant has suffered nutritional and water imbalances caused by climate change and severe manure shortages. For sustainable yields in a new environment, the plant requires suitable provision of water and nutrients, which is achieved through efficient fertilisation. To affect sugar beet productivity, the most efficient measures are the optimization of fertiliser rate and method of fertiliser application. Most researchers report that fertilisation, composed of manure and mineral fertilisers, provides maximum yield of sugar beet with high root quality (Hasanen et al., 2013; Ahmad et al., 2017; Dlamini et al., 2020). During the growing season, such fertilisation favourably affects the soil, improves its physical, chemical and biological properties, increases the content of nutrients and organic matter, establishes the conditions for uniform and balanced plant nutrition (Kabil et al., 2015; Adugna, 2016). According to Chen et al. (2007), Liu et al. (2017) and Marajan et al. (2017), under the climate change conditions, particularly important is organic-mineral fertilisation; it allows preserving soil moisture, improving water balance and water-use efficiency, shapes the conditions that mitigate the impact of the climate warming on plant growth.

Although the role of manure in sugar beet fertilisation is undeniable, in recent years, Eastern European farmers have been facing its acute shortage, which has led to a wider use of by-products, composts and food waste for the fertiliser. Bagherzadeh et al. (2014), Liu et al. (2017) and Han et al. (2018) consider that straw of winter wheat, the main pre-crop of sugar beet, can be an efficient organic fertiliser for this crop, if the nutrients, particularly nitrogen (N), are properly balanced. Straw efficiency for fertiliser strongly depends on the C to N

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ratio (Singh et al., 2011), and, under general practice of the fertilisation with straw, a dose of 10 kg N per ton of straw is applied (Gavryliuk, 2020). Such fertilisation technique reduces the immobilization of nitrogen in the soil, which averages about 24 kg $ha^{-1}$ N (Reichel et al., 2018), increases the availability of nitrogen for plants and minimizes stress caused by drought conditions (Abera et al., 2013). However, the effectiveness of straw-based fertilisation for sugar beets is still under discussion, especially if plants are grown in the areas being affected by increasing aridity (Liu et al., 2017).

An effective tool to mitigate global warming and increase the productivity of sugar beet in natural environment is the optimization of plant nutrition with micronutrients, particularly with boron (B), an element the need for which plant feels at all stages of growth and development (Hellal et al., 2009; Gupta, Solanki, 2013; Gobarah et al., 2014; Mekdad, 2015). Applied at a dose of 50 g $ha^{-1}$ (Hellal et al., 2009) to 120–150 g $ha^{-1}$ (Mekdad, 2015) through the leaves, boron significantly increased root yield and improved its attributes – the percentage of gross and white sugar, while have reduced natrium (Na), potassium (K) and α-amino N content, the percentage of sugar loss, harvest index and sugar yield loss (Mekdad, 2015).

Thus, this study aimed to answer the following questions: (1) What is the contribution of straw-based organic-mineral fertilisation to sugar beet productivity, root impurity components, water-use efficiency, nutrient uptake and balance under climate change conditions? (2) Can boron, additionally applied through leaves, significantly contribute to the effectiveness of organic-mineral fertilisation? (3) How does the water-use efficiency (WUE) index correlate with the yield of sugar beet in alternative organic-mineral fertilisation?

# Materials and methods

Field trials were conducted during 2017–2019 at the Bila Tserkva Research and Breeding Station of the Institute of Bioenergy Crops and Sugar Beet, Ukraine. A randomized experimental design was used with the main plot size: 75 $m^2$ drilling area and 50 $m^2$ harvested area; all treatments were replicated four times. In all experimental years the sugar beet (*Beta vulgaris* L.) hybrid 'Romul' was sown within the period from 8 to 15 of April; the breeder of the hybrid is Ivanivka Research-Breeding Station of the Institute of Bioenergy Crops and Sugar Beet, Ukraine. The experimental factors were (1) fertilisation and (2) conditions of the growing season.

The soil of the experimental site was *Chernozem* with a loamy texture. To determine acidity (pH), organic matter, mineral nitrogen (N), mobile phosphorus ($P_2O_5$) and potassium ($K_2O$) content, before drilling, soil samples were randomly taken from 0–30 cm layer in each replication. Soil pH was determined in 1 N KCl extraction using a potentiometric method (DSTU ISO 10390:2007. Soil quality – Determination of pH), organic matter – by the Tiurin method (DSTU 4289:2004. Soil quality. Methods for determining organic matter), mobile $P_2O_5$ and $K_2O$ – by the Chirikov method (DSTU 4115:2002. Soils quality. Determination of mobile phosphorus and potassium compounds by the modified Chirikov method) (Table 1).

