



Article

Assessment of Early, Mid-Early, and Mid-Late Soybean (*Glycine max*) Varieties in Northern Poland

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Abstract: The soybean crop (*Glycine max*) is known for its high oil and protein content, making it a valuable resource for animal feed and a crucial ingredient in vegan and vegetarian food products. Soybean is a thermophilic short-day plant, demanding specific climatic conditions for successful cultivation. In an effort to expand soybean cultivation to northern regions, a variety of trials were conducted. The aim of this study was to determine the most suitable soybean varieties for cultivation in Northern Poland. The field trials were conducted in nine locations, in the years 2020–2022. Yield, fat content, and protein content were the observed characteristics. Results for 13 varieties had been collected and were analysed using the AMMI model. The genotype–environment interaction provides information that supports estimations of the stability of certain varieties. AMMI-adjusted means, WTOP3, WAAS and GSI indices were calculated in order to assess the suitability of those varieties for cultivation in Northern Poland. It was shown that the Amiata variety had the highest mean yield among the tested varieties, whilst the Erica variety was the most stable. The Abelina variety had the lowest value of the GSI index. For fat content, the Ambella variety had the highest mean and the lowest values of the GSI index, whereas the ES Comandor variety was the most stable. For protein content, the Nessie PZO variety had the highest mean, the Aurelina variety was the most stable and had the lowest values of the GSI index. Thus, the Abelina, Ambella, and Aurelina varieties are the most favourable varieties for cultivation in that region.

Keywords: soybean; Northern Poland; stability; AMMI model



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1. Introduction

Soybean is a crop with high fat and protein content. It is primarily used to feed animals but it is also used in human consumption. Defatted soybean meal is a significant and cheap source of protein for animal feeds and various processed foods. Over recent years, the production of soybean increased. According to Food and Agriculture Organization of the United Nations (FAO), in 2021, the global production of soybean was 355,370,766.69 tonnes and was grown mainly in Brazil and the United States of America [1]. These two countries alone accounted for approximately 66% of the world's soybean production. In the EU, soybean was mainly cultivated in Italy with production of 923,470 tonnes. In Poland, this was 20,970 tonnes.

Soybean is a short-day plant, which is especially susceptible to the latitude of the growing site [2,3]. It's suitability to the region is restricted by long daytime duration, low temperature at the time of germination and flowering, and amount of rainfall [4].

Other factors affecting the soybean cultivation include soil moisture, precipitation, and photoperiod [4–10]. Furthermore, elevated temperatures and water stresses post-flowering negatively affect plant growth [6]. Temperatures between 22 °C and 25 °C are considered to be the optimal temperatures. Temperatures above 35 °C may decrease seed mass, whilst temperatures below 17 °C can inhibit seed growth [11]. Moreover, according to Zeipina et al. [3], the choice of variety with proper vegetation length plays a crucial role in a cultivation success in higher latitudes (see also [12]). On the other hand, in many agronomic studies, it was raised that management plays an essential role in achieving cultivation in northern latitudes [3,5,13–15]. For instance, early sowing dates have been found to increase seed yield and fat content, while late sowing tends to enhance protein content [16–23]. These multifaceted factors, with their intricate interplay, underscore the complexity of soybean cultivation.

At the same time, in many EU countries, variety offices (the authorities in charge of variety testing) started an organic “value for cultivation and use” (VCU) variety testing for national listing of soybean (see, e.g., [12,24,25]). In Poland, new varieties of important crops, including soybean, are assessed before registration in the VCU trials and further in the post-registration trials. In 2017, Research Centre for Cultivar Testing (COBORU) launched the program ‘Inicjatywa Białkowa’ (‘Protein Initiative’) with the aim of increasing the area of protein crops and improving the feed balance in the country. For this purpose, the number of varietal trials has been increased and the location of experimental sites has been modified. Moreover, it was allowed to test soybean varieties from the EU Common Catalog (varieties listed in other EU countries) in the post-registration trials. Based on the results of the post-registration trials, a recommendation for farmers is issued.

It is believed that the cultivation of soybean in Poland will increase in the coming years. For this reason, it is important to introduce stable varieties to the cultivation. Usually, stability of agronomic traits is assessed in multi-environment trials. A common approach is to analyse these trials using a two-stage approach (see, e.g., [26–31]), where each combination of year and site is treated as an environment. In the literature, several stability measures have been described, for example, Shukla’s stability variance model [32]; the additive main effects and multiplicative interaction model ([33,34], AMMI); the genotype main effect and genotype-by-environment interaction (GGE) model [35]. Whereas the stability analysis is routinely performed for cereals or potatoes, little attention has been paid in the literature to stability of soybean traits. Boros et al. [7] used the *F*-statistic for genotype–environment interactions, which is implemented in the Sergen program [36], as some kind of stability measure. Recently, Döttinger et al. [37] used GGE biplot and the Shukla’s stability variance to identify stable and well adapted varieties. In the same paper, they also compared the stability of varieties grown in the south and the north of Germany in terms Shukla’s stability variance. In the present, we used the AMMI model to assess stability of varieties in Northern Poland. We used the weighted average absolute scores introduced in [38] as a measure of stability. Using that methodology, we identified the most stable and well-adapted varieties for a series of field trials conducted in Northern Poland in the years 2020–2022.

2. Materials and Methods

2.1. Data

The dataset consists of variety means from soybean trials performed in the years 2020–2022 in Northern Poland. This dataset is a part of larger series of soybean field trials performed by COBORU. All trials were laid out in randomized complete block design with three replicates. The trials were conducted in experimental stations (sites) belonging to COBORU. The list of sites used in the present study is given in Table 1 (see also Figure 1). The soil and meteorological conditions are reported in the Supplement (Tables S1–S3). The fertilization, the type of tillage, and the methodology used for harvesting were applied in accordance with the current COBORU guidelines [39].

Table 1. Sowing dates and sites in Northern Poland used in the soybean trials conducted from 2020 to 2022.

