

Article

Effect of Strip-Till and Variety on Yield and Quality of Sugar Beet against Conventional Tillage

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Abstract: A two-factor field experiment using sugar beet was conducted in 2016–2018 at Sokołowo in Poland (ϕ 53°5′16.05″ N, λ 19°6′21.07″ E), in a strip-plot arrangement with four replicates. Strip-till (ST) was compared to conventional tillage (CT) using four commercial sugar beet varieties (Alegra, Armesa, Contenta, Julius). In each study year, the experiment was established on lessivé soils developed from heavy loamy sand. The soil was rich in available macronutrients, while its reaction was neutral. The plant density, sugar yield, roots quality, and technological sugar yield were determined. A significant increase was found in root yield (6.6%) and, accordingly, in technological sugar yield (8.2%) in ST treatment relative to CT. Consistently, an increasing trend was observed for the root sugar content (0.21%). For the varieties examined, no preferences were observed in respect of tillage systems applied. The direction of changes in root yield, sugar content, and technological sugar yield remained constant regardless of the variety, tillage system, or the study year. The contents of potassium, sodium, and α -amino-nitrogen responded equally to both the variety and study year; however, the direction of changes in the above parameters was ambiguous and varied among the study years.

Keywords: sugar beet; strip-till; tillage system; variety



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1. Introduction

Sugar beet production is concentrated in the EU regions, which have the most favorable soil and climate conditions. The economic importance of sugar beet cultivation relies heavily on sugar production for the domestic market and exports. This type of cultivation provides satisfactory site conditions for the aftercrops [1].

In Poland, changes in the sugar beet production were enforced by reforms to the sugar market in 2006–2010 and these differ by region. The end of sugar beet quotas in the EU led to an increase in sugar beet cultivation areas in several EU member states including Poland. Today, Poland, next to France, Germany, and the Netherlands belongs to four leading sugar producers within the EU [2]. The years 2015–2010 witnessed an increase in Poland's sugar beet cultivation area by 39.5%, while the proportion of sugar beet cultivation in the crop breakdown increased from 1.6 to 2.3% and amounted to 250 thousand ha. In Poland, the average sugar beet root yield oscillates around 60 t ha^{−1}, while the yield of technological sugar is at the level of 7.9 t ha^{−1} [3,4]. The data reported by the European Commission (2021) show a large variability in both sugar yield achieved and cultivation intensity in the individual member states [5].

Many environmental and agronomic factors influence sugar beet yield and quality. Thus, to harness maximum benefits from sugar beet, there is a need to select the most appropriate varieties, planting time, and planting methods [6,7]. Innovative solutions are sought in the field of sugar beet (*Beta vulgaris* L.) cultivation technology, to minimize the number of tillage practices and the level of mineral fertilization [8]. Instead of plowing, mulching and mixing techniques are being applied in the simplified tillage system without

soil inversion [9]. In the sugar beet production in Poland, conventional tillage (CT) still prevails which is based on plowing [10]. The CT system, however, is highly energy consuming and requires many farming practices obligatory to prepare optimal sites destined for sugar beet [11]. Ultimately, these practices may result in the increased compaction of lower soil horizons and the formation of plow pans.

Consequently, the overarching objective now is to adopt simplified systems, which reconcile maintaining site productivity and controlling wind erosion of soils, while at the same time providing an alternative for traditional tillage systems [12–15]. Interest in the simplified tillage system, which has been widely in South and North America—especially the USA and Canada over many years, has grown substantially in numerous west European and Asian countries as well as in Poland. This also applies to strip-till [15–23]. Tillage systems differing in depth and intensity are well known to alter chemical and physical soil properties affecting plant growth [17,24,25]. Advantages of strip tillage for sugar beet production include reduced soil erosion, enhanced moisture retention relative to full-width conventional tillage, improved seedbed environment relative to direct drilling, optimum fertilizer placement, increased carbon sequestration, and reduced fuel consumption [26–30]. Where soil moisture conditions are suitable, strip-tillage can be a useful alternative to other non-inversion tillage systems.

Modern machinery has made it possible to till strips in a single pass and at the same time apply fertilizers and sow seeds. In strip-tillage, strips of deeply loosened soil of several centimeters to several tens of centimeters wide are prepared for sowing seeds. These strips are separated by strips of untilled soil. A loosened soil strip is narrow and the width of non-loosened interrow is greater than in traditional seed drilling. The proportion of tilled to untilled area is about 1:2 or even higher [18,31]. Consequently, strip-till combines advantages of conventional and no-till cultivation. In the U.S., strip-tillage creates narrow tilled strips, which are typically 100–300 mm wide and raised 80–200 mm above the surrounding undisturbed ground. In recent years, strip-tillage machines have been largely re-designed using a system of shanks and colters which provide greater fuel efficiency and faster operating speeds than previous designs [19].

ST can significantly reduce fuel consumption, CO₂ emissions, the time required for field preparation, and the overall production cost compared with CT systems [31–35]. Additionally, ST shows a very favorable effect on the agricultural soil properties and on the environment [36,37]. As compared with the soil under conventional plow tillage (CT), the content of organic carbon and its fraction [38,39], the soil moisture, especially in the periods of rainfall deficit, the number of microorganisms, earthworms, and certain groups of predatory arthropods as well as the enzymatic activity, are higher [18,23]. Al-Kaisi et al. (2014) found that the effect of zero tillage and strip-till was the most beneficial for the stability of micro- and macro-aggregates. A significant positive correlation was also recorded between the content of organic carbon in soil and the water resistance of micro- and macro-aggregates [40].

Strip-till technology is being increasingly applied in other plant cultivation, especially those sown in wide-spaced rows, such as maize, soybean, sunflower, or watermelon [18,41–46]. However, strip-till gives good results too in plants with narrow spacing, such as cereal crops [47,48] rapeseed [49–51], or peas [18,52].