***Table 1.*** Chemical characteristics of *Chernozem* in 0–30 cm layer

| Soil properties | Year | | | | | |
|---|---|---|---|---|---|---|
| | 2017 | | 2018 | | 2019 | |
| | value | GNCL | value | GNCL | value | GNCL |
| $pH_{KCl}$ | 6.1 | | 5.6 | | 5.7 | |
| Organic matter % | 3.7 | III | 3.5 | III | 3.5 | III |
| Mobile $P_2O_5$ mg $kg^{-1}$ | 114 | IV | 116 | IV | 128 | IV |
| Mobile $K_2O$ mg $kg^{-1}$ | 77 | III | 72 | III | 91 | III |

*Note.* Soil indicators determined using 5 composite samples; GNCL – group of nutrient content level: III – medium, IV – high.

In parallel, nutrient content in plant samples after oven-drying at 85°C temperature for 48 h, and ashing with a mixture of sulphuric ($H_2SO_4$) and perchloric ($HClO_4$) acids (10:1) was determined: N – by the Kjeldahl method (DSTU 7169:2010), P and K – by a flame photometry according to the Denizhe method in Levitsky's modification (Gorodnii et al., 2005). The results were used for determination of nutrient removal by the plant and nutrient balance in the soil (Table 2).

In all experimental years, the pre-crop of sugar beet was winter wheat (*Triticum aestivum* L., cultivar 'Yasochka'). Sugar beet was fertilised according to the following scheme: 1) without fertilisers (control); 2) mineral fertilisation (MF): phosphorus (P) as superphosphate and potassium (K) as potassium chloride (KCl) at 100 kg $ha^{-1}$ rate of each applied on ploughland in autumn (middle September); nitrogen (N) at a rate of 100 kg $ha^{-1}$ as ammonium nitrate ($NH_4NO_3$) was applied

***Table 2.*** Nutrient content in plant material

| Nutrient content | Year | | |
|---|---|---|---|
| | 2017 | 2018 | 2019 |
| Winter wheat straw (alternative organic fertiliser) | | | |
| N % | 0.64 | 0.57 | 0.70 |
| P % | 0.21 | 0.19 | 0.24 |
| K % | 1.28 | 1.33 | 1.37 |
| Sugar beet roots | | | |
| N % | 0.94 | 0.98 | 0.90 |
| P % | 0.32 | 0.35 | 0.37 |
| K % | 1.09 | 1.02 | 1.12 |
| Sugar beet leaves | | | |
| N % | 2.27 | 2.39 | 2.40 |
| P % | 0.60 | 0.62 | 0.57 |
| K % | 3.03 | 3.17 | 2.98 |

under pre-drilling cultivation in spring (beginning of April); 3) organic-mineral fertilisation (OMF): chopped straw of winter wheat of 5 t ha$^{-1}$ and N at a rate of 50 kg ha$^{-1}$ as $NH_4NO_3$ were incorporated into the soil (8–10 cm depth) in the beginning of August; mineral fertilisers were applied in accordance with treatment 2; 4) organic-mineral fertilisation supplemented with boron (B) (OMF+B): B supplemented for foliar feeding at 10–12 and 20–24 unfolded leaf stages.

Micronutrient fertiliser Micro-Mineralis with boron was composed of ammonium carboxylate complexes: B – 10%, N – 2%; application rate – 1.5 L ha$^{-1}$, working fluid – 300 L ha$^{-1}$.

During the experimental years, sugar beet was harvested in the beginning of October. The plant samples were taken from four areas of each plot within 1 m$^2$ to determine root characters (length and diameter, cm), fresh weight of top and root and the total weight of plants (g plant$^{-1}$), which then were converted into t ha$^{-1}$. From each replication, samples of 5 roots (20 per treatment) were taken to assess root quality indicators with an automated laboratory (Venema Installations bv, The Netherlands).

Gross sugar yield was determined using the equation: Gross sugar yield (t ha$^{-1}$) = root yield (t ha$^{-1}$) × sucrose %; sugar loss – by Cooke and Scott (1993) equation: Sugar loss % = (0.29) + 0.343 (K + Na) + (0.094 α-amino N); sugar yield loss was computed as root yield (t ha$^{-1}$) × sugar loss (%).

Nutrient balance (kg ha$^{-1}$) was defined as a difference between the removal of nutrients by sugar beet roots and their supply with fertilisers, balance intensity (%) – as nutrient supply (kg ha$^{-1}$) / removal by roots (kg ha$^{-1}$) × 100%.

Evapotranspiration (ET) was determined using soil water balance method: ET (mm) = difference in soil water amount of 1.5 m soil layer between sowing and harvesting (mm) + sum of rainfall during the growing period (mm). Water-use efficiency (WUE) index (kg ha$^{-1}$ mm$^{-1}$) was calculated as the ratio: Dry-matter of sugar beet yield (roots and leaves, kg ha$^{-1}$) / ET (mm).

*Meteorological conditions.* During the experimental years, the weather conditions were hot but predominantly favourable for sugar beet cultivation. In 2017–2019, the mean daily temperature of the growing season (April–September) exceeded the long-term average by 1.7–3.0°C (Figure 1), whereas the rainfall for the aforementioned period was less by 30–115 mm than the long-term average (Figure 2).