Site	Sowing Date			Geographical Co-Ordinates		
	2020	2021	2022	Latitude	Longitude	m a.s.l.
Białogard (Bia) [†]	30 Apr	11 May	10 May [‡]	54°00' N	16°00' E	24
Chrzastowo (Ch)	30 Apr	05 May	05 May	53°11' N	17°35' E	105
Karznicka(Kar)	05 May	10 May	04 May	54°29' N	17°14' E	80
Krzyżewo(Krz) [†]	08 May	–	10 May	53°01' N	22°46' E	135
Marianowo (Ma)	04 May	11 May	11 May	53°13' N	22°07' E	140
Nowa Wieś Ujska (NWU)	07 May	11 May	–	53°02' N	16°45' E	105
Radostowo (Ra) [†]	08 May	–	10 May	53°59' N	18°45' E	40
Wróćkowo (Wr)	08 May	10 May	09 May	53°49' N	20°40' E	142
Wyczechy(Wy)	10 May	11 May	05 May	53°44' N	17°02' E	152

[†] Fat and protein contents were measured; [‡] yield was not analysed.

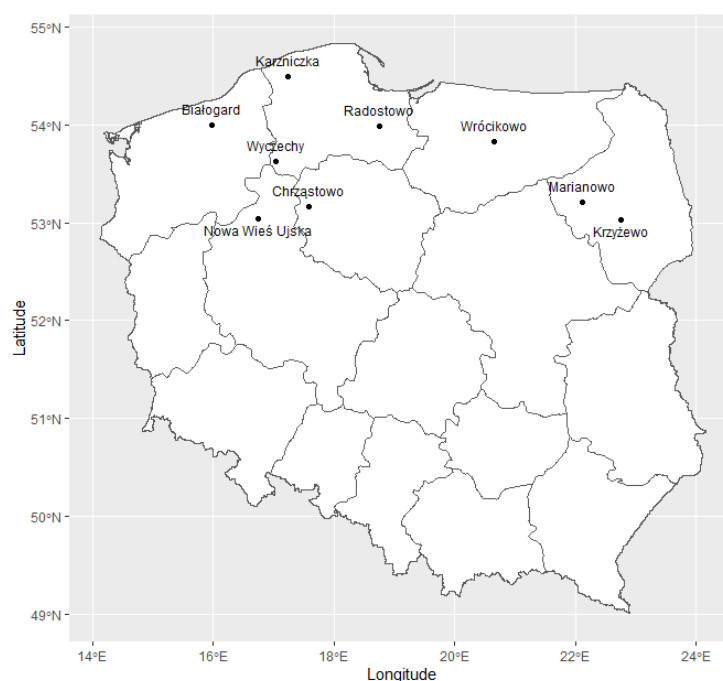


Figure 1. Map of Poland showing the locations of the experimental sites.

In the Polish soybean trials, varieties from all maturity groups are tested. However, due to the meteorological conditions, late and very late varieties do not always yield in high latitudes. For this reason, in this study we limit ourselves to early, mid-early, and mid-late varieties. During the three years of study, 13 early, mid-early, and mid-late varieties from the National List (NL) and the Common Catalog of Agricultural plants (CCA) were tested in Northern Poland. The list of varieties used in the present study—with their country of origin, registration year, and COBORU Maturity Group—is given in Table 2.

In the Polish soybean trials, yield, protein content, and fat content are some of the observed characteristics. Protein content and fat content are the means from two samples. Each sample of protein and fat content is expressed as proportion of dry matter content (%). In each sample, protein content was determined according to Kjeldahl method, whereas fat content was determined using the Soxhlet method. According to the methodology used in COBORU, yield is measured in all sites, while fat and protein content are measured only in the chosen sites. The sites, in which fat and protein content were measured, are marked with [†] in Table 1.

Table 2. Varieties used in the soybean trials conducted from 2020 to 2022.

i	Variety	Country	NL (Registration Year)/CCA	COBORU Maturity Group *	COBORU Description *
1	Abelina	Austria	NL (2016)	4	early-mid-early
2	Adessa	Austria	NL (2017)	2–3	early
3	Ambella	Austria	CCA	1	very early
4	Amiata	Austria	CCA	6	mid-late
5	Antigua	Austria	NL (2019)	3	early
6	Aurelina	Austria	NL (2019)	6	mid-late
7	Erica	Poland	NL (2017)	2	very early-early
8	ES Comandor	France	NL (2018)	6	mid-late
9	Mayrika	Czech Republic	CCA	3	early
10	Moravians	Czech Republic	CCA	6	mid-late
11	Nessie PZO	Germany	CCA	5	mid-early
12	Obelix	Germany	CCA	5	mid-early
13	Sirelia	France	CCA	5	mid-early

* based on the COBORU trial results in 2020–2022 y or more. There are 1–9 groups of earliness recognized, starting from group 1 (very early).

2.2. Statistical Analysis

The trait means were modelled according to the additive main effects and multiplicative interaction model ([33,34]; AMMI). For the sake of clarity, throughout the paper, by environment, we will mean a combination of year and location. In the present study, we use abbreviations to denote environments based on the year of study and location as indicated in Table 1. For example, 20Ma stands for Marianowo in the year 2020.

Let y_{ij} denote the trait mean of the i th variety ($i = 1, 2, \dots, I$) in the j th environment ($j = 1, 2, \dots, J$). Then, the AMMI model with $\kappa > 0$ multiplicative terms (AMMI κ) can be written as:

$$y_{ij} = \mu + g_i + e_j + \sum_{k=1}^{\kappa} \lambda_k \gamma_{ik} \delta_{jk} + \varepsilon_{ij}, \quad \kappa = 1, \dots, \min(I-1, J-1), \quad (1)$$

where μ represents the overall mean, g_i and e_j are the main effects of i th variety and of j th environment, respectively. Further, κ is the number of principal components, $\lambda_k \geq 0$ is the eigenvalue of the PCA axis k , γ_{ik} and δ_{jk} are the scores associated with the i -th genotype and j -th environment, respectively, subject to the usual estimability constraints. Finally ε_{ij} is the associated random residual error. It is assumed that the expected distribution of ε_{ij} is normal. The AMMI κ model was fitted using the statgenGxE package [40] in the R statistical program (version 4.3.0) [41].

