AMMI Analysis of the Effects of Different Insecticidal Treatments against Agrotis spp. on the Technological Yield from Sugar Beet

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Abstract: The aim of this study was to analyze the effects of different variants of insecticidal treatment against Agrotis spp. caterpillars on the technological yield from sugar beet using the AMMI (Additive Main Effect and Multiplicative Interaction) model. Data for the analysis of sugar beet yield and different insecticidal treatments were obtained from a trial in Winna Góra between 2011 and 2018. White sugar yield was estimated for each variant of treatment, and it was found to be directly proportional to the root weight and polarization. The content of potassium in molasses had an inversely proportional effect on the sugar yield in the variant of treatment based on phenological observations with calculated heat sums, as well as in controls. The content of α-amino-N had an inversely proportional effect on the technological yield of sugar for each variant of tested chemical treatments. The content of α-amino-N had a statistically significant effect on the sugar beet yield for all tested experimental combinations. AMMI analysis used to estimate the interaction of treatments based on environmental conditions showed the additive effect of the applied treatments on the quality parameters of white sugar yield from sugar beet. These effects were demonstrated for polarization and the content of sodium in molassigenic substances. Regarding the AMMI model, the results of the analysis of variance showed a significant interaction between treatment and year for all considered characteristics in the experiment.

Keywords: yield components; technological yield from sugar beet; molassigenic substances; AMMI biplot; sugar beet

1. Introduction

The production of sugar beet is aimed at achieving the highest technological sugar yield, which is the function of the root yield and its technological value [1–3]. Sugar beet plantations are characterized by a large diversity of final beet root biomass, which, together with crop density, determines yield size. The relationship between the highest weight of roots and their technological value is also important for the quality and size of an obtained yield [4]. The technological quality of sugar beet roots is of great importance, both in terms of sugar yield and the requirements of the sugar industry. The content of molassigenic substances (α-amino-nitrogen, sodium (Na), and potassium (K) ions) in sugar beet roots has a significant impact on the sugar production process. The higher their content, the worse the technological value of beets [5]. The yield and technological quality of roots depend on many environmental parameters (such as weather) and agrotechnical factors, including beet variety, fertilization, plant protection treatments, sowing and harvesting dates, weed infestation rate, and drought stress [2,6–8]. Plants attacked by pests and pathogens are able to induce an array of defense responses ranging from the rapid synthesis of toxic metabolites and defensive proteins to longer-term morphological changes. Plant defense...
responses to stress factors including herbivorous insects are costly for plants; they can have negative effects on plant growth, development, and obtained crop yield [9]. Attempts to exploit such induced resistance responses via the application of synthetic chemicals that activate defense signaling pathways, such as benzothiadiazoles, have met with rather limited success to date, perhaps in part because these benefits are constrained by the inherent costs of defense [10].

Sugar beet is attacked by many pests that may directly (feeding on plant tissue) or indirectly (vectors of plant pathogens) affect the plants. Pimental [11] estimated worldwide losses due to weeds, pathogens, and insects as 25–35% of pre-harvest and 10–20% of post-harvest agricultural plants. Viral diseases and nematodes are a serious problem for beet cultivation in most parts of the world. Similarly, cutworms, or surface caterpillars, damage sugar beet plants and have negative impacts on obtained crop yields. Several species are known to damage sugar beet, including Agrotis spp., Euxoa spp., and Xestia c-nigrum (L.) Central and Northern Europe and the USA), Peridroma saucia (Hübner), Crymodes devastator (Brace), and Feltia ducens (Walker) (in the USA); in addition to those also mentioned the larvae of many other moths such as Hydracria micacea, Loxostege sticticalis (L.), Scrobipalpa ocellatella Boyd, Spodoptera spp., and Pseudaletia unipunctata (Haworth) can also damage the foliage of beet plants [12–18].

Many species of cutworms including Agrotis segetum Den. Et Schiff. (Turnip moth) and Agrotis exclamationis L. (Heart and dart moth) affect sugar beets every year in Poland. Currently, it is estimated that the harmfulness caused by cutworms in different agricultural crops in Poland ranges from 2 to 30% depending on the different agricultural crops [12]. The abovementioned insect species belong to the family of owlet moths (Noctuidae, subfamily: Noctuinae), popularly known as cutworms. Owlet moths are soil pests that cause considerable damage to many crops, including plantations of root crops, vegetables, cereals, and ornamental plants in nurseries. There is one generation of these pest in Poland. However, it is possible for the Turnip moth to have an incomplete second generation. Autumn weather conditions have an effect on the development cycles of these insect species [12]. Larvae are considered to be the harmful stage and are the target of insecticide treatment. Controlling them is very difficult due to their hidden mode of life. A successful reduction in their harmfulness largely depends on the date on which the insecticide treatment is done. The selection of an appropriate control date for a given pest reduces the number of treatments, especially when decisions regarding the need for chemical control are individually made for each plantation while considering the economic threshold of harmfulness. Therefore, determining the optimal date of the procedure is not easy. For the purposes of short-term agricultural forecasting, the systematic monitoring of moth flight on plantations from the beginning of May is of great importance for beet protection. The date of moth flight primarily depends on the weather conditions in a given year. The easiest way to set a date is to accurately determine the mass flight of moths. For this purpose, moths are caught with the use of light traps. Catching more than one moth over 1–2 consecutive nights is a critical number that indicates the beginning of mass moth flight. According to the signaling indications, as well as an addition 30–35 days depending on weather conditions, the L2 stage caterpillar (caterpillar size < 1 cm) control date should be set. The date of the insecticide treatment can also be based on determined temperature values, i.e., the sum of heat and the sum of effective temperatures [12]. Currently, there are no insecticides registered against these pests in Poland.

The aim of this research was to evaluate the effect of different variants of insecticidal treatment against Agrotis spp. cutworms on the technological quality of sugar beet (root weight, polarization, K molasses, Na molasses, α-amino-N, and technological yield) using the AMMI (Additive Main Effect and Multiplicative Interaction) model.
2. Materials and Methods

2.1. Trial Site

Field experiments were carried out in Winna Góra (52°12′17″ N, 17°26′48″ E) (Department of Field Experimentation of the Institute of Plant Protection—National Research Institute) between 2011 and 2018. Field experiments were conducted over eight years. The trial was conducted in cooperation between the Institute of Plant Protection—National Institute of Research and Pfeifer and Langen Polska SA. Field experiments trials were established in a unifactorial random block design with four replicates. The experiments consisted of five variants: three protective variants and two control variants without chemical treatment. Insecticide protection against caterpillars of the *Agrotis* species was applied after the optimal date of chemical control was established and the threshold of economic harmfulness was exceeded. Throughout the growing season, observations were made on twenty experimental plots. The all area of field plots was around 350 m². The experiment was established on clay sands and lessive soils (soil classes IIIa, IIIb, and IVa). Soil pH was close to neutral as required for sugar beet, with a medium phosphorus (P) content and high potassium (K) and magnesium (Mg) contents. The quantitative assessment of the soil for Na, K and Mg was determined by an accredited laboratory by Polish Center Accreditation—AB317 at the regional chemical and agricultural station in Poznań.

2.2. Plant Material

Three varieties of sugar beet *Beta vulgaris* (L.) ssp. *vulgaris* were used: Jagoda (2011–2013), Janusz (2014–2016), and Maryna (2017–2018). Beet seeds were treated with Tachigaren 70 WP fungicide (active ingredient (a.i.): hymexazol—700 g/kg−1 /70%) in dose 40 g per seeds unit–1. Winter wheat was grown as the forecrop for sugar beet in each study year. The experiments were carried out according to the same methodology, assuming the use of generally accepted agrotechnical procedures and treatments for sugar beet. All plots were fertilized with the same dose of nitrogen (120 kg N ha−1). Half of the nitrogen dose was applied before sowing and when sugar beets had four pairs of leaves developed (BBCH 14). One week before sowing, the soil was fertilized with phosphorus (P), at a dose 60 kg of P₂O₅ ha−1, combined with K. During the growth period, standard herbicide and fungicide protection were used.