The year 2017 was warm and dry, followed with an acute decrease in precipitation of 115 mm. The first half of the growing season was predominantly favourable for sugar beet growth; a decrease in rainfall during April–June regarding long-term average was 71 mm with an

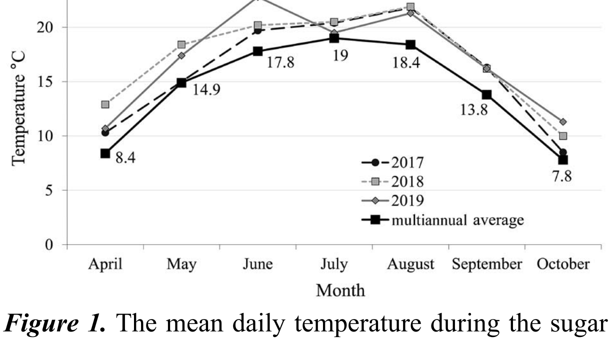



***Figure 1.*** The mean daily temperature during the sugar beet growing season (Bila Tserkva Meteorological Station)

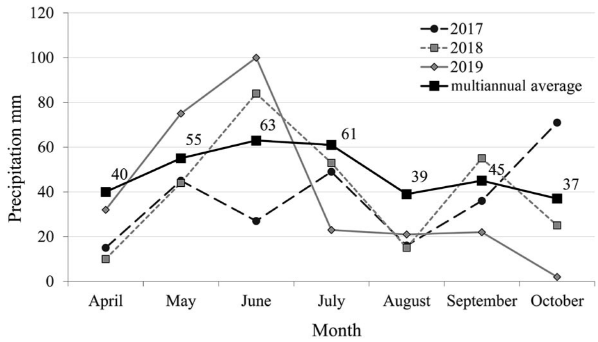



***Figure 2.*** The amount of rainfall during the sugar beet growing season (Bila Tserkva Meteorological Station)

increase in the mean daily temperature by 3.9°C. Dry weather was observed in the second half of the growing season (July–September) with a deficiency of 44 mm and an increase in the mean daily temperature of 7.3°C. Under such weather conditions in 2017, the root yield of sugar beet was about 55 t ha$^{-1}$ with a decrease of 4.1 t ha$^{-1}$ compared with three-year average.

The growing season of 2018 was the warmest of all experimental years with a small deficiency of rainfall. A decrease in rainfall regarding long-term average was 42 mm with an increase in the mean daily temperature by 3.0°C. First half of the growing season was particularly warm; the mean daily temperature was lower than the long-term average: in April – by 4.5°C, in May – by 3.5°C and in June – by 2.4°C. The middle of the growing season (July–August) was moderately warm with an increase in the mean daily temperature by 5.0°C; both periods followed with a small decrease in precipitation. Such weather conditions contributed to intensive development of sugar beet plants. September was accompanied by excessive rainfall of 55 mm, which prolonged the development of sugar beet and reduced the accumulation of sugar in the roots. In that year, the yield of sugar beet roots was the highest – more than 70 t ha$^{-1}$, while the sugar content in the roots was the lowest – 14.9–15.2%.

In 2019, the growing season was warm with a small deficit of rainfall of 30 mm. The first half of the growing season (April–June) was warm and humid with the mean daily temperature increase of 9.8°C and precipitation rate increase of 57 mm. The second half of the growing season (July–September) was warm and dry with precipitation deficiency of 79 mm and the mean daily temperature increase of 5.8°C. The weather conditions of year 2019 contributed to intensive accumulation of sugar in the roots reaching its highest value (18.2–18.5%) through the experiment and resulted in root yield of 55 t ha$^{-1}$.

*Statistical analysis.* Experimental data were statistically processed using analysis of variance (ANOVA). Differences among the experimental treatments were assessed by the least significant difference (LSD) limit ($P < 0.05$). To estimate the relations between WUE index and sugar beet yield, correlation-regression analysis was performed using software *Microsoft Excel*, version 2013 (USA).

## Results and discussion

Experimental results showed that all fertilisation treatments provided significant increase ($P < 0.05$) in the components of sugar beet productivity: root weight, root yield and sugar yield; in turn, that depended on the weather conditions of the experimental period. However, the root diameter and length, the root impurity components and sugar loss were not so directly affected.

According to the average data of 2017–2019, the impact of fertilisation on the root diameter and root length did not yield a significant difference. However, these parameters significantly increased ($P < 0.05$) in 2018. That year hot and normally humid growing season was recorded, and fertilisation had an influence on these parameters. This result conforms to the findings of Hlisnikovsky et al. (2021) for the area of moderate humidity, where the application of manure and mineral fertilisers resulted in significant increase in root length, root diameter and root yield.

During the experiment, sugar beet root weight in MF treatment increased from 419 to 618 g (47.5%), in OMF – from 419 to 652 g (55.6%) and in OMF+B – from 419 to 686 g (63.7%) compared to the treatment without fertilisers (Table 3).