In model (1), the significance of each interaction principal component (IPC) was assessed using F test statistic. The number of degrees of freedom (D.F.) to assign to the k th IPC axis was calculated as $I + J - 1 - 2k$ [33]. The forward selection algorithm (numerical implementation in the statgenGxE package, [40]) was used to determine κ in the model (1).

Next, to assess stability in the AMMI model, we calculated the weighted average of absolute scores (WAAS; [38])

$$WAAS_i = \frac{\sum_{k=1}^{\kappa} |\theta_k IPC_{ik}|}{\sum_{k=1}^{\kappa} \theta_k}, \quad (2)$$

where IPC_{ik} is the score of the i -th genotype in the k th IPC, θ_k is the explained variance of the k th IPC, and κ is the number of significant IPC's in the model (1).

To combine rankings based on the AMMI-adjusted variety mean and stability measure WAAS, for each variety and trait, the genotype selection index (GSI, see, e.g., [42]) was calculated as

$$GSI_i = RM_i + RW_i, \quad (3)$$

where RM_i is the rank of the trait mean and RW_i is the rank of the WAAS score for the i -th variety.

Further, to assess adaptability of the early, mid-early, and mid-late soybean varieties, we calculated $WTOPX$ index ([43]; see also [42]), where $X = 1, 2, 3, \dots$. The index $WTOPX$ is defined as

$$WTOPX_i = \frac{n_i}{J}, \quad i = 1, 2, \dots, I, \quad (4)$$

where n_i is the number of environments in which the i -th variety was among the top X varieties and J is the total number of environments. In the present work, the $WTOPX$ coefficient was calculated for each variety, based on the fitted values from the AMMI κ model. High values of this index indicate broad adaptability, while small values indicate specific adaptability.

Finally, for each trait, mega-environments were created by grouping environments based on their best-performing variety. Environments that share the same best variety belong to the same mega-environment.

3. Results

Mean, standard deviation (sd), minimum (min), median (med), and maximum (max) of the analysed traits for the three studied years are reported in Table 3.

Table 3. Summary statistics for yield, protein, and fat content: mean, standard deviation (sd), minimum (min), median (med), and maximum (max).

Trait	Year	Mean	sd	min	med	max
Yield	2020	27.72	8.71	11.45	27.99	46.14
	2021	24.98	10.48	9.70	23.67	52.03
	2022	26.20	6.18	15.98	25.92	43.08
Fat content	2020	23.54	1.04	21.55	23.56	25.55
	2021	21.74	1.20	20.00	21.79	24.45
	2022	24.12	1.42	21.29	23.94	27.03
Protein content	2020	34.95	2.56	30.78	34.92	39.75
	2021	35.20	3.39	28.81	35.60	40.16
	2022	31.87	2.74	26.73	31.95	38.85

The soybean yields ranged from 9.70 dt/ha to 52.03 dt/ha. The lowest and the highest mean yield were both observed in 2021. The fat content ranged from 20% to 27.03%. The lowest and the highest values of fat content were observed in 2021 and 2022, respectively. The protein content ranged from 26.73% to 40.16%. The lowest and the highest values of protein content were observed in 2022 and 2021, respectively.

Firstly, for each trait, the AMMI κ model was fitted and the forward selection algorithm was used to determine the optimal number of IPC's (κ). For this purpose, we set option $nPC = \text{NULL}$ in the $gxeAMMI$ function.

For yield the number of IPC, κ is equal to three. This means that this trait should be fitted with the AMMI3 model. On the other hand, for fat and protein content, κ was equal to two. This means that these two traits should be fitted with the AMMI2 model.

3.1. Yield

Yield was analysed using the AMMI3 model. The analysis provided several estimated parameters and statistics (Tables 4 and 5).

In Table 4, the results of ANOVA from the AMMI3 model for yield are reported. It is noted that the main effects of both the varieties and the environments were highly significant. Moreover, one can observe that the sum of squares for environments explained 78.5% of the total variation of yield. The sum of squares for varieties represented 7.1% of the total variation, while the sum of squares for the variety–environment interaction

explained 14.4%. Further, the first three interaction principal components (IPCs) jointly explained 71.4% of the whole effect it had on the variation in the yield. The first interaction principal component IPC1 accounted for 34.5% of the variation caused by interaction, while the second principal component IPC2 accounted for 25.4%. The third interaction principal component (IPC3) explained 11.5% of the variation caused by the interaction.

On Figure 2 the first two interaction principal components of the 13 varieties and 23 environments were plotted. It is noted that the 20Ma, 20NWU, 22Ma, and 22Wr environments and the Adessa (2), Ambella (3), Amiata (4), Aurelina (6), Mayrika (9), Nessie PZO (11), and Obelix (12) varieties had the biggest influence on the variety–environment interaction. Moreover, one can observe that the Erica variety (7) was the closest to the origin.

Table 4. Analysis of variance of the main effects and interactions for the analysed traits.