2.3. Trial Design

The seeds were sown in the first decade of April (between 4 and 9 April); the sowing density was 1.02 the seeding unit per ha−1. The ZÜRN D82 automatic seed drill was used for sowing sugar beet, intended for the precise sowing of test plots. The area of the plot for sowing was 13.5 m² (width—1.8 m; length—7.5 m). The number of plants per plot was 108 when sowing beet seeds every 24.0 cm and with a row spacing of 45.0 cm. The number of rows in a plot was 4. The mean final plant density was 86 sugar beet plants per plot. The decision to use an insecticide treatment was determined based on the following criteria:

- Pest alert (S)—the first adult insects (moths) captured in traps/signs of caterpillar feeding,
- Phenology (F)—calculation of the sum of effective temperatures (F1) and heat sums (F2),
- Control plots, K (no pest control), K2 (plots were sprayed with water) [12].

Samples for analysis were taken from treated and control plots. For short-term forecasting in the 4 year period of study under controlled and field conditions, the sum of temperature was defined as 501.1 °C and the sum of effective temperatures was defined as 230.0 °C for the examined period of the cutworm development [12]. The results of these studies were used to establish the optimal date of chemical control against cutworms according to the phenological criterion, which uses the calculated sum of the heat and the sum of effective temperatures of the harmful stages. The date of the treatment was phenologically determined by adding the average day temperatures (a minimum of 30 days) from the day following the initial moth mass flight (for each of the localities analysed).
Observations for the appearance and feeding of larvae were carried out on all plots (optimal date of treatment).

All chemical treatments were performed after finding traces of caterpillars feeding on leaves and roots, exceeding the threshold of economic harmfulness, and considered the analysed criteria. In sugar beet, this is the moment when 4–6 caterpillars of cutworm from the L_1–L_2 stage are found per 1 m^2 [12]. Chemical foliar treatments against two species of cutworms *A. segetum* and *A. exclamationis* were made with using following active ingredients (a.i.) of lambda-cyhalothrin, deltamethrin, diazinon, chlorpyrifos, and esfenvalerate. Plant protection was carried out in accordance with the Plant Protection Recommendations issued by the Ministry of Agriculture in Poland. In 2011, two protective treatments were applied by using Basudin 25 EC (a.i. diazinon—25%) as an emulsifying solution at the recommended dose for soil spraying at a concentration of 0.5% and mixing in the soil before sowing sugar beets. Once the date of the insecticide treatment was set, Karate Zeon 050 CS (a.i. lambda-cyhalothrin—50 g/4.81%) was applied in foliar spray against the caterpillars at a dose of 0.2 l/ha^-1. In the next year of the experiment, only one foliar treatment was conducted with an insecticide—Decis 2.5 EC (a.i. deltamethrin—25 g/2.8%) at a dose of 0.25 l/ha^-1. In 2013, foliar treatment was carried out with Dursban 480 EC (a.i. chlorpyrifos—480 g/44.86%) at a dose of 1 liter per hectare. Sumi-Alpha 050 EC (a.i. esfenvalerate—50 g/5.54%) was used to control caterpillars of the *Agrotis* species at the recommended dose of 0.1 l/ha^-1 in the following year. Karate Zeon 050 CS at the recommended dose, i.e., 0.2 l per hectare, was used in 2015. In the years 2016–2018, foliar spraying was carried out with the Pyrinex 480 Ec insecticide (a.i. chlorpyrifos—480 g/44.4%) at a dose of 0.9 l/ha^-1. All chemical treatments were carried out with the use of a plot sprayer with the recommended amount of water of about 400–450 l per hectare. The spraying fluid had a pressure of 0.3 MPa. For spraying, two-stream Teejet (AITTJ60) ejector nozzles were used with an average droplet size (good penetration and application).

2.4. Data Collection

Each year, the beet were harvested in the second decade of October. The roots were collected by hand from each plot and the four central rows (10.8 m^2), next cleaned, and weighed (after removing the leaves). Two rows in the plot were used for harvesting. Qualitative and quantitative parameters were analysed for 20 roots of sugar beet. On the harvest day, representative root samples were collected in accordance with the PN-R-74452 standard in order to determine technological quality. Root weight, polarization, K molasses, Na molasses, N-amino, technological yield size were assessed. The technological values of the raw material were measured with a Venema line. Approximately 50,000 samples of sugar beet roots were analysed by the technology laboratory in Straszków each year. Sucrose content was polarimetrically determined in degrees °Z. The contents of Na and K were determined with a flame photometer, and the content of N-amino was assessed fluorometrically. The content of molasses was defined in mval per 1000 grams of pulp. White sugar yield – technological yield was calculated with the formula proposed by Buchholz et al. [19].

2.5. Statistical Analysis

The analysis of harvested roots (yield) was conducted for data gathered in 2011–2018 using the AMMI model. AMMI is one of the most effective and popular statistical tools; it relies on various modifications of two-way ANOVA combined with regression analysis to determine the significance, power of correlation, and dependence of traits [20–22]. The AMMI model combines the additive main effects of treatments (T) and years (Y) with the multiplicative interaction effects (I) for TYI estimated by principal component analysis (PCA). The results of the AMMI analysis are presented in biplots. The AMMI model [23] is represented by:

\[ y_{ge} = \mu + \alpha_g + \beta_e + \sum_{n=1}^{N} \lambda_n \gamma_{gn} \delta_{en} + Q_{ge}, \]
where $y_{ge}$ is the mean effect of treatment $g$ in year $e$, $\mu$ is the grand mean, $a_g$ is the mean deviation for treatment, $b_e$ is the mean deviation for the year, $N$ is the number of the PCA axis retained in the adjusted model, $\lambda_n$ is the singular value for PCA axis $n$, $\gamma_{gn}$ is the treatment eigenvector for PCA axis $n$, $\delta_{en}$ is the year eigenvector for PCA axis $n$, and $Q_{ge}$ represents residuals including AMMI noise and pooled experimental error. An AMMI stability value (ASV) was used to compare the stability of treatment, as described by Purchase et al. [23]:

$$ASV = \sqrt{\frac{SS_{IPCA1}}{SS_{IPCA2}}(IPCA_1)^2 + (IPCA_2)^2},$$

(2)

where $SS_{IPCA1}$ is the sum of squares for $IPCA1$, $SS_{IPCA2}$ is the sum of squares for $IPCA2$, the values of $IPCA1$ and $IPCA2$ are the results of treatment in the AMMI model, and IPCA means interactive principal component analysis. A lower ASV value indicates a higher stability of treatment over the years [24,25]. All analyses were performed using the GenStat v. 18 statistical software package.

3. Results

3.1. Results of AMMI Analysis

Two variables, i.e., the year and the treatment variant (TYI interaction), were statistically significant for all six analysed traits (Table 1) of the sugar beet yield. The applied variant of the insecticidal treatment had a statistically significant effect on the weight of sugar beet roots and technological yield at $p < 0.001$ (Table 1).

| Source of Variation | d.f. | Root Weight | Polarization | Potassium | Molasses | Sodium | Molasses | $\alpha$-Amino-Nitrogen | Technological Yield |
|---------------------|------|-------------|--------------|-----------|---------|--------|---------|------------------------|-------------------|
|                     |      | m.s. | ve | m.s. | ve | m.s. | ve | m.s. | ve | m.s. | ve | m.s. | ve |
| Total               | 159  | 34.26 | 1.86 | 103.91 | 1.98 | 72.11 | 6900 |
| Treatments, T       | 4    | 20.66 * | 1.50 | 0.55 | 0.7 | 8.52 | 0.2 | 0.42 | 0.5 | 22.86 | 0.8 | 5526 * | 2.0 |
| Years, Y            | 7    | 560.15 *** | 72.0 | 34.12 *** | 80.8 | 2032.30 *** | 86.1 | 35.99 *** | 80.1 | 1051.71 *** | 64.2 | 103,216 *** | 65.9 |
| Block               | 24   | 7.93 | 3.5 | 0.72 *** | 5.8 | 48.71 *** | 7.1 | 0.45 | 3.4 | 59.64 *** | 12.5 | 1988 | 4.4 |
| TY Interactions     | 28   | 16.35 ** | 8.4 | 0.50 ** | 4.7 | 12.27 ** | 2.1 | 0.66 ** | 5.8 | 30.22 * | 7.4 | 4111 ** | 10.5 |
| IPCA 1              | 10   | 37.30 *** | 81.4 | 1.09 *** | 78.0 | 19.90 ** | 57.9 | 1.44 *** | 78.5 | 49.19 ** | 58.2 | 9556 *** | 83.0 |
| IPCA 2              | 8    | 8.06 * | 14.0 | 0.26 * | 15.1 | 10.89 * | 25.3 | 0.32 | 13.7 | 26.57 * | 25.2 | 1949 * | 13.5 |
| IPCA 3              | 6    | 2.03 | 2.6 | 0.15 | 6.2 | 7.11 | 12.5 | 0.17 | 5.5 | 14.71 | 10.4 | 444 | 2.3 |
| Residuals           | 4    | 2.02 | 1.8 | 0.02 | 0.7 | 3.72 | 4.4 | 0.11 | 2.3 | 12.92 | 6.2 | 323 | 1.1 |
| Error               | 96   | 8.28 | 0.24 | 7.84 | 0.33 | 18.08 | 1976 |

d.f.—number of degrees of freedom; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$. IPCA—interactive principal component analysis.