***Table 3.*** Sugar beet root parameters depending on fertilisation and growing season

| No. | Fertilisation treatment | Year 2017 | Year 2018 | Year 2019 | | Increase % |
|---|---|---|---|---|---|---|
| | | Diameter cm | | | | |
| 1 | Without fertilisation (control) | 10.7 a | 10.8 a | 11.0 a | 10.8 A | – |
| 2 | Mineral (MF) | 11.3 a | 12.1 b | 11.4 a | 11.6 A | 7.4 |
| 3 | Organic-mineral (OMF) | 11.4 a | 12.0 b | 11.2 a | 11.6 A | 7.4 |
| 4 | Organic-mineral + boron (OMF+B) | 11.4 a | 12.4 b | 11.6 a | 11.8 A | 9.3 |
| | Average | 11.2 A | 11.8 A | 11.3 A | – | – |
| | | Length cm | | | | |
| 1 | Without fertilisation (control) | 17.3 a | 17.4 a | 17.6 a | 17.4 A | – |
| 2 | Mineral (MF) | 17.9 a | 19.1 a | 18.1 a | 18.4 A | 5.8 |
| 3 | Organic-mineral (OMF) | 18.4 a | 19.5 b | 18.4 a | 18.8 A | 8.1 |
| 4 | Organic-mineral + boron (OMF+B) | 18.5 a | 20.2 b | 18.3 a | 19.0 A | 9.2 |
| | Average | 18.0 A | 19.1 B | 18.1 A | | |
| | | Weight g | | | | |
| 1 | Without fertilisation (control) | 387 a | 422 a | 449 a | 419 A | – |
| 2 | Mineral (MF) | 552 b | 716 b | 587 b | 618 B | 47.5 |
| 3 | Organic-mineral (OMF) | 620 c | 746 b | 590 b | 652 B | 55.6 |
| 4 | Organic-mineral + boron (OMF+B) | 626 c | 801 c | 631 c | 686 C | 63.7 |
| | Average | 546 A | 671 B | 564 A | | |

*Note.* Labelled with different letters, root parameters are significantly different ($P < 0.05$) depending on fertilisation (a, b, c); average root parameters are significantly different ($P < 0.05$) depending on growing season and on average per trial period (A, B, C).

These results correspond with the findings of other researchers (Mekdad, 2015; Ahmad et al., 2017). A significant increase ($P < 0.05$) in root weight was provided by OMF compared to MF treatment, which was 74 g in dry 2017, 85 g in hot 2018 and 44 g in moderate 2019 year. The year 2018 was marked by the highest root weight, and the weather conditions of the year significantly affected ($P < 0.05$) this value. This suggests that supplementing mineral fertilisation with organic component and boron assured significant increase in root weight in years of hot and moderately humid growing seasons.

During the experiment, the yield of sugar beet roots varied from 35.4 t ha$^{-1}$ in 2017 (without fertilisers) to 72.7 t ha$^{-1}$ in 2018 (OMF+B) with an average root yield of 55.3 t ha$^{-1}$ during 2017–2019 (Table 4).

***Table 4.*** Sugar beet productivity depending on fertilisation and growing season

| No. | Fertilisation treatment | Year 2017 | Year 2018 | Year 2019 | | Increase % |
|---|---|---|---|---|---|---|
| | | Root yield t ha$^{-1}$ | | | | |
| 1 | Without fertilisation (control) | 35.4 a | 37.3 a | 42.3 a | 38.3 A | – |
| 2 | Mineral (MF) | 52.4 b | 66.8 b | 56.4 b | 58.5 B | 52.7 |
| 3 | Organic-mineral (OMF) | 56.8 bc | 70.5 bc | 55.5 b | 60.9 BC | 59.0 |
| 4 | Organic-mineral + boron (OMF+B) | 59.4 c | 72.7 c | 58.4 bc | 63.5 C | 65.8 |
| | Average | 51.0 A | 61.8 B | 53.2 A | | |
| | | Root sugar % | | | | |
| 1 | Without fertilisation (control) | 17.1 a | 15.2 a | 18.5 a | 16.9 A | – |
| 2 | Mineral (MF) | 17.0 a | 14.9 a | 18.2 a | 16.7 A | – |
| 3 | Organic-mineral (OMF) | 17.3 a | 15.0 a | 18.3 a | 16.9 A | – |
| 4 | Organic-mineral + boron (OMF+B) | 17.5 b | 15.2 a | 18.4 a | 17.0 A | 0.6 |
| | Average | 17.2 A | 15.1 B | 18.4 C | | |
| | | Gross sugar t ha$^{-1}$ | | | | |
| 1 | Without fertilisation (control) | 6.05 a | 5.67 a | 7.83 a | 6.52 A | – |
| 2 | Mineral (MF) | 8.91 b | 9.95 b | 10.27 b | 9.71 B | 48.9 |
| 3 | Organic-mineral (OMF) | 9.83 c | 10.58 c | 10.16 b | 10.19 BC | 56.3 |
| 4 | Organic-mineral + boron (OMF+B) | 10.40 d | 11.05 c | 10.75 c | 10.73 C | 64.6 |
| | Average | 8.80 A | 9.32 AB | 9.76 B | | |
| | | Foliage yield t ha$^{-1}$ | | | | |
| 1 | Without fertilisation (control) | 15.2 a | 20.8 a | 20.7 a | 18.9 A | – |
| 2 | Mineral (MF) | 23.1 b | 37.1 b | 27.6 b | 29.3 B | 55.0 |
| 3 | Organic-mineral (OMF) | 23.9 b | 39.6 bc | 27.2 b | 30.2 BC | 59.8 |
| 4 | Organic-mineral + boron (OMF+B) | 26.7 c | 41.4 c | 28.6 b | 32.2 C | 70.4 |
| | Average | 22.2 A | 34.7 B | 26.0 A | | |