The spread of strip-till is consistent with the challenges of climate policies since reducing the number of cultivation treatments diminishes greenhouse gas emissions [53]. Strip-till in crop production presents an advantageous solution both economically and environmentally. The results of studies by Faber and Jarosz (2018) indicate that Polish agriculture has the capacity to cut greenhouse gas emissions by about 30% due to appropriate changes in agricultural practices up to the year 2030 [54]. Bearing in mind the commitment to meet the European requirements concerning the reduction in GHG emissions, the implementation of strip-till in the sugar beet cultivation is fully justified. The present study was undertaken with a view to getting farmers on board with changing their techniques of sugar beet cultivation.

The hypothesis adopted in this study is that strip-till outperforms conventional tillage and leads to an increase in root and sugar yield, irrespective of the variety applied.

2. Materials and Methods

2.1. Experimental Design

Field experiments using sugar beet were conducted in 2016–2018 at Sokołowo near Golub-Dobrzyń in the Kujawsko-Pomorskie voivodeship (ϕ 53°5′16.05″ N, λ 19°6′21.07″ E (Figure 1)). Analyses were made based on the results of a two-factor experiment set in a strip-plot arrangement with four replicates. The experimental factors involved: (i) tillage method: plowing (CT) and strip-till (ST) as well as (ii) four diploid varieties of sugar beet (*Beta vulgaris* ssp. *vulgaris*).

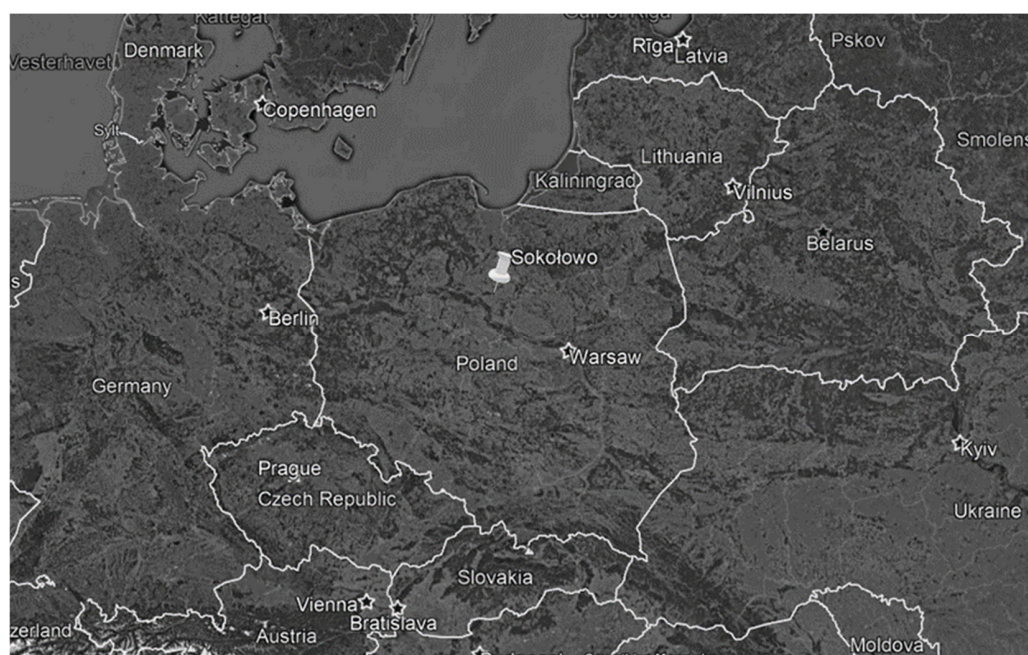


Figure 1. Geographical location of the study, Sokołowo, Poland, [55].

In each study year, the experiment was established on lessivé soils developed from heavy loamy sand and classified to IVa soil quality class. The soil was rich in available phosphorus (7.8–17.9 mg kg^{−1}), potassium (24.1–25.7 mg kg^{−1}), and magnesium (8.2–10.5 mg kg^{−1}), while its reaction was neutral (pH 6.3–6.8).

Notwithstanding the tillage system, the level of mineral fertilization was equal for all the treatments. Phosphorus in the form of enriched superphosphate (17.4% P) was applied in a single dose of 17.4 P ha^{−1}, prior to sowing a cover crop in autumn. Potassium in the amount of 100 kg K ha^{−1} was sown in split doses: 40 kg K ha^{−1} after forecrop harvesting, and 60 kg K ha^{−1} as potassium chloride salt (49.8% K) in the spring, four weeks prior to beet planting. Nitrogen fertilizers were applied on two dates: 40 kg N ha^{−1} on the sowing day, in the form of nitrochalk (27% N), and 80 kg N ha^{−1} after two weeks from sowing, as urea ammonium nitrate solution (RSM 32). On the first date, nitrogen was surface spread in the CT treatment, while in the ST treatment, applied into the rows at a depth of 0.15–0.25 m. The forecrop was winter wheat, which after harvest, was tilled using stubble aggregate, and an intercrop was sown using an aftercrop mix of white mustard (dominating species), fodder pea, sunflower, and common (blue) phacelia. In the traditional tillage treatment, the aftercrop biomass was incorporated into the soil during plowing at a depth of 0.20 m, while in the strip-till it remained as mulch for the winter. Strip tillage was performed with an RTK-GPS-based 6- or 12-row shank tiller (row width 0.45 m) equipped with a leading colter, row-cleaner, covering disk, and packer roll-er wheel (Kverneland, Kultistrip, DE, or Horsch, Focus, DE). The strips were 0.17–0.22 m deep and 0.20 m wide. Beet seeds were

sown on the following dates: 4 April 2016; 15 April 2017, and 12 April 2018, with 0.20 m between plants and 0.45 m between rows.