3.1.1. Root Weight

The sum of squares for the main effect of the year explained 72.0% of the total variability of root weight. The differences between treatments explained 1.5% of the total variability of root weight, and the effects of TYI explained 8.4% of it (Table 1). The values of the first and second principal components were also significant and together accounted for 95.4% of the total effect on root weight; the first principal component (IPCA 1) of interaction explained 81.4% of the variability attributed to the interaction, and IPCA 2 explained 14.0% of it. Depending on the treatment variant, the root weight ranged from 6.49 (K2, 2015) to 25.91 Mg ha$^{-1}$ (K2, 2012), and the mean for eight years was 12.71 Mg ha$^{-1}$ (Table 2). The mean weight of sugar beet root was highest for the K variant (14.84 Mg ha$^{-1}$) and lowest for the K2 variant (12.76 Mg ha$^{-1}$). The mean weight of roots for these variants ranged from 6.81 in 2015 to 24.14 Mg ha$^{-1}$ in 2012. (Table 2). The stability of the compared protective treatments was assessed using biplots for the root weight (Figure 1). The effectiveness of the performed insecticidal treatments was influenced by the weather conditions in each
given year of study. There was a positive interaction between the variant without treatment (K) and year 2013 but a negative interaction with 2012 and 2017 (Figure 1). The analysis revealed high adaptability for some treatments; however, most of them had specific adaptability. AMMI stability values (ASVs) differed in terms of stability of root weight between three treatments (variant based on the sums of effective temperatures (F1); the heat sums (F2); pest alerts (S)) (Table 2). Following the work of Purchase et al. [17], a stable protective treatment is characterized by an ASV close to zero. According to this definition, it was demonstrated that treatments S (ASV 2.291) and F1 (ASV 2.800) were most stable, and the K2 variant (15.618) was least stable (Table 2).

Table 2. Mean values of root weight (Mg ha\(^{-1}\)) and standard deviation for the protective treatments and years, principal component analysis values, and AMMI stability value (ASV) of tested treatments.

| Year | Treatment | F1 # | F2 | K | K2 | S | Mean | IPCAg1 | IPCAg2 | IPC Ae1 | IPC Ae2 |
|------|-----------|------|----|---|----|---|------|--------|--------|---------|---------|
| 2011 | 15.10 ± 0.65 | 14.46 ± 0.89 | 15.51 ± 2.46 | 15.01 ± 0.56 | 13.19 ± 1.21 | 14.65 ± 1.57 | -0.444 | -0.407 |
| 2012 | 23.80 ± 5.91 | 24.86 ± 5.12 | 22.77 ± 2.27 | 25.91 ± 5.56 | 23.38 ± 4.25 | 24.14 ± 4.91 | -1.099 | 0.589 |
| 2013 | 15.58 ± 2.72 | 15.32 ± 0.96 | 19.76 ± 3.38 | 14.98 ± 4.68 | 13.49 ± 1.38 | 15.82 ± 3.62 | 0.225 | -1.697 |
| 2014 | 9.93 ± 1.95 | 12.47 ± 2.61 | 12.40 ± 2.20 | 10.13 ± 1.47 | 11.15 ± 2.67 | 11.22 ± 2.52 | 0.053 | 0.247 |
| 2015 | 6.78 ± 1.21 | 6.78 ± 1.74 | 7.43 ± 0.48 | 6.49 ± 0.72 | 6.56 ± 1.38 | 6.81 ± 1.24 | -0.258 | 0.127 |
| 2016 | 16.90 ± 1.50 | 17.60 ± 2.26 | 19.25 ± 2.12 | 6.89 ± 1.23 | 16.27 ± 2.12 | 15.38 ± 4.75 | 2.716 | 0.487 |
| 2017 | 12.34 ± 0.85 | 12.50 ± 0.81 | 12.48 ± 1.52 | 13.74 ± 1.34 | 13.42 ± 0.90 | 12.89 ± 1.26 | -0.744 | 0.545 |
| 2018 | 8.60 ± 1.18 | 8.84 ± 0.24 | 9.14 ± 1.77 | 8.97 ± 3.49 | 8.29 ± 2.37 | 8.77 ± 2.14 | -0.448 | 0.109 |
| Mean | 13.63 ± 5.69 | 14.10 ± 5.70 | 14.84 ± 5.52 | 12.76 ± 6.62 | 13.22 ± 5.34 | 13.71 ± 5.83 | - | - |

**ASV** | 2.800 | 3.379 | 7.665 | 15.618 | 2.291 | - | - |
| IPCAg1 | 0.484 | 0.574 | 1.301 | -2.699 | 0.340 | - | - |
| IPCAg2 | 0.034 | 0.630 | -1.437 | -0.405 | 1.178 | - | - |

\* F1—phenology based on the calculated sums of effective temperatures; F2—phenology based on the calculated sums of heat sums (F2); K—no pest control plot; K2—control plot sprayed with water; S—pest alert/the first adult insects (moths) captured in traps/signs of caterpillar feeding; IPCAg—interactive principal component analysis for genotype; ASV—AMMI stability value.

Figure 1. Biplot for protective treatments by years interaction of root weight in the protective treatments in eight years, showing the effects of the first and second components (IPCA 1 and IPCA 2, respectively). F1—phenology based on the calculated sums of effective temperatures; F2—phenology based on the calculated sums of heat sums (F2); K—no pest control plot; K2—control plot sprayed with water; S—pest alert/the first adult insects (moths) captured in traps/signs of caterpillar feeding; IPCA—interactive principal component analysis.
3.1.2. Polarization

The sum of squares for the main effect in study years accounted for 90.8% of polarization. The differences between the treatments explained 0.7% of the variability in polarization, and the effects of TYI explained 4.7% of it (Table 1). The values of the two principal components were also significant and together explained 93.1% of the total effect on polarization variability. IPCA 1 explained 78.0% of the variability caused by the interaction, and IPCA 2 explained 15.1% of it. Depending on the treatment, the content of sugar in roots ranged from 14.3% (variant F2, 2012) to 18.9% (variant S, 2015), and the mean for eight years was 17.0% (Table 3). The mean polarization was highest for roots from control plots (K2) (17.1%) and lowest for the F2 variant (16.8%). The mean polarization in the study years in relation to all treatment variants ranged from 14.5% in 2012 to 18.7% in 2015. Water spraying (K2) had a positive effect in 2016 but a negative effect in 2012, 2014, and 2017 (Figure 2). There was a positive interaction between treatments based on pest alerts (S) for 2018, and the interaction was positive for the experiments without insecticide treatment in 2012 and 2017. Treatments F1 (ASV 0.569) and K (ASV 0.880) were most stable, while K2 (5.647) was least stable (Table 3). Highly significant reductions in sugar percentage were recorded in the infested roots compared to uninfested ones. This means that the pest infestations reduced the sugar content percentage in the post-harvest of sugar beet roots. Rosenkranz et.al. [26] showed that the wounding of sugar beet roots induces invertase activity, which contributes to post-harvest sucrose losses.