*Note.* Labelled with different letters, productivity indicators ($P < 0.05$) are significantly different in columns depending on fertilisations (a, b, c, d); average productivity indicators ($P < 0.05$) are significantly different depending on growing season and on average per trial period (A, B, C).

According to the three-years average data, all fertilisation treatments significantly increased ($P < 0.05$) root yield compared to the control treatment without fertilisers: 52.7% with MF, 59.0% with OMF and 65.8% with OMF+B. Maximum root yield was obtained, when 5 t $ha^{-1}$ of winter wheat straw, 50 kg $ha^{-1}$ N and mineral fertilisers were applied to the soil, and sugar beet was twice foliar treated with boron (63.5 t $ha^{-1}$ OMF+B). In the year of hot and moderately humid growing season (2018), this four-component fertilisation had the greatest effect on root yield (72.7 t $ha^{-1}$). For two years (2017–2018) out of three, OMF+B had a significant effect ($P < 0.05$) on root yield with its increase by 13.4% in dry 2017, by 8.8% in hot 2018 with no significant influence under typical weather conditions of 2019 year. This finding agrees with the conclusion of Kabil et al. (2015) and Adugna (2016) about a high beneficial effect of the organic fertilisers on soil organic matter, nutrient status and plant nutrition management, while mitigating the effect of seasonal fluctuations of the precipitation that usually results in significantly increased sugar beet biomass and sugar yield.

The results of the current study also correspond to the scientific conclusions about the importance of boron for achieving sustainable yields of sugar beet. Foliar feeding of sugar beet with boron 60 days after sowing (Armin, Asgharipour, 2011), twice after 80 and 110 days (Dewdar et al., 2015) and after 120 and 150 days (Kandil et al., 2020) had a significant effect on root yield, biological yield and root quality. However, Wiesmeier et al. (2015) and Zarski et al. (2020) have reported that the maximum sustainable effect on sugar beet productivity can be achieved, when fertilisation is based on the joint application of organic and mineral fertilisers. Such fertilisation mitigates the loss of organic carbon in the soil, preserves soil water and overcomes yield stagnation, which are pressing issues for Central and Northern Europe.

Fertilisation did not have a significant effect on the accumulation of sugar in the roots. In 2017, which was the driest year of the experiment, fertilisation that included OMF+B significantly increased ($P < 0.05$) the sugar content in the roots with exceeding the control treatment without fertilisers by 0.4%, MF – by 0.5% and OMF – by 0.2%. This result is consistent with the study of Armin and Asgharipour (2011) on the effect of boron on the accumulation of sugar in roots, when its use the concentration of sucrose increased by 26.4%. Root sugar content was also significantly affected ($P < 0.05$) by the dry weather in September. The driest September of 2019 provided the highest sugar accumulation in the roots (18.2–18.5%), while moderately and too humid weather in September 2017 and 2018 caused a significant decrease ($P < 0.05$) in sugar content to 17.0–17.5% and 14.9–15.2%, respectively.

During the experiment, fertilisation significantly affected ($P < 0.05$) leaf yield and gross sugar yield. Compared to the control, all fertilisation treatments average leaf yield increased by 55.0–70.4%, gross sugar yield – by 48.9–64.6% with the indicators' values in the control treatment 18.9 and 6.52 t $ha^{-1}$, respectively. The highest gross sugar yield (10.73 t $ha^{-1}$) was obtained in OMF+B treatment. The addition of straw and boron to the mineral system of sugar beet fertilisation the yield of sugar significantly increased ($P < 0.05$) by 1.02 t $ha^{-1}$. In one year (2017) out of three, the year of warm and dry growing season, both the OMF and OMF+B provided a significant increase ($P < 0.05$) in gross sugar yield compared to MF treatment reaching sugar yield of 9.83 and 10.40 t $ha^{-1}$, respectively. These results are in agreement with those reported by Hlisnikovsky et al. (2021) about high efficacy of OMF in the conditions of moderate humidity.

Root quality depended less on the fertilisation. The treatment of sugar beet with the fertilisers significantly increased ($P < 0.05$) the average concentration of the K and α-amino-N by 7.7–10.6% and 16.5–20.5% in beet pulp compared to the control treatment without fertilisers, while the changes in Na and alkalinity coefficient were not significant (Table 5). Such an increase worsened the purity of beet pulp and led to an increase in sugar losses by 0.21–0.22 absolute percent and sugar yield losses – by 0.67–0.82 t $ha^{-1}$. This agrees with the study of Bagherzadeh et al. (2014), where the quality of the roots was affected only by the rate of N and the N to C ratio, when nitrogen fertilisers were applied together with straw.