2.2. Plant Material

Four commercial varieties of sugar beet (*Beta vulgaris* ssp. *vulgaris*) were used with the following trade names specified on the labels (Alegra, Armesa, Contenta, and Julius). The Alegra and Contenta varieties were admitted to cultivation in Poland based on ‘The Polish National List’ (NLI) [56] while Armesa and Julius based on ‘Common catalog of varieties of agricultural plant species’ (CCA) [57]. The varieties are characterized in Table 1.

Table 1. Characteristics of the varieties.

Variety	Breeder	Representative	Type	Year of Registration
Alegra	DLF Seeds A/S Roskilde, Denmark	Hilleshög sp. z o.o. Iława, Poland	N	2012
Armesa	DLF Beet Seed ApS Holeby, Denmark	Hilleshög sp. z o.o. Iława, Poland	N	2014
Contenta	DLF Seeds A/S Roskilde, Denmark	Hilleshög sp. z o.o. Iława, Poland	N	2015
Julius	Strube D&S GmbH Söllingen, Germany	Hilleshög sp. z o.o. Iława, Poland	NZ	2011

N type—higher yield and average sugar content; NZ type—combined yield and sugar content.

2.3. Sample Collection and Analysis

The plant density per plot unit was determined on two instances during the growing season: at BBCH 12 phase (2 leaves—first pair of leaves—unfolded) and BBCH 49 phase (beet root has reached harvestable size) of technological maturity. At the BBCH 49 phase, beets were hand-harvested upon scalping, sampling plants from the four central 6 m long rows which resulted in a surface of 10.8 m² per plot. The total experimental plot surface for a given treatment was (2.7 × 20 m) 54 m². Results are expressed in t/ha.

The roots quality (contents of sugar, potassium (K), sodium (Na), α-amino nitrogen (N-α)) was determined based on 32 roots sampled randomly from each plot. Analyses of the quality parameters were performed on the Venema automatic line at the Kutno Sugar Beet Breeding Laboratory Ltd. (Straszków, Poland) in Straszków.

Sugar content was measured according to ICUMSA Method GS 6-3 (1994) “Polarization of sugar beet by the macerator or cold aqueous digestion and aluminum sulphate single method”.

Potassium and sodium content was measured according to ICUMSA Method GS 6-7 (2007) “Determination of potassium and sodium in sugar beet by flame photometry—official single method”.

N-α was measured according to ICUMSA Method GS 6-5 (2007) “α-Amino nitrogen in sugar beet by the copper method single method”.

The refined sugar content (RSC) was computed following the algorithm below [58]:

$$\text{RSC} = \text{Pol} - [0.177 \cdot (\text{K} + \text{Na}) + 0.247 \cdot (\text{N} - \alpha) + 1.08] \quad (1)$$

$$\text{YST} = (\text{YRY} \cdot \text{RSC}) : 100 \quad (2)$$

where:

Pol—sugar content (%);

K, Na, N-α—the content of potassium, sodium, α—amino-nitrogen (mmol 100 g^{−1});

YRY—root yield (Mg ha^{−1});

YST—technological sugar yield.

2.4. Statistical Methods

The results were statistically analyzed using ANOVA analysis of variance for a two-factor experiment according to the scheme for the strip-plot designs [59,60]. The study years were adopted as a constant effect. Homogenous groups were determined using the Tukey test at a significance level of $p = 0.05$. To intercompare the contributions assigned to each of the experimental factors and their interactions in explaining the variance of the dependent variable relative to their common errors, the partial coefficients eta-square (η_p^2) were calculated [61]. Additionally, an independent analysis of contrasts was conducted to estimate the differences between varieties under various tillage systems, for each variety and parameter [62]. Calculations were made using Statistica 12.0 software (TIBCO, Palo Alto, CA, USA) and ARM 2021.0 (Agricultural Research Management) (GDM Data, Brookings, SD, USA).

2.5. Weather Conditions

For assessing weather conditions in the examined region, average monthly values and long-term data for precipitation and temperature were obtained from the Institute of Meteorology and Water Management IMGW (the Głódowo Station) (Figure 2). Weather conditions varied over the study years, in terms of both precipitation amount and temperature distribution. Precipitation deficiencies relative to the normative long-term values were found in April and September 2016, amounting to 64% and 33%, respectively. The subsequent year of study (2017) was extremely wet and cool, with the only exception noted in April when precipitation was 64% lower relative to the normative values. For the period June–September, the monthly precipitation amounts significantly exceeded the many-year average. The increases in precipitation were most pronounced in June and September, and were 91% and 128%, respectively. At the same time, monthly average temperatures were lower than the normative values. Unlike 2017, 2018 was very dry and warm. Except for April, precipitation deficiencies were observed over the entire growing season with the highest severity in August and September (48% and 38% of the average norm). The average daily temperatures over the above period were higher than the many-year averages with the largest deviation in April and May, amounting to 3.5 and 3.2 °C, respectively.