Table 3. Mean values of polarization (%) and standard deviation for the protective treatments and years, principal component analysis values, and AMMI stability value (ASV) of tested treatments.

| Year | Treatment | Mean | IPCA1 | IPCA2 |
|------|-----------|------|-------|-------|
|      | F1 * | F2  | K    | K2   | S    | IPCA1 | IPCA2 |
| 2011 | 18.0 ± 0.4 | 17.9 ± 0.6 | 18.0 ± 0.2 | 18.1 ± 0.3 | 18.2 ± 0.3 | 18.1 ± 0.4 | 0.064 | -0.036 |
| 2012 | 14.4 ± 0.4 | 14.3 ± 0.5 | 14.9 ± 0.1 | 14.5 ± 0.6 | 14.5 ± 0.4 | 14.5 ± 0.5 | 0.119 | 0.244 |
| 2013 | 16.4 ± 0.9 | 16.0 ± 0.8 | 16.1 ± 0.6 | 16.4 ± 0.7 | 16.3 ± 0.7 | 16.2 ± 0.8 | -0.052 | 0.204 |
| 2014 | 16.4 ± 0.1 | 16.3 ± 0.4 | 16.2 ± 0.1 | 16.3 ± 0.7 | 16.2 ± 0.8 | 16.3 ± 0.5 | 0.052 | 0.312 |
| 2015 | 18.5 ± 0.8 | 18.4 ± 0.2 | 18.6 ± 0.3 | 18.8 ± 0.3 | 18.9 ± 0.5 | 18.7 ± 0.5 | -0.014 | -0.187 |
| 2016 | 17.3 ± 0.2 | 16.9 ± 0.6 | 17.3 ± 0.3 | 18.9 ± 0.6 | 17.3 ± 0.1 | 17.5 ± 0.8 | -1.038 | -0.506 |
| 2017 | 17.0 ± 0.5 | 16.8 ± 0.4 | 16.7 ± 0.7 | 16.7 ± 0.2 | 16.8 ± 0.2 | 16.8 ± 0.4 | 0.142 | 0.316 |
| 2018 | 17.4 ± 0.4 | 17.9 ± 0.7 | 17.7 ± 0.2 | 17.2 ± 0.3 | 18.5 ± 0.8 | 17.7 ± 0.7 | 0.726 | -0.547 |
| Mean | 16.9 ± 1.3 | 16.8 ± 1.4 | 16.9 ± 1.2 | 17.1 ± 1.5 | 17.1 ± 1.5 | 17.0 ± 1.4 | - | - |

* F1—phenology based on the calculated sums of effective temperatures; F2—phenology based on the calculated sums of heat sums (F2); K—no pest control plot; K2—control plot sprayed with water; S—pest alert/the first adult insects (moths) captured in traps/ signs of caterpillar feeding; IPCAe—interactive principal component analysis for environment; IPCAg—interactive principal component analysis for genotype; ASV—AMMI stability value.
Table 3. Mean values of polarization (%) and standard deviation for the protective treatments and years, principal component analysis values, and AMMI stability value (ASV) of tested treatments.

| Year | Treatment | Mean IP | IPCA<sub>e1</sub> | IPCA<sub>e2</sub> |
|------|-----------|---------|-------------------|-------------------|
| 2011 |           | 18.0 ± 0.4 | 17.9 ± 0.6 | 18.0 ± 0.2 | 18.1 ± 0.3 | 18.2 ± 0.3 | 0.064 |
| 2012 |           | 14.4 ± 0.4 | 14.3 ± 0.5 | 14.9 ± 0.1 | 14.5 ± 0.6 | 14.5 ± 0.4 | 0.119 | 0.244 |
| 2013 |           | 16.4 ± 0.9 | 16.0 ± 0.8 | 16.1 ± 0.6 | 16.4 ± 0.7 | 16.3 ± 0.7 | -0.052 | 0.204 |
| 2014 |           | 16.4 ± 0.1 | 16.3 ± 0.4 | 16.2 ± 0.1 | 16.3 ± 0.7 | 16.2 ± 0.8 | 0.052 | 0.312 |
| 2015 |           | 18.5 ± 0.8 | 18.4 ± 0.2 | 18.6 ± 0.3 | 18.8 ± 0.3 | 18.9 ± 0.5 | -0.014 | -0.187 |
| 2016 |           | 17.3 ± 0.2 | 16.9 ± 0.6 | 17.3 ± 0.3 | 18.9 ± 0.6 | 17.3 ± 0.1 | 17.5 ± 0.8 | -1.038 | -0.306 |
| 2017 |           | 17.0 ± 0.5 | 16.8 ± 0.4 | 16.7 ± 0.7 | 16.7 ± 0.2 | 16.8 ± 0.2 | 16.8 ± 0.4 | 0.142 | 0.316 |
| 2018 |           | 17.4 ± 0.4 | 17.9 ± 0.7 | 17.7 ± 0.2 | 17.2 ± 0.3 | 18.5 ± 0.8 | 17.7 ± 0.7 | 0.726 | -0.547 |
| Mean |           | 16.9 ± 1.3 | 16.8 ± 1.4 | 16.9 ± 1.2 | 17.1 ± 1.5 | 17.1 ± 1.5 | 17.0 ± 1.4 | - - |
| ASV  |           |          |                   |                   |                   |                   |                   | 0.569 | 2.169 |
| IPCA<sub>g1</sub> |   | 0.022 | 0.422 | 0.167 | -1.098 | 0.486 | - - |
| IPCA<sub>g2</sub> |   | 0.557 | 0.037 | 0.191 | -0.203 | -0.581 | - - |

# F1—phenology based on the calculated sums of effective temperatures; F2—phenology based on the calculated sums of heat sums (F2); K—no pest control plot; K2—control plot sprayed with water; S—pest alert/the first adult insects (moths) captured in traps/ signs of caterpillar feeding; IPCA—interactive principal component analysis.

Figure 2. Biplot for protective treatments by years interaction of polarization in the protective treatments in eight years, showing the effects of the first and second components (IPCA 1 and IPCA 2, respectively). F1—phenology based on the calculated sums of effective temperatures; F2—phenology based on the calculated sums of heat sums (F2); K—no pest control plot; K2—control plot sprayed with water; S—pest alert/the first adult insects (moths) captured in traps/ signs of caterpillar feeding; IPCA—interactive principal component analysis.

3.1.3. Potassium (K) Molasses

The sum of squares for the main effect of the year explained 86.1% of the total variability in K molasses, and the TYI effects explained 2.1% of it (Table 1). The values of the first and second principal components were also significant and together explained 83.1% of the total effect on the variability in K molasses. Principal component 1 (IPCA 1) explained 57.9% of the variability caused by the interaction, and IPCA 2 explained 25.3% of it. Depending on the variant of insecticidal treatment, the amount of extracted K molasses ranged from 29.23 (2016) to 60.60 mmol kg<sup>-1</sup> (2013), and the mean for eight years was 42.37 mmol kg<sup>-1</sup> (Table 4). The analysis demonstrated that the highest mean concentration of K molasses for sugar beets was in the K2 plots (42.9 mmol kg<sup>-1</sup>) and the lowest was in the F1 plots (41.82 mmol kg<sup>-1</sup>). The stability of the compared protective treatments was assessed based on biplots for K molasses (Figure 3). The variant without treatment (K) had a positive effect in years 2011, 2013, and 2014 but a negative effect in 2016 and 2017 (Figure 3). The treatment applied based on the heat sums (F2) had a positive interaction with 2012 but a negative interaction with 2015 and 2018. Treatment applied based on pest alerts (S) had a positive interaction with 2015 and 2018 but a negative interaction with 2012 (Figure 3). Protective treatments according to variants S and F1, with ASVs of 1.059 and 1.144, respectively, were the most stable, while the control variant (K) (ASV 4.644) was the least stable when considering K molasses (Table 4).
Table 4. Mean values of potassium molasses (mmol kg\(^{-1}\)) and standard deviation for the protective treatments and years, principal component analysis values, and AMMI stability value (ASV) of tested treatments.

| Year | Treatment | Mean | IPCAe1 | IPCAe2 |
|------|-----------|------|--------|--------|
| 2011 | F1 #      | 41.88 ± 1.49 | 43.62 ± 2.75 | 40.60 ± 0.60 | 41.90 ± 2.99 | 42.01 ± 2.33 | −0.769 | 0.231 |
| 2012 | F2        | 59.70 ± 5.91 | 53.65 ± 4.62 | 56.75 ± 4.95 | 54.50 ± 5.42 | 56.20 ± 5.23 | 0.608 | −1.850 |
| 2013 | K         | 55.95 ± 3.50 | 59.42 ± 5.60 | 60.60 ± 6.24 | 57.38 ± 6.62 | 58.58 ± 8.14 | 58.38 ± 6.41 | −1.063 | 0.216 |
| 2014 | K2        | 36.83 ± 2.86 | 39.60 ± 3.04 | 41.23 ± 1.60 | 37.40 ± 1.37 | 36.00 ± 1.96 | 38.21 ± 2.97 | −1.304 | −0.238 |
| 2015 | S         | 34.95 ± 1.34 | 35.90 ± 2.23 | 36.98 ± 2.22 | 38.00 ± 2.37 | 36.05 ± 0.55 | 36.38 ± 2.14 | 0.117 | 0.647 |
| 2016 | 30.73 ± 1.15 | 30.60 ± 1.00 | 29.23 ± 4.22 | 35.80 ± 0.67 | 32.07 ± 2.47 | 31.69 ± 3.22 | 1.648 | 0.730 |
| 2017 | 33.38 ± 5.11 | 32.55 ± 2.10 | 31.05 ± 2.55 | 33.58 ± 1.89 | 32.58 ± 2.17 | 32.62 ± 3.14 | 0.723 | −0.099 |
| 2018 | 44.29 ± 2.70 | 42.59 ± 1.56 | 43.81 ± 3.49 | 43.70 ± 2.42 | 43.00 ± 2.53 | 43.48 ± 2.68 | 0.040 | 0.362 |

ASV = AMMI stability value. IPCAe = interactive principal component analysis. IPCAg = interactive principal component analysis for genotype.