***Table 5.*** Sugar beet root impurity components and sugar loss depending on fertilisation (average 2017–2019 years)

| No. | Fertilisation treatment | Impurity components mmol 100 $g^{-1}$ beet | | | Sugar loss | | White sugar yield t $ha^{-1}$ |
|---|---|---|---|---|---|---|---|
| | | K | Na | α-amino-N | sugar % | yield t $ha^{-1}$ | |
| 1 | Without fertilisation (control) | 4.16 a | 2.14 a | 3.03 a | 2.73 a | 1.05 a | 5.47 a |
| 2 | Mineral (MF) | 4.48 b | 2.24 a | 3.65 b | 2.94 b | 1.72 b | 7.99 b |
| 3 | Organic-mineral (OMF) | 4.60 b | 2.16 a | 3.57 b | 2.95 b | 1.80 b | 8.39 bc |
| 4 | Organic-mineral + boron (OMF+B) | 4.56 b | 2.20 a | 3.53 b | 2.94 b | 1.87 b | 8.86 c |
| | Average | 4.45 | 2.19 | 3.45 | 2.89 | 1.61 | 7.68 |

*Note.* Labelled with different letters (a, b), impurity indicators are significantly different ($P < 0.05$) in columns depending on fertilisation.

The highest white sugar yield (8.86 t $ha^{-1}$) was obtained in OMF+B treatment. Fertilisation treatment with straw, mineral fertilisers and boron was more efficient than MF. OMF+B significantly increased ($P < 0.05$) the yield of white sugar by 0.87 t $ha^{-1}$ compared to MF treatment and ensured maximum productivity of sugar beets during all experimental years.

The WUE index usually reflects the efficiency of moisture use by the plants during the growing season. One of the main factors that defines crop yield is water supply to a plant during its growth (Grzebisz et al., 2013). According to the average data of 2017–2019, all fertilisation treatments significantly increased ($P < 0.05$) the WUE index by 45.4–56.3% without significant effect on evapotranspiration compared to the control treatment without fertilisers. Maximum water-use efficiency by the plant (WUE index) was achieved in OMF+B – 44.7 kg $ha^{-1}$ $mm^{-1}$, while this fertilisation treatment provided no significant increase in WUE index compared to MF and OMF, whose indexes were 41.7

and 42.9 kg ha$^{-1}$ mm$^{-1}$, respectively (Table 6). Only in the dry year 2017, supplementing mineral fertilisers with straw and boron the WUE index significantly increased ($P < 0.05$) by 5.1 kg ha$^{-1}$ mm$^{-1}$ (12.3%) compared to MF treatment without significant effect in years of moderate precipitation (2018–2019). This agrees with the study of Peng et al. (2015), where the application of straw mulch in dryland farming in China the average soil water content in the 0–200 cm soil layer increased by 0.7–22.5% followed by an increase in the WUE index by 24.2–32.7%.

***Table 6.*** Evapotranspiration (ET) and water-use efficiency (WUE) by sugar beet depending on fertilisation and growing season

| No. | Fertilisation treatment | Year 2017 | 2018 | 2019 | | Increase % |
|---|---|---|---|---|---|---|
| | | ET mm ha$^{-1}$ | | | | |
| 1 | Without fertilisation (control) | 344 a | 393 a | 409 a | 382 A | – |
| 2 | Mineral (MF) | 354 a | 437 b | 421 a | 404 A | 5.8 |
| 3 | Organic-mineral (OMF) | 348 a | 445 b | 428 a | 407 A | 6.5 |
| 4 | Organic-mineral + boron (OMF+B) | 360 a | 450 b | 433 a | 414 A | 8.4 |
| | Average | 352 A | 431 B | 423 B | | |
| | | WUE index kg ha$^{-1}$ mm$^{-1}$ | | | | |
| 1 | Without fertilisation (control) | 28.0 a | 28.3 a | 29.5 a | 28.6 A | – |
| 2 | Mineral (MF) | 41.4 b | 45.4 b | 38.0 b | 41.6 B | 45.4 |
| 3 | Organic-mineral (OMF) | 45.2 bc | 46.3 b | 37.1 b | 42.9 B | 50.0 |
| 4 | Organic-mineral + boron (OMF+B) | 46.5 c | 48.9 b | 38.6 b | 44.7 B | 56.3 |
| | Average | 40.3 A | 42.2 A | 35.8 B | | |

*Note.* Labelled with different letters, WUE indicators are significantly different ($P < 0.05$) in columns depending on fertilisation (a, b, c); average WUE indicators are significantly different ($P < 0.05$) depending on growing season and on average per trial period (A, B).

According to the Zhang et al. (2020), field practice of straw returns improved soil properties: in the cultivated layer the content of soil water increased by 4.79–25.44%, and its highest absolute value provided of 19.10–21.84%. The incorporation of plant residues in the soil is an important measure that improves the water supply of plants, mitigates the impact of climate change on plant growth and development (Xing et al., 2017). Also, this is in line with the findings of Gupta and Solanki (2013) on the importance of boron in counteracting the effect of drought. Thus, results of our research have shown that winter wheat straw, mineral fertilisers and boron are effective nutrients that ensure the sustainability of sugar beet cultivation under changing climate conditions.