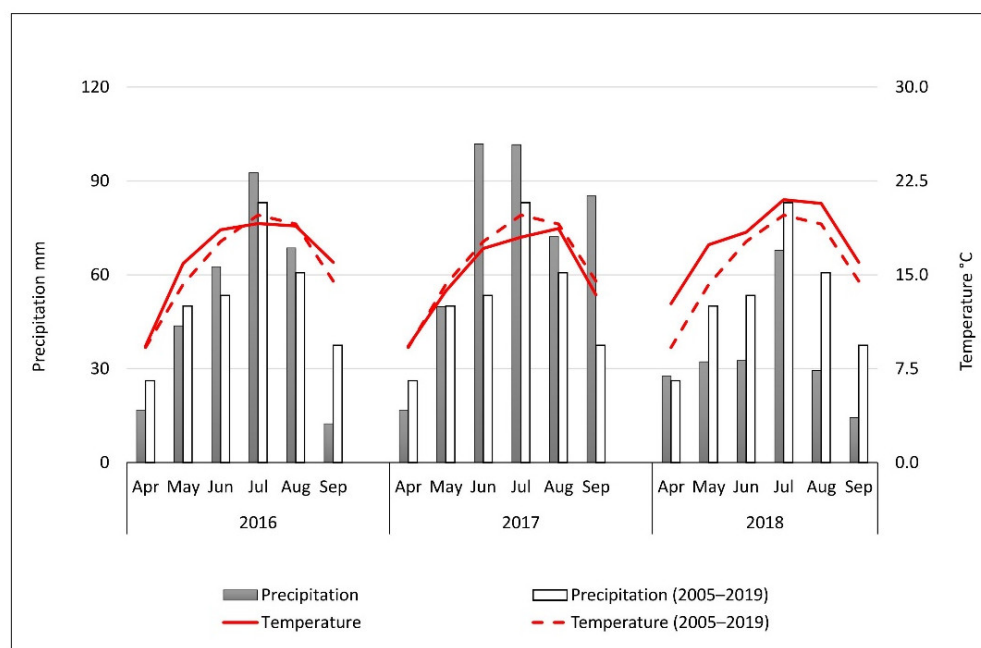


Figure 2. Weather conditions during sugar beet vegetation (April–September) of the normal long-term value (2005–2019) at the Głódowo meteorological station.

3. Results

3.1. Root Yield and Technological Sugar Yield

Analysis of variance revealed that the tillage method had a significant effect on yields of roots (Figure 3) and technological sugar (Figure 4). A significant increase in the root yield $F(1,3) = 77.85$; $p = 0.003$; $\eta_p^2 = 96.3\%$ as well as in the technological sugar yield (SY) $F(1,3) = 62.85$; $p = 0.004$; $\eta_p^2 = 95.4\%$, was found in ST relative to CT, amounting to 6.6% and 8.2%, respectively. Variety was also found to have a highly significant effect on the variability of root yield $F(3,9) = 11.31$, $p = 0.002$, $\eta_p^2 = 79.0\%$, the root sugar content $F(3,9) = 76.65$, $p < 0.001$, $\eta_p^2 = 9.2\%$ as well as on the technological sugar yield $F(3,9) = 4.74$, $p = 0.030$, $\eta_p^2 = 61.2\%$.

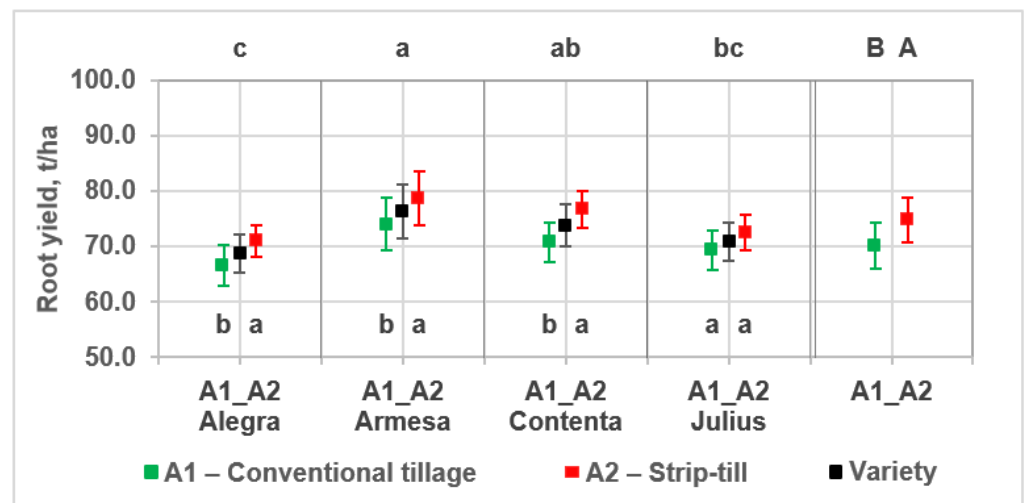


Figure 3. Effect of tillage system and variety on root yield in field experiment in the years 2016–2018. Means followed by the same letter are not significantly different according to Tukey's test at $p = 0.05$; the lettering at the top of the chart is for averages for the variety—lowercase and tillage systems—uppercase; the lettering at the bottom of the chart is for a single contrast of the tillage systems within one variety.

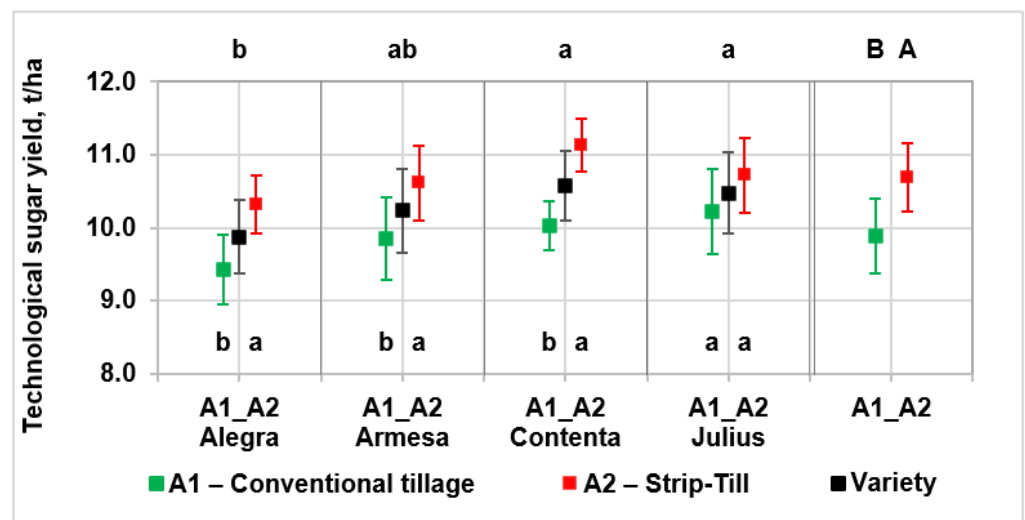


Figure 4. Effect of tillage system and variety on technological sugar yield in field experiment in the years 2016–2018. Means followed by the same letter are not significantly different according to Tukey's test at $p = 0.05$; the lettering at the top of the chart is for averages for the variety—lowercase and tillage systems—uppercase; the lettering at the bottom of the chart is for a single contrast of the growing systems within one variety.