Figure 3. Biplot for protective treatments by years interaction of potassium molasses in the protective treatments in eight years, showing the effects of the first and second components (IPCA 1 and IPCA 2, respectively). F1—phenology based on the calculated sums of effective temperatures; F2—phenology based on the calculated sums of heat sums (F2); K—no pest control plot; K2—control sprayed with water; S—pest alert/the first adult insects (moths) captured in traps/ signs of caterpillar feeding; IPCAe—interactive principal component analysis for environment; IPCAg—interactive principal component analysis for genotype; ASV—AMMI stability value.

3.1.4. Sodium (Na) Molasses

The sum of squares for the main effect of the year explained 80.1% of the total variation in Na molasses, and the effects of TYI explained 5.8% of it (Table 1). The value of the first principal component was considerable and explained 78.5% of the total effect it had on...
the variability in Na molasses. Depending on the protective variant, the concentration of Na molasses in sugar beet ranged from 1.25 (variant S, 2015) to 5.5 mmol kg$^{-1}$ (F1, 2018), and the mean concentration of Na molasses for eight years was 2.655 mmol kg$^{-1}$ (Table 5). The mean concentration of Na molasses was highest for the sugar beets harvested from plot F2 (2.825 mmol kg$^{-1}$) and lowest for those harvested from plot K2 (2.531 mmol kg$^{-1}$). The stability of the compared protective treatments for Na molasses was estimated using biplots (Figure 4). There was a positive effect of variants S, F1, and K2 in 2013, 2017, and 2018 but a negative effect in 2016 (Figure 4). Variant K had a positive effect in 2011 and 2014 but a negative effect in 2012. Variant F2 had a positive effect in 2016 but a negative effect in 2013 and 2018. Treatments applied based on F1 and S, with ASVs of 0.869 and 0.874, respectively, were the most stable, while the treatment based on F2 (6.725) was the least stable (Table 5).

Table 5. Mean values of sodium molasses (mmol kg$^{-1}$) and standard deviation for the protective treatments and years, principal component analysis values, and AMMI stability value (ASV) of tested treatments.

| Year | Treatment | F1 | F2 | Mean | IPCAe1 | IPCAe2 |
|------|-----------|----|----|------|--------|--------|
| 2011 | 2.05 ± 0.52 | 2.00 ± 0.52 | 2.63 ± 0.98 | 1.68 ± 0.30 | 1.75 ± 0.26 | 2.06 ± 0.65 | 0.174 | -0.651 |
| 2012 | 4.03 ± 0.35 | 4.15 ± 0.96 | 3.80 ± 0.52 | 3.60 ± 0.22 | 4.10 ± 0.66 | 3.94 ± 0.64 | -0.097 | 0.237 |
| 2013 | 1.30 ± 0.32 | 1.30 ± 0.16 | 1.40 ± 0.19 | 1.85 ± 0.62 | 1.75 ± 0.15 | 1.52 ± 0.41 | 0.379 | 0.404 |
| 2014 | 2.30 ± 0.19 | 2.80 ± 0.21 | 2.98 ± 0.62 | 2.48 ± 0.25 | 2.58 ± 0.15 | 2.63 ± 0.41 | 0.005 | -0.321 |
| 2015 | 1.28 ± 0.24 | 1.35 ± 0.23 | 1.43 ± 0.08 | 1.35 ± 0.23 | 1.25 ± 0.15 | 1.33 ± 0.21 | 0.145 | -0.030 |
| 2016 | 2.23 ± 0.25 | 4.10 ± 1.82 | 2.17 ± 0.23 | 1.63 ± 0.63 | 2.30 ± 0.12 | 2.49 ± 1.21 | -1.218 | 0.082 |
| 2017 | 2.00 ± 0.37 | 1.95 ± 0.22 | 1.93 ± 0.26 | 2.13 ± 0.20 | 1.85 ± 0.15 | 1.97 ± 0.27 | 0.201 | 0.124 |
| 2018 | 5.50 ± 0.49 | 4.95 ± 0.51 | 5.34 ± 0.48 | 5.35 ± 0.39 | 5.43 ± 0.80 | 5.31 ± 0.62 | 0.411 | 0.155 |
| Mean | 2.59 ± 1.41 | 2.83 ± 1.53 | 2.71 ± 1.34 | 2.53 ± 1.31 | 2.63 ± 1.39 | 2.66 ± 1.40 | - | - |
| ASV | 0.869 | 6.725 | 1.599 | 3.69 | 0.874 | - | - |
| IPCAg1 | 0.151 | -1.176 | 0.247 | 0.644 | 0.133 | - | - |
| IPCAg2 | 0.072 | 0.023 | -0.745 | 0.222 | 0.428 | - | - |

F1—phenology based on the calculated sums of effective temperatures; F2—phenology based on the calculated sums of heat sums (F2); K—no pest control plot; K2—control plot sprayed with water; S—pest alert/the first adult insects (moths) captured in traps/ signs of caterpillar feeding; IPCAg—interactive principal component analysis for genotype; IPCAe—interactive principal component analysis for environment; IPCAg1—interactive principal component analysis for genotype and environment; IPCAg2—interactive principal component analysis for genotype and environment; ASV—AMMI stability value.

3.1.5. α-Amino-Nitrogen Molasses (N-Amino)

In ANOVA, the sum of squares for the years of main effect was 64.2% of the total N-amino molasses, and this factor had the strongest influence on α-amino-N. The effects of TYI explained 7.4% of the variability (Table 1). The values of the first and second principal components of TYI were also statistically significant and together accounted for 83.4% of the total effect on the variability of N-amino molasses. Principal component 1 (IPCA 1) explained 58.2% of the variability caused by the interaction, and IPCA2 explained 25.2% of it (Figure 5). Depending on the tested variants of protective treatments, the content of α-amino-N in sugar beet roots ranged from 6.32 (variant F1, 2011) to 34.25 mmol kg$^{-1}$ (Table 6). The mean content of N-amino molasses in the study years ranged from 6.97 mmol kg$^{-1}$ in 2011 to 29.35 mmol kg$^{-1}$ in 2015. The mean content of α-amino-N was highest in roots harvested from the F2 plots (20.54 mmol kg$^{-1}$) and lowest in roots collected from the F1 plots (18.58 mmol kg$^{-1}$). The stability of the tested treatments was estimated based on biplots for α-amino-N (Figure 5). Protective treatments applied based on the phenological criterion (F2) and control treatments with water had a positive effect in 2016 but a negative effect in 2018 (Figure 5). The control variant (K) had a positive effect in 2014 and 2015 but a negative effect in 2012, 2013, and 2017. The protective treatment based on pest alert (S) was...
the most stable (ASV 1.745), and the variant without insecticidal treatment was the least stable (ASV 5.598) (Table 6).

Figure 4. Biplot for protective treatments by years interaction of sodium molasses in the protective treatments in eight years, showing the effects of the first and second components (IPCA 1 and IPCA 2, respectively). F1—phenology based on the calculated sums of effective temperatures; F2—phenology based on the calculated sums of heat sums (F2); K—no pest control plot; K2—control plot sprayed with water; S—pest alert/the first adult insects (moths) captured in traps/signs of caterpillar feeding; IPCAe—interactive principal component analysis for environment; IPCAg—interactive principal component analysis for genotype; ASV—AMMI stability value.