Trait	Source of Variation [†]	D.F.	S.S.	M.S.	F	Variability Explained [%]
Yield	V	12	1596.2	133.0	10.8 ***	7.1
	E	22	17,673.2	803.3	65.3 ***	78.5
	V × E	264	3246.3	12.3		14.4
	IPC1	33	1120.2	33.9	6.2 ***	34.5
	IPC2	31	824.8	26.1	4.9 ***	25.4
	IPC3	29	371.6	12.8	2.4 ***	11.5
	Residuals	171	929.6	5.4		28.6
Fat content	V	12	60.0	5.0	6.4 ***	31.4
	E	6	74.9	12.5	16.0 ***	39.2
	V × E	72	56.0	0.8		29.4
	IPC1	17	26.2	1.5	5.1 ***	46.8
	IPC2	15	17.8	1.2	3.9 ***	31.7
	Residuals	40	12.0	0.3		21.5
Protein content	V	12	68.7	5.7	1.4 ns	7.7
	E	6	521.3	86.9	20.7 ***	58.4
	V × E	72	301.9	4.2		33.9
	IPC1	17	151.9	8.9	5.3 ***	50.3
	IPC2	15	83.0	5.5	3.3 **	27.5
	Residuals	40	67.0	1.7		22.2

[†] V = variety; E = environment; V × E = variety × environment interaction; IPC1 = 1st interaction principal component; IPC2 = 2nd interaction principal component; IPC3 = 3rd interaction principal component. D.F. = degrees of freedom; S.S. = sum of squares; M.S. = mean square. *** $p < 0.001$, ** $p < 0.01$; ns = not significant.

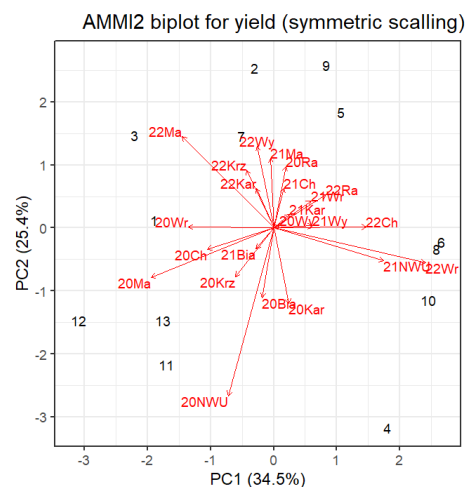


Figure 2. AMMI2 biplot showing the first two interaction principal components of the effects of 13 varieties and 23 environments. Abbreviations for environments refer to the year (e.g., 20 means 2020) and to the following sites: Bia—Białogard; Ch—Chrzastowo; Kar—Karzniczka; Krz—Krzyżewo; Ma—Marianowo; NWU—Nowa Wieś Ujska; Ra—Radostowo; Wr—Wróćkowo; Wy—Wyczechy.

Table 5 reports the AMMI-adjusted variety means, values of the weighted average of absolute scores (WAAS), WTOP3 index, and the values of the genotype selection index (GSI).

Table 5. Variety means and the values of the WAAS stability index, GSI, and WTOP3 index for yield.

i	Variety	Mean [dt/ha]	WAAS	GSI	WTOP3
1	Abelina	27.78 (5)	0.90 (2)	7	0.30
2	Adessa	25.36 (8)	1.01 (4)	12	0.13
3	Ambella	23.67 (11)	1.49 (10)	21	0
4	Amiata	30.82 (1)	1.81(12)	13	0.78
5	Antigua	23.34 (13)	0.99 (3)	16	0
6	Aurelina	25.34 (9)	1.15 (5)	14	0.04
7	Erica	23.92 (10)	0.79 (1)	11	0
8	ES Comandor	27.61 (6)	1.42 (7)	13	0.39
9	Mayrika	23.66 (12)	1.34 (6)	18	0
10	Moravians	26.38 (7)	1.48 (8)	15	0.17
11	Nessie PZO	28.63 (3)	1.49 (9)	12	0.35
12	Obelix	28.73 (2)	1.91 (13)	15	0.48
13	Sirelia	28.24 (4)	1.50 (11)	15	0.35

In column three of Table 5, the AMMI-adjusted variety means are reported. Among the tested varieties, the Amiata variety had the highest yield. This variety was also the best among the Austrian varieties. Among the German varieties, the Obelix variety had the highest yield and was ranked second overall. The best French variety (Sirelia) was ranked fourth, while the best Czech (Moravians) variety was ranked seventh. The Polish Erica variety was ranked tenth, but it had one of the shortest vegetation length among the registered varieties.

In column four of Table 5, values of the WAAS stability index are reported. One can notice that the Polish Erica variety had the smallest value of the WAAS stability index, which means that this variety was the most stable among the tested varieties. The second-best variety in terms of the WAAS stability index was the Abelina variety, and was the most stable variety among the Austrian varieties. Among the Czech varieties, the Mayrika variety was the most stable, whereas the ES Comandor variety was the most stable variety among the French varieties. On the other hand, the Obelix variety was the most unstable and the highest yielding variety was the second worst in terms of stability.

The values of the GSI index are reported in column five of Table 5. It is noted that the Abelina variety had the smallest value of the GSI index, which was equal to 7. This means that this variety is the most desirable. The Polish Erica variety was the second-best in terms of the GSI index. On the other hand, the highest value of the GSI index was obtained for the Ambella variety.

In the last column of Table 5, the values of WTOP3 index are reported. It is noted that the highest yielding Amiata variety showed wide adaptability to the agro-meteorological conditions in Northern Poland each cropping season and in all cropping seasons. For the Obelix variety, the value of WTOP3 index was equal to 0.48 which means that this variety showed moderate adaptability to the agro-meteorological conditions in Northern Poland. A different pattern can be observed for the Abelina, Adessa, Aurelina, ES Comandor, Moravians, Nessie PZO, and Sirelia varieties. For these varieties, the values of WTOP3 index was less than 0.4, which means that these varieties showed specific adaptability to the agro-meteorological conditions in Northern Poland. For example, the Sirelia variety was among top three varieties in the following environments: 20Kar, 20Krz, 20Ma, 21Wr, 22Kar, 22Krz, and 22Ma. The Abelina variety was among top three varieties in the following environments: 20Ch, 20Wr, 21Ma, 22Kar, 22Krz, 22Ma and 22Wy. On the other hand, the Adeassa and Moravians varieties showed specific adaptability to the following agro-meteorological conditions in environments: 20Ra, 21Ma, and 22Wy, and 21NWU, 21Wr, 22Ch, and 22Wr, respectively. To illustrate the above patterns (Figure 3), we plotted the

AMMI-adjusted variety–environment interaction means for the abovementioned varieties against environments, which were latitudinally ordered.