None of the interactions: tillage system \times variety ($A \times B$) and year \times tillage system \times variety ($R \times A \times B$) were found to be statistically significant for the root yield, root sugar content, or the technological sugar yield. However, interaction: year \times variety ($R \times B$), $F(6,9) = 5.32$; $p < 0.013$; $\eta_p^2 = 78.0\%$ was observed to significantly affect the level of sugar content. This shows that changes in sugar content were ambiguous and varied between the study years.

From among the features examined, interaction: year \times tillage system ($R \times A$) was significant only in the case of root yield $F(2,3) = 12.38$; $p = 0.036$; $\eta_p^2 = 89.2\%$. In 2016, the root yields were comparable under both treatments, whereas in 2017 and 2018, they were higher under ST treatment, with differences ranging to 1.5, 7.3, and 11.6%, respectively.

Considering the average yield values gained over the three study years, the highest root yield was obtained for the Armesa variety ($76.39 \text{ t} \cdot \text{ha}^{-1}$), while the lowest for the Alegra ($68.82 \text{ t} \cdot \text{ha}^{-1}$), the difference being 11.0%. Taking into account factors such as variety and tillage system, a higher root yield was observed under ST, irrespective of the variety. Regardless of the tillage system, the size of root yield followed a declining trend: Armesa > Contenta > Julius > Alegra.

Relative to the CT system, statistically significant differences were obtained in terms of increased yield: for the Alegra variety ($t(1,51) = 2.62$; $p = 0.012$), Armesa ($t(1,51) = 2.74$; $p = 0.008$) and Contenta ($t(1,51) = 3.51$; $p < 0.001$), amounting to 6.7%, 6.3%, and 8.5%, respectively. No significant difference in yield was observed for the Julius variety ($t(1,51) = 1.89$; $p = 0.064$); nevertheless, an increasing trend (4.7%) was noted under the ST system.

The highest yield of technological sugar was obtained for the Contenta variety ($10.58 \text{ t} \cdot \text{ha}^{-1}$), while the lowest for the Alegra variety ($9.87 \text{ t} \cdot \text{ha}^{-1}$). The two latter varieties differed by 7.2%. Regardless of the study year and the variety, a significantly higher yield of technological sugar was obtained under the ST system: Alegra $t(1,51) = 3.82$; $p < 0.001$, Armesa $t(1,51) = 3.31$; $p = 0.002$, Contenta $t(1,51) = 4.78$; $p < 0.001$, and Julius $t(1,51) = 2.13$; $p = 0.038$). In terms of the sugar yield, the differences between the varieties were 9.4, 7.8, 11.0, and 4.7%, respectively.

No significant effect was found of the tillage treatment and variety on the plant density in both the BBCH 12 and BBCH 49 phases. The average plant density in the BBCH 12 phase was at the level of 99.34 thousand plants per ha^{-1} . The number of plants was slightly reduced over the growing season, on average by 4.7% (Table 2).

Table 2. Effect tillage system and variety on plants density per 10 m^2 .

Factor	Plant Growth Stage	
	BBCH 12	BBCH 49
Tillage system (A)		
Conventional tillage	99.79 ± 12.22	94.43 ± 13.01
Strip-Till	98.90 ± 10.09	94.88 ± 12.37
	ns	ns
Variety (B)		
Alegra	98.71 ± 10.12	93.08 ± 10.60
Armesa	98.29 ± 11.23	95.59 ± 14.28
Contenta	100.42 ± 11.86	96.65 ± 14.57
Julius	99.96 ± 11.88	93.30 ± 10.98
	ns	ns

ns—F statistic not significant.

3.2. Qualitative Assessment of Sugar Beets

3.2.1. Sugar Content

The technical quality of sugar beet roots is defined by the content of sugar and some compounds, which interfere with the extraction of white sugar in the course of the production process. The above compounds are generally defined as molassogenic substances and include α -amino-nitrogen, sodium, and potassium [63]. From a technological perspective, the higher the sugar content and the lower that of impurities, the higher the quality of sugar beets.

No notable differences were observed between the ST and CT systems in terms of the sugar content, $F(1,3) = 6.63$; $p = 0.082$; $\eta_p^2 = 6.9\%$; nevertheless, an increasing trend was largely noted under ST, which was on average 0.21 percent points (pp) (Figure 5). The highest sugar content was noted for the Julius variety (16.66%), and the lowest for the Armesa variety (15.38%). The abovementioned varieties differed by 1.29 pp. Depending on the varieties examined, the root sugar content was either positively or not at all affected by the ST system. A significantly higher sugar content was demonstrated for the Alegra ($t(1,51) = 3.14$; $p = 0.003$) and Contenta varieties ($t(1,51) = 2.74$; $p = 0.008$). The increases, relative to the CT system, were 0.37 and 0.33 pp, respectively.