The correlation-regression analysis of data showed strong linear correlation between root yield and WUE index with the determination coefficient of 0.859 and with Student's criterion, where tr is greater than t0.05 (tr = 7.81 > t0.05 = 2.23) (Figure 3).

Both the fertilisation and weather conditions significantly affected ($P < 0.05$) the uptake of nutrients by sugar beet plants. According to the average data of 2017–2019, fertilisation the uptake of N increased by 55.5–69.4%, P – by 56.8–70.5% and K – by 56.6–73.2% compared to the control treatment without fertilisers (Table 7). The nutrient uptake was significantly higher (*P*

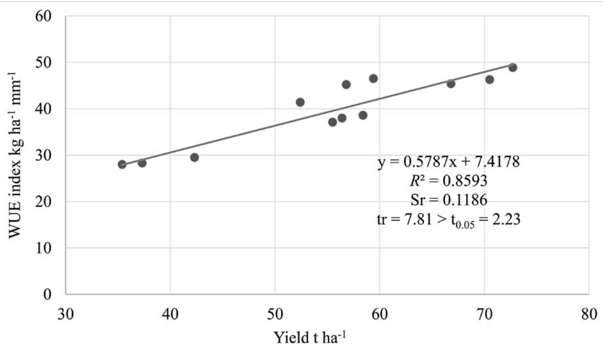



***Figure 3.*** The relationship between water-use efficiency (WUE) index and root yield (2017–2019)

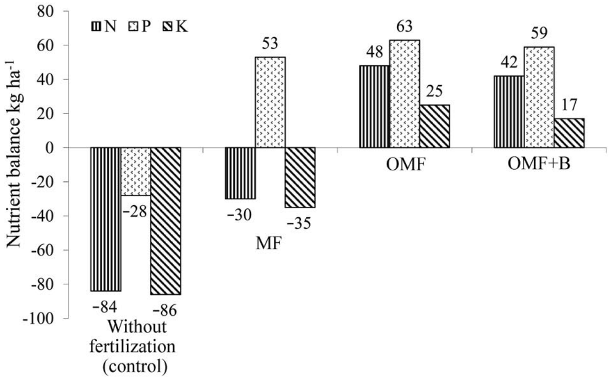
***Table 7.*** The removal of nutrients by biological yield of sugar beet depending on fertilisation and growing season

| No. | Fertilisation treatment | Year 2017 | 2018 | 2019 | | Increase % |
|---|---|---|---|---|---|---|
| | | N kg ha$^{-1}$ | | | | |
| 1 | Without fertilisation (control) | 131 a | 151 a | 158 a | 147 A | – |
| 2 | Mineral (MF) | 202 b | 274 b | 214 b | 230 B | 55.5 |
| 3 | Organic-mineral (OMF) | 212 b | 289 b | 211 b | 237 B | 61.2 |
| 4 | Organic-mineral + boron (OMF+B) | 228 b | 299 b | 219 b | 249 B | 69.4 |
| | Average | 193 A | 253 B | 201 A | | |
| | | P kg ha$^{-1}$ | | | | |
| 1 | Without fertilisation (control) | 37 a | 45 a | 49 a | 44 A | – |
| 2 | Mineral (MF) | 57 b | 83 b | 66 b | 69 B | 56.8 |
| 3 | Organic-mineral (OMF) | 62 bc | 85 b | 68 b | 72 B | 63.6 |
| 4 | Organic-mineral + boron (OMF+B) | 66 c | 88 b | 72 b | 75 B | 70.5 |
| | Average | 56 A | 75 B | 64 A | | |
| | | K kg ha$^{-1}$ | | | | |
| 1 | Without fertilisation (control) | 155 a | 175 a | 175 a | 168 A | – |
| 2 | Mineral (MF) | 235 b | 318 b | 236 b | 263 B | 56.6 |
| 3 | Organic-mineral (OMF) | 250 bc | 339 bc | 234 b | 274 B | 63.1 |
| 4 | Organic-mineral + boron (OMF+B) | 271 c | 353 c | 248 b | 291 B | 73.2 |
| | Average | 228 A | 296 B | 223 A | | |

*Note.* Labelled with different letters, nutrients removal is significantly different ($P < 0.05$) in columns depending on fertilisations (a, b, c); average nutrients removal is significantly different ($P < 0.05$) depending on growing season and on average per trial period (A, B).

< 0.05) in warm and moderate humid year 2018 than in dry 2017 and moderate 2019; the warm and humid growing season maximally contributed to this indicator value.

The results of the experiment showed that only OMF shaped positive nutrient balance in the soil. According to the average data of 2017–2019, OMF formed positive balance of N – 48, P – 63 and K – 25 kg ha$^{-1}$, OMF+B – 42, 59 and 17 kg ha$^{-1}$, respectively. Meanwhile, MF led to a deficit of N and K of 30 and 35 kg ha$^{-1}$, respectively, with a positive P balance of 53 kg ha$^{-1}$ (Figure 4).