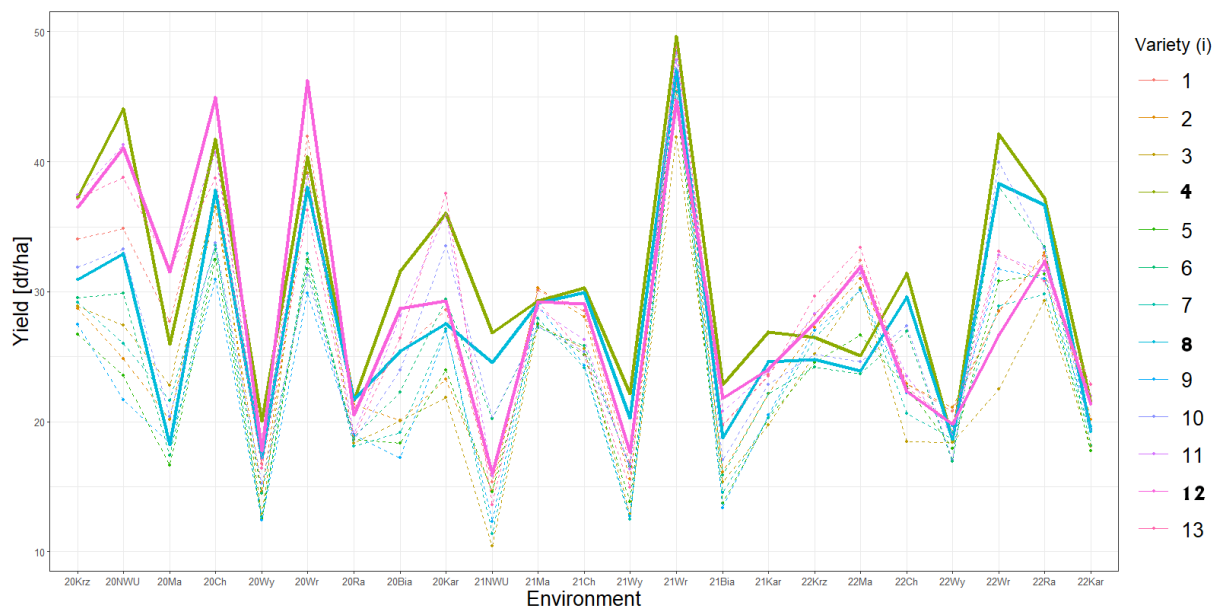


Figure 3. Adaptive yield response patterns across 23 environments in Northern Poland for 13 varieties. Varieties with the highest values of WTOP3 index are highlighted with the solid lines and highlighted with a bold font in the legend. Abbreviations for environments refer to the year (e.g., 20 means 2020) and to the following sites: Bia—Białogard; Ch—Chrzastowo; Kar—Karniczka; Krz—Krzyżewo; Ma—Marianowo; NWU—Nowa Wieś Ujska; Ra—Radostowo; Wr—Wróclikowo; Wy—Wyczechy.

Finally, based on the AMMI-adjusted variety–environment interaction means (see also Figure 3), one can distinguish six mega-environments in the region of interest. The first mega-environment and the biggest one was mega-environment M1 (20Bia, 20NWU, 20Wy, 21Bia, 21Ch, 21Kar, 21NWU, 21Wr, 21Wy, 22Ch, 22Ra, 22Wr), in which the Amiata variety was the best-performing variety. The second mega-environment M2 consists of the following environments: 20Kar, 20Ma, 22Kar, 22Krz, and 22Ma. In this mega-environment, the Sirelia variety was the highest-yielding variety. The Adessa variety was the best-performing variety in mega-environment M3 (21Ma, 22Wr), while the Obelix variety was the best in mega-environment M4 (20Ch, 20Wr). The last two mega-environments M5 (20Ra) and M6 (20Krz) were created by the ES Comandor and Nessie PZO varieties, respectively.

3.2. Fat Content

Fat content was analysed with the AMMI2 model. The analysis provided several estimated parameters and statistics (Tables 4 and 6).

In Table 4, the results of ANOVA from the AMMI2 model for fat content are reported. It is noted that the main effects of both the varieties and those of the environments were highly significant. Moreover, one can observe that the sum of squares for environments explained 39.2% of the total variation of fat content. The sum of squares for varieties represented 31.4% of the total variation, while the sum of squares for the variety–environment interaction explained 29.4%. Furthermore, the first three interaction principal components (IPCs) jointly explained 78.5% of the whole effect it had on the variation on the fat content. The first interaction principal component accounted IPC1 for 46.8% of the variation caused by interaction, while the second principal component IPC2 explained 31.7% of the variation caused by interaction.

On Figure 4 the first two interaction principal components of the 13 varieties and seven environments were plotted. It is noted that the 20Bia, 22Bia, and 22Krz environments and the Abelina (1), Adessa (2), Ambella (3), Erica (7), Obelix (12), and Sirelia (13) varieties had

the biggest influence on the variety–environment interaction. Moreover, one can observe that the ES Comandor (8) and Amiata (4) varieties were the closest to the origin.

Table 6 reports the AMMI-adjusted variety means, the values of the weighted average of absolute scores (WAAS), WTOP3 index, and the values of the genotype selection index (GSI).