Figure 5. Biplot for protective treatments by years interaction of α-amino-nitrogen in the protective treatments in eight years, showing the effects of the first and second components (IPCA 1 and IPCA 2, respectively). F1—phenology based on the calculated sums of effective temperatures; F2—phenology based on the calculated sums of heat sums (F2); K—no pest control plot; K2—control plot sprayed with water; S—pest alert/the first adult insects (moths) captured in traps/signs of caterpillar feeding; IPCA—interactive principal component analysis.
Table 6. Mean values of α-amino-nitrogen (mmol kg$^{-1}$) and standard deviation for the protective treatments and years, principal component analysis values, and AMMI stability value (ASV) of tested treatments.

| Year | Treatment | Mean | IPCAe1 | IPCAe2 |
|------|-----------|------|--------|--------|
| F1  | F2         | K    | K2     | S      |
| 2011| 6.32 ± 1.29 | 4.64 ± 1.67 | 7.88 ± 1.97 | 6.98 ± 1.23 | 7.25 ± 1.71 | 6.97 ± 1.70 | 0.502 | 0.210 |
| 2012| 24.82 ± 5.48 | 25.45 ± 6.31 | 23.88 ± 6.04 | 23.71 ± 4.96 | 21.71 ± 3.68 | 23.91 ± 5.52 | −0.052 | 0.409 |
| 2013| 19.66 ± 8.57 | 20.18 ± 4.95 | 17.44 ± 5.82 | 17.84 ± 5.62 | 17.10 ± 5.65 | 18.45 ± 6.37 | −0.162 | 0.793 |
| 2014| 11.43 ± 3.23 | 18.72 ± 4.47 | 19.71 ± 3.51 | 14.20 ± 3.78 | 14.94 ± 5.10 | 15.80 ± 5.08 | 0.865 | −1.524 |
| 2015| 27.00 ± 9.61 | 27.25 ± 2.68 | 34.25 ± 7.93 | 30.35 ± 6.67 | 27.88 ± 3.37 | 29.35 ± 7.15 | 1.260 | −1.154 |
| 2016| 17.77 ± 2.22 | 25.90 ± 8.56 | 15.13 ± 1.10 | 27.38 ± 5.23 | 17.90 ± 0.68 | 20.81 ± 6.73 | −2.866 | −0.804 |
| 2017| 15.27 ± 3.00 | 13.78 ± 1.69 | 12.80 ± 1.67 | 14.18 ± 1.16 | 13.20 ± 1.56 | 13.84 ± 2.10 | −0.052 | 0.954 |
| 2018| 26.34 ± 0.85 | 26.55 ± 1.27 | 25.50 ± 2.25 | 24.35 ± 1.48 | 28.80 ± 1.82 | 26.31 ± 2.18 | 0.505 | 1.115 |

Mean 18.58 ± 8.71 | 20.54 ± 8.23 | 19.57 ± 8.91 | 19.87 ± 8.54 | 18.60 ± 7.63 | 19.43 ± 8.47 | - | - |

ASV 1.996 3.212 5.598 4.223 1.745 - - -

IPCAg1 0.123 −1.369 2.355 −1.787 0.678 - - -

IPCAg2 1.976 −0.551 −1.313 −0.880 0.768 - - -

* F1—phenology based on the calculated sums of effective temperatures; F2—phenology based on the calculated sums of heat sums (F2); K—no pest control plot; K2—control plot sprayed with water; S—pest alert/the first adult insects (moths) captured in traps/signs of caterpillar feeding; IPCAe—interactive principal component analysis for environment; IPCAg—interactive principal component analysis for genotype; ASV—AMMI stability value.

3.1.6. Technological Yield—White Sugar Yield

Three variables (treatment based on the phenological criterion (F1 and F2) and pest alert (S)) had a statistically significant effect on white sugar yield from sugar beet. The sum of the squares for this effect in study years explained 65.9% of the total variability in the white sugar yield, the differences between the protective treatments explained 2.0% of it, and the TYI effects explained 10.5% of it (Table 1). The values of the first and second principal components were also significant, and together they accounted for 96.6% of the total effect on the variability in white sugar yield. Principal component 1 (IPCA 1) explained 83.0% of the variability attributable to interaction, and IPCA 2 explained 13.0% of it. The mean white sugar yield differed by study year and ranged from 114.4 t ha$^{-1}$ in 2015 to 335.5 t ha$^{-1}$ in 2012, and the mean yield was 216.06 t ha$^{-1}$ (Table 7). The highest mean white sugar yields were found for the K control plots (235.5 t ha$^{-1}$), and the lowest were found for the K2 control sprayed with water (200.2 t ha$^{-1}$). The stability of the tested protective treatments was estimated based on biplots for white sugar yield (Figure 6). The variant without treatment (K) had a positive effect in 2013 but a negative effect in 2012, 2014, 2015, 2017, and 2018 (Figure 6). Stability was the highest (ASV 10.59) for treatment applied based on pest alerts (S) and lowest (ASV 66.46) for variant K2 (Table 7).
Table 7. Mean values of technological yield (t ha⁻¹) and standard deviation for the protective treatments and years, principal component analysis values, and AMMI stability value (ASV) of tested treatments.

| Year | Treatment | F1 # | F2 | K | K2 | S | Mean | IPCAg1 | IPCAg2 |
|------|-----------|------|----|---|----|---|------|--------|--------|
| 2011 | 263.9 ± 15| 251.0 ± 16| 270.7 ± 47| 264.1 ± 10| 232.6 ± 22| 256.5 ± 29| 2.001| -1.915|
| 2012 | 328.5 ± 84| 341.3 ± 77| 324.8 ± 31| 357.6 ± 69| 325.2 ± 58| 335.5 ± 68| 3.751| 1.555|
| 2013 | 244.3 ± 56| 232.1 ± 14| 304.2 ± 48| 234.0 ± 79| 207.4 ± 30| 244.4 ± 60| -0.437| -6.653|
| 2014 | 154.4 ± 33| 191.4 ± 38| 189.7 ± 35| 156.4 ± 29| 169.7 ± 37| 172.3 ± 38| 0.057| 1.255|
| 2015 | 114.2 ± 28| 112.5 ± 32| 124.2 ± 10| 109.1 ± 15| 111.9 ± 27| 114.4 ± 24| 1.084| 0.712|
| 2016 | 282.0 ± 22| 285.0 ± 27| 322.9 ± 32| 117.4 ± 21| 272.6 ± 39| 256.0 ± 77| -11.105| 1.388|
| 2017 | 200.2 ± 11| 200.8 ± 13| 199.7 ± 21| 221.0 ± 23| 217.4 ± 12| 207.8 ± 19| 3.024| 2.658|
| 2018 | 136.0 ± 21| 144.8 ± 7 | 148.1 ± 30| 142.2 ± 62| 137.9 ± 38| 141.8 ± 37| 1.626| 1.000|
| Mean | 215.4 ± 82| 219.9 ± 78| 235.5 ± 82| 200.2 ± 92| 209.3 ± 74| 216.1 ± 83| - | - |
| ASV  | 13.24 | 13.04 | 31.55 | 66.46 | 10.59 | - | - | - |
| IPCAg1 | -2.157 | -2.091 | -5.073 | 10.840 | -1.518 | - | - | - |
| IPCAg2 | 0.594 | -3.474 | -5.066 | -4.646 | 5.050 | - | - | - |

*F1—phenology based on the calculated sums of effective temperatures; F2—phenology based on the calculated sums of heat sums (F2); K—no pest control plot; K2—control plot sprayed with water; S—pest alert/the first adult insects (moths) captured in traps/signs of caterpillar feeding; IPCAg1—interactive principal component analysis for genotype; IPCAg2—interactive principal component analysis for environment; IPCAg1—interactive principal component analysis for genotype; IPCAg2—interactive principal component analysis for environment; IPCAg1—interactive principal component analysis for genotype; IPCAg2—interactive principal component analysis for environment; IPCAg1—interactive principal component analysis for genotype; IPCAg2—interactive principal component analysis for environment; IPCAg1—interactive principal component analysis for genotype; IPCAg2—interactive principal component analysis for environment; IPCAg1—interactive principal component analysis for genotype; IPCAg2—interactive principal component analysis for environment.*

Figure 6. Biplot for protective treatments by years interaction of technological yield in the protective treatments in eight years, showing the effects of the first and second components (IPCA 1 and IPCA 2, respectively). F1—phenology based on the calculated sums of effective temperatures; F2—phenology based on the calculated sums of heat sums (F2); K—no pest control plot; K2—control plot sprayed with water; S—pest alert/the first adult insects (moths) captured in traps/signs of caterpillar feeding; IPCAg1—interactive principal component analysis for environment; IPCAg2—interactive principal component analysis for genotype; ASV—AMMI stability value.