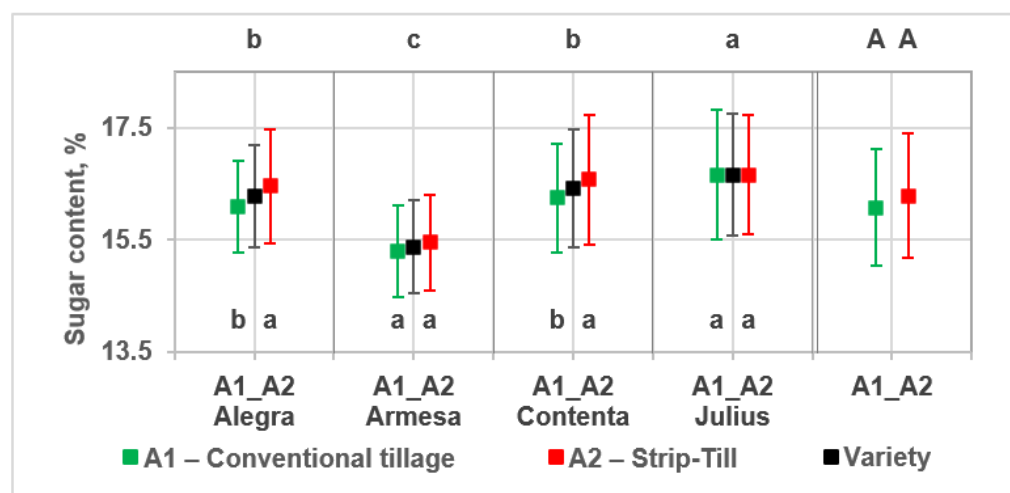


Figure 5. Effect of tillage system and variety on sugar content in root in field experiment in the years 2016–2018. Means followed by the same letter are not significantly different according to Tukey's test at $p = 0.05$; the lettering at the top of the chart is for averages for the variety—lowercase and tillage systems—uppercase; the lettering at the bottom of the chart is for a single contrast of the growing systems within one variety.

3.2.2. Content of Potassium, Sodium and α -Amino-Nitrogen in Roots

Irrespective of the study year, no significant effect was observed of the tillage system on the root content of molassogenic substances (K, Na, and N- α) (Figures 6–8). The variability among the above parameters responded mainly to the year of study and the variety, whereas that of sodium was affected by the combined action of the parameters and the tillage system.

Considering the root content of K, Na, and N- α , the coefficient η_p^2 was highest for the effect of variety (B) and the interaction: year \times variety (R \times B). The above relations were: for K—94.5 and 80.2%; for Na—98.3 and 98.4%; and for N- α —91.5 and 95.1%, respectively.

Taking account of the three-year average values of the above parameters, interpreted separately for each variety, no effect was found of the tillage system on the root content of K and N- α . The analysis of contrasts revealed that the tillage system had no significant effect on the content of K and N- α in roots.

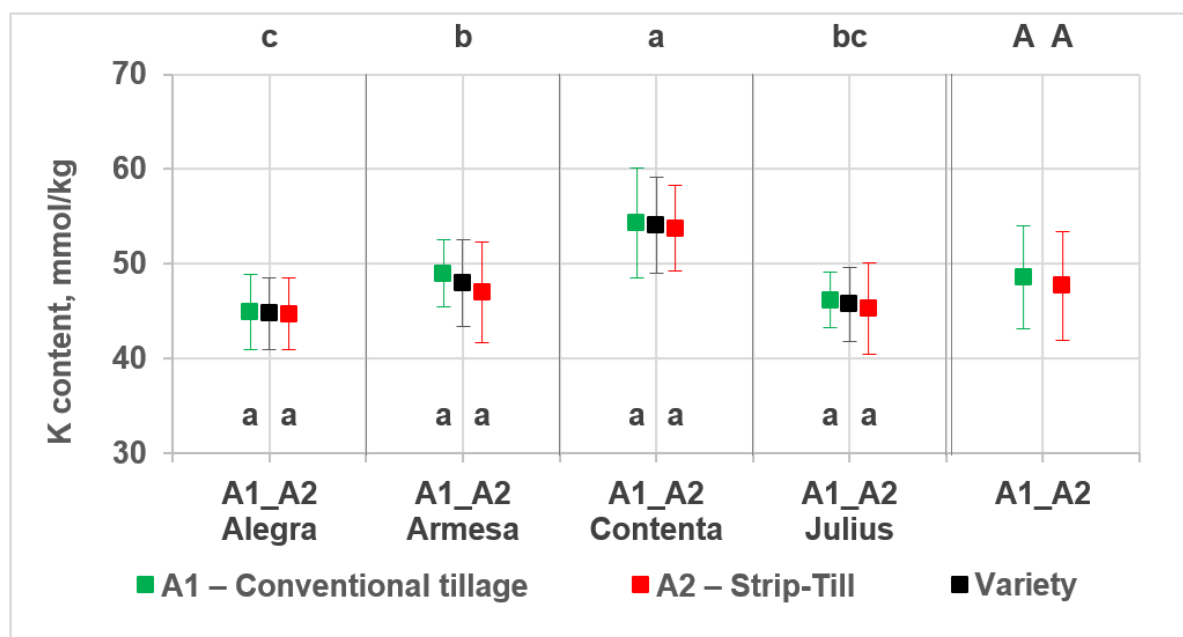


Figure 6. Effect of tillage system and variety on K content in root in field experiment in the years 2016–2018. Means followed by the same letter are not significantly different according to Tukey's test at $p = 0.05$; the lettering at the top of the chart is for averages for the variety—lowercase and tillage systems—uppercase; the lettering at the bottom of the chart is for a single contrast of the growing systems within one variety.