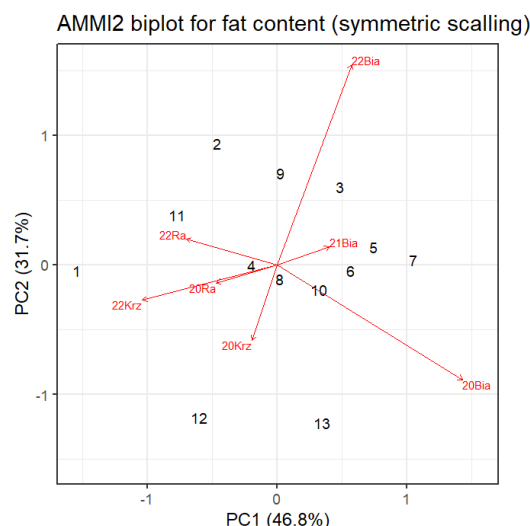


Figure 4. AMMI2 biplot for fat content showing the first two interaction principal components of the effects of 13 varieties and seven environments. Abbreviations for environments refer to the year (e.g., 20 means 2020) and to the following sites: Bia—Białogard; Krz—Krzyzewo; Ra—Radostowo.

Table 6. Variety means, WAAS stability index, GSI, and the values of WTOP3 index for fat content.

i	Variety	Mean [%]	WAAS	GSI	WTOP3
1	Abelina	24.28 (3)	0.87 (13)	16	0.57
2	Adessa	24.73 (2)	0.60 (10)	12	0.71
3	Ambella	25.32 (1)	0.49 (7)	8	1
4	Amiata	22.93 (11)	0.12 (2)	13	0
5	Antigua	23.21 (9)	0.46 (6)	15	0
6	Aurelina	23.31 (7)	0.36 (5)	12	0
7	Erica	23.38 (6)	0.59 (9)	15	0.14
8	ES Comandor	22.34 (13)	0.05 (1)	14	0
9	Mayrika	23.63 (5)	0.28 (4)	9	0.14
10	Moravians	22.66 (12)	0.26 (3)	15	0
11	Nessie PZO	22.95 (10)	0.57 (8)	18	0
12	Obelix	23.22 (8)	0.77 (12)	20	0
13	Sirelia	23.96 (4)	0.65 (11)	15	0.43

In column three of Table 6, the AMMI-adjusted variety means are reported. Among the tested varieties, the Ambella variety had the highest fat content and was also the best among the Austrian varieties. The Adessa variety had the second highest fat content. The best French variety (Sirelia) was ranked fourth, while the best Czech (Mayrika) variety was fifth overall. For the Polish variety Erica, fat content was equal to 23.38% and was ranked sixth overall.

In column four of Table 6, the values of the WAAS stability index are reported. One can notice that, the French ES Comandor variety had the smallest value of the WAAS stability index, which means that this variety was the most stable among the tested varieties. The second-best variety in terms of the WAAS stability index was Amiata variety. This variety was also the most stable variety among the Austrian varieties. Among the Czech varieties, the Moravians variety was the most stable. The Polish Erica variety was ranked ninth overall. On the other hand, the Abelina variety was the most unstable variety.

Values of the GSI index are reported in column five of Table 6. It is noted that Ambella variety had the smallest value of the GSI index, which was equal to 8. This means that this variety is the most desirable. The second-best in terms of the GSI index was the Czech Mayrika variety. On the other hand, the highest value of the GSI index was obtained for the Obelix variety.

In the last column of Table 6, the values of the WTOP3 index are reported. It is noted that varieties Ambella and Adessa showed wide adaptability to the agro-meteorological conditions in Northern Poland each cropping season and in all cropping seasons. For the Abelina and Sirelia varieties, the values of the WTOP3 index were equal to 0.57 and 0.43, respectively. This means that these varieties showed moderate adaptability to the agro-meteorological conditions in Northern Poland. A different pattern can be observed for varieties Erica and Mayrika. For these two varieties, the values of WTOP3 index were less than 0.14, which means that these varieties showed specific adaptability to the agro-meteorological conditions in Northern Poland. Varieties Erica and Mayrika showed specific adaptability to the agro-meteorological conditions in environments 20Bia and 22Bia, respectively. To illustrate the above patterns (Figure 3), we plotted the AMMI-adjusted variety–environment interaction means for the abovementioned varieties against environments, which were ordered latitudinally.

Finally, based on the AMMI-adjusted variety–environment interaction means (see also Figure 5), one can distinguish three mega-environments in the region of interest. The mega-environment M1, in which the Abelina variety was the best-performing variety, consisting of environments 20Ra, 22Krz, and 22Ra. The second mega-environment M2 consists of the following environments: 20Krz, 21Bia, and 22Bia. In this mega-environment, the Ambella variety had the highest fat content. The last mega-environment M3 (20Bia), which was also the smallest one, was created by the Sirelia variety.



Figure 5. Adaptive fat content response patterns across 7 environments in Northern Poland for 13 varieties. Varieties with the highest values of WTOP3 index are highlighted with the solid lines and highlighted with a bold font in the legend. Abbreviations for environments refer to the year (e.g., 20 means 2020) and to the following sites: Bia—Białogard; Krz—Krzyżewo; Ra—Radostowo.

3.3. Protein Content

Protein content was analysed with the AMMI2 Model. The analysis provided several estimated parameters and statistics (Tables 4 and 7).

In Table 4, the results of ANOVA in the AMMI Model for protein content are reported. It is noted that the main effects of environments were highly significant. However, the main

effects of varieties were not highly significant. One can observe that the sum of squares for environments explained 58.5% of the total variation of protein content. The sum of squares for varieties represented 7.7% of the total variation, while the sum of squares for the variety–environment interaction explained 33.9%. Moreover, the first two interaction principal components accounted jointly for 77.8% of the whole effect it had on the variation on the protein content. IPC1 accounted for 50.3% of the variation caused by interaction, while IPC2 accounted for 27.5% of the variation caused by interaction.

In Figure 6 the first two interaction principal components of the 13 varieties and 7 environments were plotted. It is noted that the 20Bia, 21Bia, and 22Krz environments and the Adelina (1), Ambella (3), Erica (7), and Moravians (10) varieties had the biggest influence on the variety–environment interaction. Moreover, one can observe that the Mayrika variety (9) was the closest to the origin.