4. Discussion

The AMMI model for the estimation of genotype–environment interaction is frequently used in studies investigating traits of many plant species [27–33]. AMMI is an effective
tool for detecting patterns of interactions between variables and improving the accuracy of estimated results from field trials. In this model, genotypes can be grouped based on the similarity of traits in response to the identifiable potential trends in environments [34]. The use of AMMI for the analysis of our findings provided more information on the interaction (TYI) between the applied variants of protective treatments against soil pests in individual years of study and the obtained components of the white sugar yield over 8 years of the trial. Many authors have demonstrated that the AMMI analysis can be used to identify specific treatments with the highest yields in different years [33,35].

The relationship between the effect of quantitative characteristics and the technological yield of sugar has been studied by many authors [4,5,36–39]. After sugar beet plants are harvested, they undergo several operations that, if not properly done, reduce sucrose content during root extraction. Reymond et al. [40] indicated that during the life span of higher plants, wounding is a common event. An open wound surface causes uncontrolled water loss and offers an entry point for pathogens. White sugar yield from sugar beet increases with the length of the growing season, i.e., the number of days between sowing and harvest. Our results indicate that the beet varieties, study years, and weather conditions in these years during the sugar beet growing season had significant impact on the obtained root yield, sugar content, and formation of assimilates in the process of plant growth and development. Hoffmann and Kluge-Severin [35] and Draycott [41] reported a close correlation between the growth rate, biomass production, and air temperature. In addition, a close correlation was observed between the quantity of intercepted solar radiation, and favorable humidity. For this reason, each agrotechnical factor limiting the growth of foliage biomass has a negative impact on the final root yield and white sugar yield. It is likely that the combination of various environmental factors interacting with the genotype influences the distribution of assimilates in the whole plant [42]. Moreover, one of the factors limiting the high technological yield of sugar beets, and hence the high level sugar content, is damage caused by herbivorous pests. Rosenkranz et al. [26] showed that the wounding of sugar beet roots induced invertase activity, which contributes to post-harvest sucrose losses.

In dry years when water availability is limited, the growth of foliage is inhibited, the assimilators migrate to the storage root, and molasses is accumulated. White sugar yield largely depends on these compounds. We analysed relationships between selected traits of sugar beet roots and white sugar yields for the tested sugar beet. The effect of these root traits on sugar beet yield was separately analysed over the study years. Analyses indicated a statistically significant and directly proportional effect of root weight on the white sugar yield from sugar beet for all eight years of research. Similar conclusions were reached by Musolf et al. [43], their analysis of patterns revealed that the sugar yield was mainly determined by root yield and less by polarization. Therefore, the role of molassigenic substances is less important. This leads to the logical conclusion that the differences in the sugar yield were primarily determined by the differences in the root yield. It was indicated that polarization did not determine the sugar beet yield only in 2016. The white sugar yield from sugar beet was significantly related to the Na content only in 2017. The content of N-amino determined the sugar beet yield in 2011, 2012, and 2015, and all these relationships were inversely proportional. There was an inversely proportional effect of K content on the beet yield for the control fields (K) and for the variant of treatment applied according to heat sums (F2). The results of our eight year study were characterized by greater yield variability between the years of research, depending on the analysed factors. Similar conclusion were reached by Lafta and Fugate [44], who indicated that temperature, root health during harvesting, respiration, excessive microbial growth, moisture loss, damage during harvest and transport, and the amount of mud, weeds, and debris going into piles affect the sugar content in sugar beet roots. The activation of primed resistance by chemical treatments may therefore provide a simple way of providing crop plants with long-term improvements in stress resistance with minimal impacts on productivity [8].
Reducing the harmfulness of pests and pathogens by synthetic pesticides in crop plants is becoming increasingly less desirable, so the use of more environmentally friendly approaches are required for a more sustainable future. Another problem is the withdrawal of insecticides from the market and the phenomenon of pest resistance to insecticides. This is why the search for alternative substances (including secondary plant metabolites), often of plant origin, is very important in reducing pest damage. For instance, Maurya et al. [45] indicated that indole (plant-derived volatiles) can effectively help control herbivorous pests. In turn, Lima et al. [46] showed that Neotropical Solanaceae species are potential sources of compounds with insecticidal and growth inhibition activity against *Spodoptera frugiperda*. Kovalikova et al. [47] emphasized the importance of phenols in plant protection against insect pests. The use of elicitors of plant defenses, or ‘plant activators’ as they have been termed, has been proposed as an alternative approach to crop protection [48–50]. However, commercial success in this area is currently limited.

It should be emphasized that it is very important to determine the optimal date of a plant protection product’s application regardless of its type because conducting insecticide treatment at an appropriate date will ensure effective plant protection (reduce the number of insect pest and obtain a better yield in terms of quality and quantity) and reduce the amount of used plant protection product. Therefore, it is important to consider several factors to accurately determine the application date of plant protection treatment.

5. Conclusions

1. The AMMI model can be a useful tool for detecting these interactions (TYI) and improving estimation accuracy. In the AMMI model, the obtained qualitative and quantitative parameters of yield can be grouped based on the similarity of the analysed trait and the identification of potential trends observed in the study years.

2. The results of the analysis of variance of our study indicated that significant treatment × year interaction for all considered physiological traits in the experiment were occurred.

3. Findings from this study indicate that environmental conditions, e.g., soil fertility, crop variety, and abiotic factors (such as temperature and rainfall), are very important parameters with a wide range of variability between the applied treatment variants, years, and their interactions. These significant interactions (TYI) suggest that it is possible to select stable variants of treatments over time.

4. AMMI analysis used to estimate the interaction of treatments based on environmental conditions showed the additive effect of the applied treatments on the quality parameters of white sugar yield from sugar beet. These effects were demonstrated for polarization and the content of Na in molassigenic substances.

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Abbreviations
AMMI—Additive Main Effect and Multiplicative Interaction model; TYI—effects of treatments (T) and years (Y), as well as multiplicative interaction effects (I); IPCAe—interactive principal component analysis for environment; IPCAg—interactive principal component analysis for genotype.

References
1. Artyszak, A.; Podlaska, J.; Madry, W. Analiza współczynników ścieżek technologicznego plonu cukru buraka cukrowego i cech źnania ujawniających się w trakcie ontogenizy. Roz. Nauk. Rol. Ser. A 1999, 114, 41–54.
2. Hoffmann, C.M.; Huijbregts, T.; Van Swaaij, N.; Jansen, R. Impact of different environments in Europe on yield and quality of sugar beet genotypes. Eur. J. Agron. 2009, 30, 17–26. [CrossRef]
3. Hoffmann, C.M.; Kenter, C. Yield potential of sugar beet—Have we hit the ceiling? Front. Plant Sci. 2018, 9, 289. [CrossRef] [PubMed]
4. Řezbová, H.; Belová, A.; Škubna, O. Sugar beet production in the European Union and their future trends. Agris Line Pap. Econ. Inform. 2015, 3, 165–178.
5. Jakubowska, M.; Cyplik, A.; Bocianowski, J.; Wielkopolsan, B. Wpływ wybranych cech chemicznych na wartość technologiczną plonu buraka cukrowego po zastosowaniu zabiegów na szkodniki glebowe [Effect of selected chemical features on the technological value of sugar beet yield after application of treatments on soil pests]. Prog. Plant Prot. 2020, 60, 275–282. [CrossRef]
6. Scott, R.K.; English, S.D.; Wood, D.W.; Unsworth, M.H. The yield of sugar beet in relation to weather and length of growing season. J. Agric. Sci. 1973, 81, 339–347. [CrossRef]
7. Klotz, K.L.; Finger, F.L. Impact of temperature, length of storage and postharvest disease on sucrose catabolism in sugar beet. Postharvest Biol. Technol. 2004, 34, 1–9. [CrossRef]
8. Worrall, D.; Holfroyd, G.H.; Moore, J.P.; Glowacz, M.; Croft, P.; Taylor, J.E.; Paul, N.D.; Roberts, M.R. Treating seeds with activators with the induction of a vascular invertase isoform. J. Exp. Bot. 2001, 52, 283–290. [CrossRef]

Abbreviations
AMMI—Additive Main Effect and Multiplicative Interaction model; TYI—effects of treatments (T) and years (Y), as well as multiplicative interaction effects (I); IPCAe—interactive principal component analysis for environment; IPCAg—interactive principal component analysis for genotype.