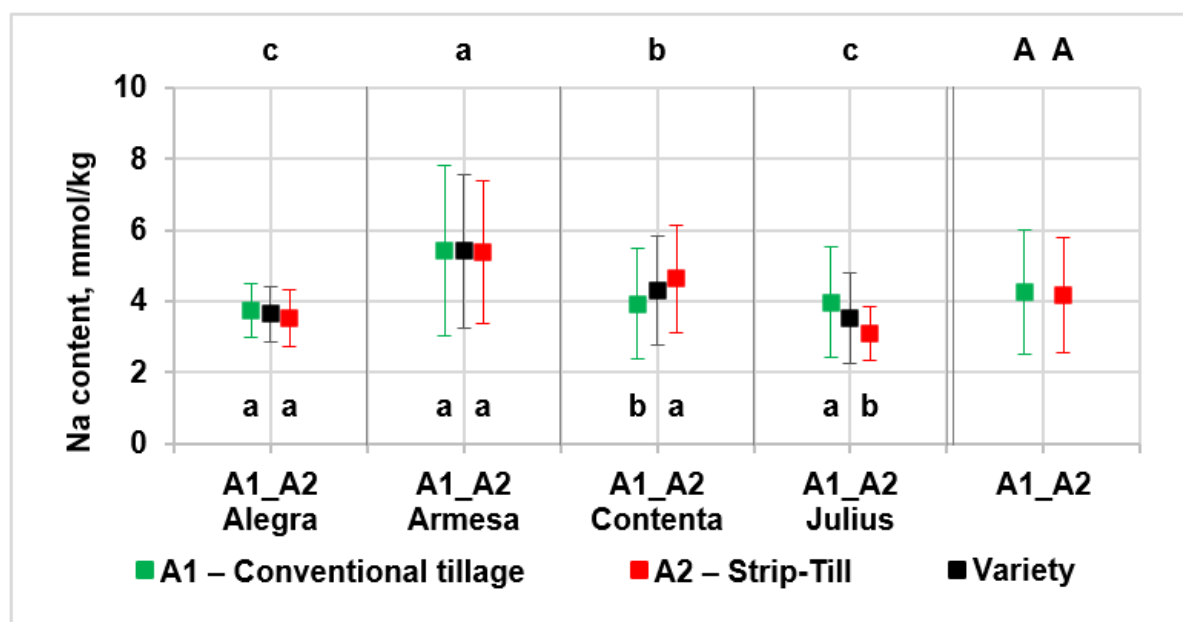


Figure 7. Effect of tillage system and variety on Na content in root in field experiment in the years 2016–2018. Means followed by the same letter are not significantly different according to Tukey's test at $p = 0.05$; the lettering at the top of the chart is for averages for the variety—lowercase and growing systems—uppercase; the lettering at the bottom of the chart is for a single contrast of the tillage systems within one variety.

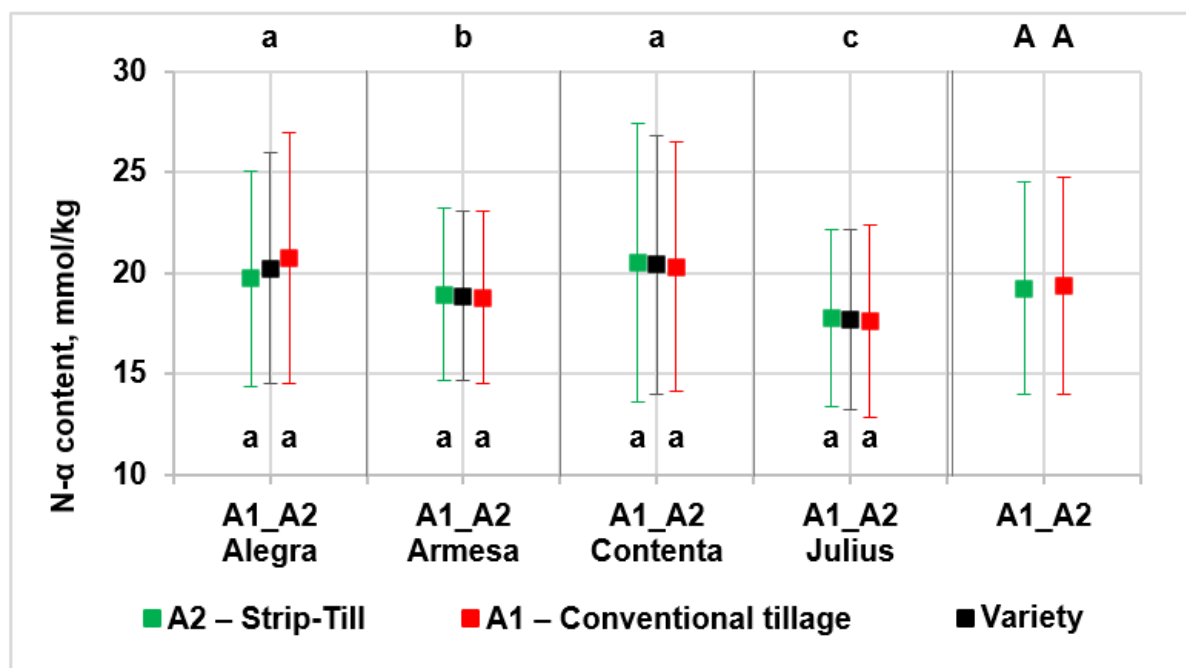


Figure 8. Effect of tillage system and variety on N- α -amin content in root in field experiment in the years 2016–2018. Means followed by the same letter are not significantly different according to Tukey's test at $p = 0.05$; the lettering at the top of the chart is for averages for the variety—lowercase and growing systems—uppercase; the lettering at the bottom of the chart is for a single contrast of the tillage systems within one variety.

However, the impact of the tillage treatment on the root sodium content was ambiguous. Depending on the variety, ST resulted in either an increase or decrease in the sodium content in roots. Significant contrasts were proven for both the Contenta-, $t(1,51) = 3.72$, $p < 0.001$ and Julius varieties, $t(1,51) = -4.55$, $p < 0.001$. The differences under ST relative to CT were 18.0% and −21.8%, respectively.

The impact of the tillage system on the root sodium content was ambiguous. An insignificant contrast was found for the Armesa and Alegra varieties. A significantly higher root content of sodium for the Contenta variety was found under ST, $t(1,51) = 3.72$, $p < 0.001$, whereas for the Julius variety under CT, $t(1,51) = -4.55$, $p < 0.001$.