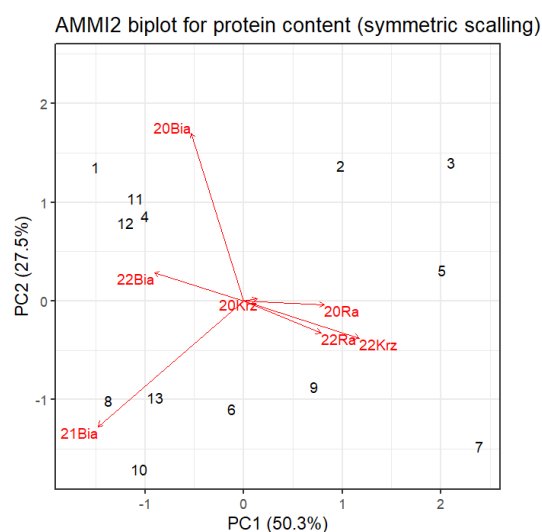


Figure 6. AMMI2 biplot showing the first two interaction principal components of the effects of 13 varieties and seven environments. Abbreviations for environments refer to the year (e.g., 20 means 2020) and to the following sites: Bia—Białogard; Krz—Krzyżewo; Ra—Radostowo.

Table 7 reports the AMMI-adjusted variety means, the values of the WTOP3 index, weighted averages of absolute scores (WAAS), and the values of the genotype selection index.

In column three of Table 7, the AMMI-adjusted variety means are reported. Among the tested varieties, the Nessie PZO variety (11) had the highest protein content. This variety was the best among the German varieties. Among the Austrian varieties, the Aurelina variety (6) was the best and the fourth overall. Among the Czech varieties, the Moravians variety (10) was the best and third overall. The ES Comandor variety (8) was the best French variety and fifth overall. The Polish Erica variety had mediocre percentage of protein content.

In column four of Table 7, the values of the WAAS stability index are reported. One can notice that the Aurelina variety (6) had the smallest value of the WAAS stability index, which means that this variety was the most stable among the tested varieties. The second-best variety in terms of the WAAS stability was the Mayrika variety (9), and that was the most stable variety among the Czech varieties. Among the French varieties, the Sirelia variety (13) was the most stable and the third most stable overall. The Amiata variety (4) was the fourth most stable variety and was the most stable among Austrian varieties. The Polish Erica variety (7) was the most unstable variety.

Values of the GSI index are reported in column five of Table 7. It is noted that the Aurelina variety (6) had the smallest value of the GSI index, which was equal to 5 and which means that this variety is the most desirable. German varieties Nessie PZO (11) and Obelix (12) were the second-best in terms of the GSI index. On the other hand, the highest value of the GSI index was obtained for the Ambella variety (3).

4. Discussion

Cultivation of legumes is of great importance for the application of crop rotation and is an important element of biodiversity. With the progression of climate warming, many scientists and crop experts from a variety of offices began to test soybean varieties in northern latitudes [3,12,24,25,37]. However, in order to be successful in cultivation in northern latitudes, one needs to grow stable varieties of the proper vegetation length [3]. Döttinger et al. [37], in their comparative study of the two halves of Germany, reported that they had no or only partial data at the two northern sites. In that study, the comparison was made on 8 varieties from different maturity groups (MG0000-MG0) and 42 lines. In the present study, all tested varieties were classified by the breeders as early varieties (MG0000 or MG000). According to the methodology used in COBORU, they were classified in terms of vegetation length and different maturity groups. The late and very late varieties were excluded from the analysis because we had no or only partial data for these varieties in the region of interest. In a different study, Osiecka and Przystalski [12], using data from the whole country, showed that varieties classified by breeders as early varieties differ significantly in the vegetation length. In the same study, they also showed that the difference between the shortest and the longest vegetation length was 21 days. This difference could be crucial for farmers in northern latitudes.

Usually, the stability of agronomic traits is assessed in multi-environment trials, which are analysed using either one-stage approach or two-stage approach [26–31,44]. In the one-stage approach, the analysis is performed on plot data. In the latter approach, one first performs the analysis of each trial separately and next the variety means are analysed using linear mixed model or the AMMI model. In the present study, we followed the two-stage approach and the AMMI model was used to analyse the varietal means for four traits. However, through using the AMMI model, one faces the problem of how to determine the number of principal components. In the literature, several solutions to this problem have been proposed, which are based either on parametric bootstrap [45] or on non-parametric bootstrap [46]. The simple bootstrap procedure has been implemented in the Bilinear R package [47]. In the present study, the forward selection algorithm was used, which is based on the F test. For comparison, we also fitted the AMMI κ model in the Bilinear package and we obtained similar results for yield and protein content. For fat content, the simple bootstrap declared only one interaction principal component. This can be partially explained, as for this trait the first singular value was bigger than the rest of singular values. Moreover, Forkman and Piepho [45], in their simulation study, have shown that the simple bootstrap procedure is more conservative than the F test. Furthermore, all abovementioned algorithms rely on the same stopping rule, i.e., each algorithm takes the last value, for which the null hypothesis $H_{0K} : K = \kappa$ has been rejected at a given significance level α , as an optimal number of interaction principal components κ . According to Choi et al. [48], this is the simple stop procedure. However, for datasets with large number of varieties and environments, the number of optimal principal components can be high (see, e.g., [49]). For this reason, Forkman and Piepho [45] and Malik et al. [46] suggested that we test the null hypotheses $H_{0K} : K = \kappa$ only for $\kappa = 1, 2, \dots, 5$. In a different study, Studnicki et al. [44] used the same restriction and considered only factor-analytic covariance matrices of order $q = 1, \dots, 5$. On the other hand, for large datasets, the procedure of finding κ based on the simple stop procedure does not guarantee that the simultaneous test procedure would be at significance level α . For this reason, Choi et al. [48] proposed a strong stop procedure which controls family wise error (FWER). In Bilinear package a Bonferroni correction for multiple hypotheses testing has been implemented. In the present study, the dataset was small; however, for large datasets, it is advised to use procedures that control FWER or with Bonferroni correction.