References
1. Artyszak, A.; Podlaska, J.; Madry, W. Analiza współczynników ścieżek technologicznego plonu cukru buraka cukrowego i cech źnania ujawniających się w trakcie ontogenizy. Roz. Nauk. Rol. Ser. A 1999, 114, 41–54.
2. Hoffmann, C.M.; Huijbregts, T.; Van Swaaij, N.; Jansen, R. Impact of different environments in Europe on yield and quality of sugar beet genotypes. Eur. J. Agron. 2009, 30, 17–26. [CrossRef]
3. Hoffmann, C.M.; Kenter, C. Yield potential of sugar beet—Have we hit the ceiling? Front. Plant Sci. 2018, 9, 289. [CrossRef] [PubMed]
4. Řezbová, H.; Belová, A.; Škubna, O. Sugar beet production in the European Union and their future trends. Agris Line Pap. Econ. Inform. 2015, 3, 165–178.
5. Jakubowska, M.; Cyplik, A.; Bocianowski, J.; Wielkopolsan, B. Wpływ wybranych cech chemicznych na wartość technologiczną plonu buraka cukrowego po zastosowaniu zabiegów na szkodniki glebowe [Effect of selected chemical features on the technological value of sugar beet yield after application of treatments on soil pests]. Prog. Plant Prot. 2020, 60, 275–282. [CrossRef]
6. Scott, R.K.; English, S.D.; Wood, D.W.; Unsworth, M.H. The yield of sugar beet in relation to weather and length of growing season. J. Agric. Sci. 1973, 81, 339–347. [CrossRef]
7. Klotz, K.L.; Finger, F.L. Impact of temperature, length of storage and postharvest disease on sucrose catabolism in sugar beet. Postharvest Biol. Technol. 2004, 34, 1–9. [CrossRef]
8. Worrall, D.; Holfroyd, G.H.; Moore, J.P.; Glowacz, M.; Croft, P.; Taylor, J.E.; Paul, N.D.; Roberts, M.R. Treating seeds with activators with the induction of a vascular invertase isoform. J. Exp. Bot. 2001, 52, 283–290. [CrossRef]
27. Fotso, A.K.; Hanna, R.; Kulakow, P.; Parkes, E.; Iluebbey, P.; Ngome, F.A.; Suh, C.; Massussi, J.; Choutnji, I.; Wirnkar, V.L. AMMI analysis of cassava response to contrasting environments: Case study of genotype by environment effect on pests and diseases, root yield, and carotenoids content in Cameroon. *Euphytica* 2018, 214, 155. [CrossRef]

28. Hassani, M.; Heidari, B.; Dadkhodaie, A.; Stevanato, P. Genotype by environment interaction components underlying variations in root, sugar and white sugar yield in sugar beet (*Beta vulgaris* L.). *Euphytica* 2018, 214, 79. [CrossRef]

29. Bocianowski, J.; Książe, J.; Nowosad, K. Genotype by environment interaction for seeds yield in pea (*Pisum sativum* L.) using additive main effects and multiplicative interaction model. *Euphytica* 2019, 215, 191. [CrossRef]

30. Bocianowski, J.; Niemann, J.; Nowosad, K. Genotype-by-environment interaction for seed quality traits in interspecific cross-derived Brassica lines using additive main effects and multiplicative interaction model. *Euphytica* 2019, 215, 7. [CrossRef]

31. Bocianowski, J.; Nowosad, K.; Szulc, P. Soil tillage methods by years interaction for harvest index of maize (*Zea mays* L.) using additive main effects and multiplicative interaction model. *Acta Agric. Scand. B Soil Plant Sci.* 2019, 69, 75–81. [CrossRef]

32. Bocianowski, J.; Tratwal, A.; Nowosad, K. Genotype by environment interaction for main winter triticale varieties characteristics at two levels of technology using additive main effects and multiplicative interaction model. *Euphytica* 2021, 217, 26. [CrossRef]

33. Bocianowski, J.; Szulc, P.; Nowosad, K. Soil tillage methods by years interaction for dry matter of plant yield of maize (*Zea mays* L.) using additive main effects and multiplicative interaction model. *J. Integr. Agric.* 2018, 17, 2836–2839. [CrossRef]

34. Podlaski, S.; Choluj, D.; Wiśniewska, A. Kształtowanie się plonu buraka cukrowego w zależności od wybranych czynników środowiskowych. *Adv. Agric. Sci. Probl.* 2017, 590, 59–71. [CrossRef]

35. Hoffmann, C.M.; Kluge-Severin, S. Growth analysis of autumn and spring sown sugar beet. *Eur. J. Agron.* 2011, 34, 1–9. [CrossRef]

36. Märländer, B.; Hoffmann, C.M.; Koch, H.J.; Ladening, E.; Merkes, R.; Petersen, J.; Stockfisch, N. Environmental situation and yield performance of the sugar beet crop in Germany: Heading for sustainable development. *J. Agron. Crop Sci.* 2003, 189, 201–226. [CrossRef]

37. Kenter, C.; Hoffmann, C.M.; Märländer, B. Effects of weather variables on sugar beet yield development (*Beta vulgaris* L.). *Eur. J. Agron.* 2006, 24, 62–69. [CrossRef]

38. Bzowska-Bakalarz, M.; Banach, M. Właściwości technologiczne surowca buraczanego produkowanego w zmodyfikowanej technologii nawożenia. *Acta Agrophys.* 2009, 14, 31–40.

39. Moliszewska, E. Cechy morfologiczne buraka cukrowego a jakość plonu. *Adv. Agric. Sci. Probl.* 2015, 582, 43–51.

40. Reymond, P.; Weber, H.; Damond, M.; Farmer, E. Differential gene expression in response to mechanical wounding and insect feeding in Arabidopsis. *The Plant Cell.* 2000, 12, 707–719. [CrossRef]

41. Draycott, A.P. Introduction. In *Sugar Beet*; Draycott, A.P., Ed.; Blackwell Publishing Ltd: Oxford, UK, 2006; pp. 1–8.

42. Webb, C.R.; Werke, A.R.; Gilligan, C.A. Modelling the dynamical components of sugar beet crops. *Ann. Bot.* 1997, 80, 427–436. [CrossRef]

43. Musolf, R.; Grzebisz, W.; Szczepaniak, W. Wpływ nawożenia potasem na tle zróżnicowanych warunków wodnych na plon i jakość korzeni buraka cukrowego (*Beta vulgaris* L.) Część II. Jakość technologiczna korzeni i plony cukru. [Effect of potassium fertilization under diversified water conditions on yield and quality of sugar beets (*Beta vulgaris* L.) Part II. Quality of taproots and yield of sugar]. *Biul. Inst. Hod. I Aklim. Roślin* 2004, 234, 115–121.

44. Lafta, A.M.; Fugate, K.K. Dehydration accelerate respiration in post-harvest sugar beet roots. *Postharvest Biol. Physiol.* 2009, 54, 32–37. [CrossRef]

45. Maurya, A.K.; Patel, R.C.; Frost, C.J. Acute toxicity of the plant volatile indole depends on herbivore specialization. *J. Pest Sci.* 2020, 93, 1107–1117. [CrossRef]

46. Lima, A.F.; Ribeiro, L.P.; Gonçalves, G.L.P.; Maimone, N.M.; Gissi, D.S.; de Lira, S.P.; Vendramim, J.D. Searching for bioactive compounds from Solanaceae: Lethal and sublethal toxicity to *Spodoptera frugiperda* and untargeted metabolomics approaches. *J. Pest Sci.* 2021. [CrossRef]

47. Kovalikova, Z.; Kubes, J.; Skalicky, M.; Kuchtickova, N.; Maskova, L.; Tuma, J.; Vachova, P.; Hejnak, V. Changes in content of polyphenols and ascorbic acid in leaves of white cabbage after pest infestation. *Molecules* 2019, 45, 2622. [CrossRef]

48. Vallad, G.E.; Goodman, R.M. Systemic acquired resistance and induced systemic resistance in conventional agriculture. *Adv. Agric. Sci. Probl.* 2015; Draycott, A.P., Ed.; Blackwell Publishing Ltd: Oxford, UK, 2006; pp. 1–8.

49. Bruce, T.J.A. Tackling the threat to food security caused by crop pests in the new millennium. *Food Sec.* 2010, 2, 133–141. [CrossRef]

50. Skalicky, M.; Kubes, J.; Shokoofeh, H.; Tahjib-Ul-Arif, M.D.; Vachova, P.; Hejnak, V. Betacyanins and betaxanthins in cultivated varieties of *Beta vulgaris* L. compared to weed beets. *Molecules* 2020, 25, 5395. [CrossRef]