4. Discussion

Taking into account the study's objective, we focused on the evaluation of the yield efficiency of tillage systems and the quality parameters of four sugar beet varieties. As the benchmark, the classic conventional tillage system was adopted, which is still a dominating practice in Poland for growing sugar beet. The quick and uniform emergence of sugar beet plants is a prerequisite for the rapid development of an adequate leaf canopy that facilitates efficient light interception and high yield [64]. The tillage system in our study did not affect the emergence speed and, ultimately, the plant stocking density on the set dates. Similarly, Afshar et al. [65] showed no differences in the plant density between the three systems of sugar beet cultivation. Yield is determined by many interacting factors and the effects of tillage systems are neither consistent nor predictable. One of the basic elements essential for evaluating the conditions of growth and yield production performance for a given variety is to relate the results obtained to the yield potential [66]. Over the study years (2016–2018), the yield potential of sugar beets, as defined by COBORU [56], was as follows: 88.4 t ha^{-1} ; 88.9 t ha^{-1} and 80.5 t ha^{-1} . In our study, the yield production performance of sugar beets was utilized in 83% in 2016, 87% in 2017, and 82% in 2018, relative to the yield potential established by COBORU. The size of the root and sugar yields obtained in this study may be explained based on a group of natural and agrotechnical

factors, and principally, in terms of variability of weather conditions (precipitation sum and distribution, temperature) and agrochemical conditions, i.e., nutrient availability. Weather conditions varied greatly over the study years, from extremely dry in 2018 to extremely wet in 2017, which was the major driver of yield variability over the respective years. Muchova et al. [67], Hartmann et al. [68], and Pacuta et al. [69] also showed the effect of weather conditions on the root and sugar yield performance in sugar beets. Moisture is critically important at the phase of intensive leaf development, which attains the maximal size at the turn of July and August. In our study, water deficiency was particularly severe in 2016 and 2017. However, despite the moisture deficit in the periods of critical demand, the level of root and technological sugar yield obtained was relatively high and significantly exceeded the country's average, which reflects the fertility of the study sites.

To date, the studies on alternative tillage systems in sugar beet production technology have yielded no explicit results and have revealed a wide differentiation of root and sugar yields as well as of quality parameters [2,24]. Van den Putte et al. [70] found that sugar beet yield reduction under no-till was very substantial and concluded that this practice is not economically viable. Several year-long studies by Kordas and Zimny [71] revealed that, especially in the early vegetation stage, direct sowing results in a significant increase in soil compaction, which eventually, may be reflected in the declining yield. Results of most research studies [19,31,72] show that strip-tillage does not differ from conventional tillage systems for sugar beet yield and sugar production. Strip tillage for sugar beet production was superior to direct drilling in most cases. Given the similar yields and potential cost savings from fuel and labor, strip-tillage is a feasible and potentially profitable alternative to conventional full-width tillage for sugar beet production. Research by Gaj et al. [15] showed explicitly that the choice of tillage method was a secondary issue if plants were grown on fertile sites and over the years with a regular precipitation distribution during the growing season. The tillage method also affects the uptake of nutrients by sugar beets. Gaj et al. [73] demonstrated that nutrient uptake per yield unit was higher in sugar beets in the classic system with plowing than in the treatments with reduced tillage. A lower uptake of nitrogen under reduced tillage may be due to the abundant growth of lateral roots in the mulch systems as well as a shorter main root, which indicates disturbances of vertical growth, and consequently, a lower uptake of nutrients from deeper soil layers as well as changes in the quality parameters. Laufer and Koch (2017) reported that a lower nitrogen uptake in the strip-tillage system is due to a slower rate of N mineralization processes occurring in the soil. Therefore, using non-inversion tillage systems that disturb less soil compared to plow-based systems may suffer transitory N limitation because soil organic matter decomposes more slowly, thus decreasing the rate of nitrogen mineralization [74]. Other researchers [70,75–78] have proven that tillage and incorporation of the intercrop residue into the soil decrease soil thickness and increase the total soil porosity. This helps to improve moisture conditions and increases the content of organic carbon, total nitrogen, and the available forms of potassium and magnesium. Consequently, these processes lead to enhanced soil fertility, an increased rate of microbial decomposition of intercrop biomass, which, ultimately, is reflected in the improvement of the root yield size.

The site effect and genotype–environment interaction do not relate solely to the root yield, but also to its technical quality, including polarization and the content of molassogenic substances [79,80]. Compounds such as α -amino nitrogen, K, and Na in beet pulp are considered substances that affect sugar recovery [81]. The tillage systems tested had a significant effect on the technological sugar yield, which was higher in ST.

In our study, the sugar beet quality parameters were only slightly dependent on the tillage system applied.

The variety effect regarding the sugar content was more pronounced than the effect of the tillage system. Barłóg and Grzebiś [82] demonstrated that the variability in weather conditions is the largest determinant to the quality of sugar beets, yet there are differences between varieties. At the same time, the authors emphasize the complexity of the relationship between the quantitative and qualitative features of sugar beet yield, and between the

yield size and parameters such as polarization and the content of molassogenic substances, in particular.

Rother [83], based on studies conducted in several locations in 1994–1995, found that the root sugar content varied between years and sites with differences up to 6%, whereas between the fertilization levels, varieties, and harvest date showed differences up to 4%. Thus, the issue of sugar beet quality in the alternative tillage systems requires special attention from the producer, in view of a series of additional factors restricting the growth of plants. The literature data [73,84] show that a reduction in the root sugar content and an increase in α -amino-nitrogen are due to the increase in the root nitrogen. Hoffmann [85] and Hoffmann and Märlander [86] emphasize the importance of location and weather conditions in determining the quality of sugar beet.

5. Conclusions

The results of this study showed that strip-till is highly effective for sugar beet production. Relative to conventional tillage, in strip-till, a significant increase was found for root yield (6.6%) and technological sugar (8.2%). The variability in the above parameters depended primarily on the tillage system applied, while that of the root sugar content was largely associated with the variety. Among the varieties, no preferences were observed towards the tillage systems tested; nevertheless, there was significant variability in the yields of roots and technological sugar, as well as in the contents of sugar, potassium, sodium, and α -amino-nitrogen. However, the direction of changes in the above parameters was ambiguous and varied between the study years.

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