The analysis conducted in this study displayed that, of the three traits analysed, yield and protein content depended largely on environmental conditions. For these two environmental characteristics, they explained almost 78.5% and 59.5% of the total variation, respectively, while cultivars accounted for approximately 7%. Regarding fat content, all sources of variability (va-

rieties, environments, and their interactions) contributed almost equally to the total variability. This may suggest that both yield and protein content are mainly determined by environmental conditions, while fat content depends on both genetic and environmental factors. However, in the literature, many authors point out that seed yield and fat and protein content depend on environmental conditions [7–10,50,51]. In [9], the authors stated that seed yield was mainly determined by meteorological conditions. A similar conclusion was found by Boros et al. [7]. Moreover, they concluded that higher values of hydrothermal index and higher heat sums had decisive impact on yield, irrespective on the soil conditions. Sobko et al. [8] showed that higher temperatures during reproductive growth tend to result in higher fat content. Naeve and Huerd [16] showed that an increase of 1 °C in temperature during seed filling and ripening increased the fat content. According to Benzain and Lane [50], protein content depends more on environmental conditions than on genotype. In another study, Vollman et al. [52] reported that high protein content is determined by temperature and total rainfall during seed filling.

In the present study, the correlation between the fat and protein content was equal to -0.63 and was significant. A similar result was obtained in McDonald et al. (2023) [53], in which the corresponding correlation was equal to -0.66 . Negative correlation of fat content and protein content of soybeans has been reported since the mid 1960s [8]. The reason for the strong negative correlation between fat content and protein content is unclear. Certain combination of genes is responsible for both fat content and protein content. Thus, it is difficult to increase one of those properties without leaving the other unchanged [8].

In the current study, average yields ranged from 24.94 to 27.72 dt/ha. Based on the Swedish field experiments, Fogelberg and Recknagel [13] concluded that early varieties could achieve yields of approximately 25 dt/ha. In another study, Döttinger et al. [37] showed that average yields in Northern Germany ranged from 21.60 to 30.47 dt/ha. Moreover, the average yields for the Nessie PZO and Adessa varieties were 27.35 dt/ha and 25.67 dt/ha, respectively. Similar average yields for those two varieties were obtained in Northern Poland. Moreover, a detailed analysis of the German results showed that the average yield in Gülzow-Prüzen in 2021 was 29.35 dt/ha. The average yield in Wrócikowo located at the same latitude as Gülzow-Prüzen, in 2021 was higher and equal to 46.44 dt/ha. Using the AMMI4 Model, we also analysed TGW (thousand grain weight). The main effects of environment and varieties were highly significant. The Obelix, ES Comandor, and Aurelina varieties had the highest variety means, whilst the Mayrika, Abelina, and Ambella varieties had the lowest variety means. The highest mean was 210.42 g (Obelix) and the lowest mean was 159.08 g (Mayrika). Further, the average protein content in our three-year study was equal to 33.67%. In 2021, the average protein content in Northern Poland was 35.20% and was lower than the value found in the German study (45.09%) [37]. This can be partially explained by the fact that Döttinger et al. [37] reported the protein content for the entire country. However, in 2021, the fat content in Northern Poland ranged from 23.81% to 27.32%, while in the German study these values were lower.

Finally, we conclude from the current study that varieties did not differ significantly in terms of protein content. This result was surprising, but it can be partially explained by the fact that we included in the analysis only varieties from three maturity groups. However, in another study, Jarecki and Bobrecka-Jamro [15] also found negligible differences between cultivars in terms of protein content. On the other hand, in the case of fat content, the variety effects were highly significant. A similar result was obtained by Biel et al. [54]. In that study, they also found that soybean variety had a significant effect on fat and ash content.

5. Conclusions

Our findings revealed that the main effects of variety significantly influenced various traits of soybean, except for protein content. Notably, for fat content, a balance between environmental factors, varieties, and their interactions played a pivotal role in explaining the observed variances. This indicates the complex interplay of factors affecting soybean quality and yield.

In terms of AMMI-adjusted variety means, specific varieties stood out for their performance in different traits. The Amiata variety exhibited the highest mean for yield, suggesting its suitability for optimal soybean production. On the other hand, the Ambella variety demonstrated the highest mean for fat content, making it a favourable choice for those seeking higher fat yields. For protein content, the Nessie PZO variety outperformed the others, emphasizing its potential in contributing to soybean's nutritional value.

The WAAS score was used to evaluate the stability of varieties. The Erica variety was the most stable in terms of yield, the ES Comandor variety was the most stable in terms of fat content, and the Aurelina variety was the most stable in terms of protein content. The WTOP3 index was used to estimate the adaptability of the particular variety. The Amiata variety had the highest adaptability for yield, the Ambella variety had full adaptability for fat content, and the Aurelina variety had the highest adaptability for protein content. Additionally, the Abelina, Ambella, and Aurelina varieties had the lowest values in the GSI index for yield, fat content, and protein content, respectively. Thus, one can draw a conclusion that the Abelina, Ambella, and Aurelina varieties should be recommended.

The Obelix variety was an unusual case, as it had high mean results for both yield and protein content (ranked 2nd for both) and it had intermediate adaptability (0.48 for yield and 0.43 for protein content) to agro-meteorological conditions in Northern Poland, despite having low stability.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agronomy13122879/s1>, Table S1: Mean temperatures in eight experimental sites in the years 2020–2022.; Table S2: Monthly sums of precipitation (mm) in eight experimental sites in the years 2020–2022; Table S3: Soil characteristics in eight experimental sites in the years 2020–2022.

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Abbreviations

The following abbreviations are used in this manuscript:

AMMI	additive main effects and multiplicative interaction model
AMMI κ	AMMI model with $\kappa > 0$ multiplicative terms
V	variety
E	environment
V $\times$ E	variety–environment interaction
D.F.	degrees of freedom
S.S.	sum of squares
M.S.	mean square
IPC	interaction principal component
WAAS	weighted average absolute score
GSI	genotype selection index

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