*Note.* Balance value refers to the nutrient consumption only by roots; fertilisation treatments: MF – mineral, OMF – organic-mineral, OMF+B – organic-mineral supplemented with boron.

***Figure 4.*** The effect of fertilisation on nutrient balance in the soil (2017–2019)

## Conclusions

1. All fertilisation treatments had a positive effect ($P < 0.05$) on sugar beet yield and gross and white sugar yield. The highest averages of the aforementioned parameters were obtained with the fertilisation that included combined application of 5 t ha$^{-1}$ of winter wheat straw, 50 kg ha$^{-1}$ N and mineral fertilisers to the soil and boron foliar applied twice (OMF+B) – 63.5, 10.73 and 8.86 t ha$^{-1}$, respectively. This fertilisation had a more pronounced effect on sugar beet productivity in the year of hot and moderately humid growing season (2018) than in dry (2017) and moderate (2019) years.

2. Supplementing mineral fertilisers with straw and OMF+B shaped a positive nutrient balance in the soil and the highest water-use efficiency (WUE) index (44.7 kg ha$^{-1}$ mm$^{-1}$), provided efficient use of water and the sustainability of sugar beet cultivation under climate change conditions, while mineral fertilisation (MF) led to nutrient imbalance and low stability.

3. Fertilisation with straw and OMF+B significantly increased ($P < 0.05$) the main productivity indicators in comparison with MF treatment – the root weight, root yield and gross sugar yield with no significant impact on root sugar and root impurity components.

4. The accumulation of sugar in the roots mainly depended on the dry weather in September. The driest September of 2019 provided the maximum sugar accumulation in the roots – 18.2–18.5%, while moderately and too humid weather in September of 2017 and 2018 caused a significant decrease ($P < 0.05$) in sugar content to 17.0–17.5% and 14.9–15.2%, respectively.

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# Cukrinių runkelių tręšimas siekiant tvaraus derliaus klimato kaitos sąlygomis

V. Ivanina[1], R. Shapovalenko[1], O. Strilets[1], S. Senchuk[2]

[1]Bioenerginių augalų ir cukrinių runkelių institutas (NAAS), Ukraina
[2]Bila Tserkva bioenerginių augalų ir cukrinių runkelių instituto tyrimų ir selekcijos stotis, Ukraina

## Santrauka

Tyrimo tikslas – nustatyti, kaip skirtingos tręšimo sistemos veikia cukrinių runkelių produktyvumą, vandens naudojimo efektyvumo indeksą, maisto medžiagų pasisavinimą bei balansą ir nustatyti efektyvų augalų tręšimą. Taikyta dviejų veiksnių atsitiktine tvarka išdėstytų keturių variantų ir keturių pakartojimų eksperimento schema: 1) be trąšų (kontrolinis), 2) tręšimas mineralinėmis trąšomis (MT), 3) alternatyvus organinis-mineralinis tręšimas (OMT) ir 4) tręšimas organinėmis-mineralinėmis trąšomis, papildytomis boru (B) (OMT+B). Eksperimento rezultatai parodė, kad visi tręšimo būdai turėjo esminės įtakos ($P$ < 0,05) cukrinių runkelių šakniavaisių derliui, suminiam ir baltojo cukraus derliui. Šių rodiklių didžiausias vidurkis gautas tręšiant OMT+B – atitinkamai 63,5, 10,73 ir 8,86 t ha$^{-1}$, kai buvo kartu panaudotos mineralinės trąšos, žieminių kviečių šiaudai ir du kartus tręšta boru per lapus. Cukrinių runkelių produktyvumui OMT+B turėjo didesnę įtaką karšto ir vidutiniškai drėgno vegetacijos laikotarpio (2018) nei sausais (2017) ir vidutiniškai drėgnais (2019) metais. OMT+B lėmė teigiamą maisto medžiagų balansą dirvožemyje ir didžiausią vandens naudojimo efektyvumo indeksą (44,7 kg ha$^{-1}$ mm$^{-1}$), užtikrino efektyvų vandens naudojimą ir cukrinių runkelių auginimo ekologinę pusiausvyrą klimato kaitos sąlygomis, o tręšimas mineralinėmis trąšomis lėmė maisto medžiagų disbalansą ir mažą stabilumą. Cukraus kaupimasis šaknyse labiausiai priklausė nuo sausų rugsėjo mėnesio orų. Sausiausias 2019 m. rugsėjis lėmė didžiausią cukraus kiekį šaknyse – 18,2–18,5 %, o vidutiniškai ir per daug drėgni 2017 ir 2018 m. rugsėjo mėnesių orai lėmė reikšmingą ($P$ < 0,05) cukraus kiekio sumažėjimą atitinkamai iki 17,0–17,5 % ir 14,9–15,2 %.

Reikšminiai žodžiai: *Beta vulgaris*, derlius, tręšimas, tvarumas.