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Multi-trait evaluation of oilseed rape varieties

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Abstract: The multifaceted nature of agricultural management and environmental factors complicates the production of winter oilseed rape (*Brassica napus* L.). This study evaluated 25 varieties (21 hybrids and four populations) in three growing seasons (2020/21, 2021/22 and 2022/23) in Poland. The focus was on yield, fat content, and resistance to *Sclerotinia sclerotiorum*. The analyses revealed significant variability among the varieties, with the hybrids performing better consistently in terms of yield and fat content. The level of resistance to *Sclerotinia* was similar in hybrid and population varieties. Furthermore, DK Excited was found to be the highest-yielding variety, while Duke had the highest fat content. Derrick was the most resistant to *S. sclerotiorum*. Advocat and Dynamic were identified as the best varieties. In the analysed series of field trials, yield was found to be affected by high temperatures and a lack of rainfall in March, June, and July. For fat content, a lack of rainfall in July was the main limiting factor.

Keywords: multiple character analysis; comparison of hybrids with population varieties; Shukla's stability variance

Winter oilseed rape (*Brassica napus* L.) plays a crucial role in agriculture and industry worldwide, serving as a major source of edible oil and biofuel. At the same time, the middlings and oilcake produced after extraction can be used as high-protein animal feed. It is one of the world's most important oilseed crops, ranking second only to soybeans in terms of area and production. With the increasing importance of rapeseed products in the global industry, there is a growing interest in rapeseed cultivation and breeding. In recent years, many agronomists have been studying crop rotation, fertilisation and cultivation techniques for oilseed rape (Jankowski et al. 2016, Stepien et al. 2017, Béreš et al. 2019, Krček et al. 2019, Bečka et al. 2024). Many studies have shown that oilseed rape productivity is highly dependent on environmental conditions, such as temperature, rainfall, and soil fertility (see, e.g., Wójtowicz 2013, Brown et al. 2019), making it difficult to predict and optimise yields. Brown et al. (2019) showed that higher early winter temperatures can lead to lower yields, highlighting the need to develop varieties that are tolerant to climate variability and resistant to environmental stresses such as drought or nutrient deficiencies.

At the same time, plant breeders have focused on enhancing the performance of varieties in different environmental conditions (Würschum et al. 2012, Fletcher et al. 2015, Werner et al. 2018) and their resistance to biotic stresses. Chen et al. (2021) investigated the impact of drought stress during the early reproductive stage on pod and seed development. In a separate study, Chandra Gupta et al. (2025) reviewed the advances in understanding resistance mechanisms. Meanwhile, Hervé (2018) described the challenges and current knowledge surrounding the

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breeding of insect-resistant oilseed rape. In many oilseed rape breeding programmes, key traits include yield, fat content and resistance to diseases (including *Sclerotinia sclerotiorum*) and insects. Bocianowski and Lierch (2021) aimed to identify lines with the best yield performance, whereas Liersch et al. (2024) focused on selecting promising lines for seed quality traits. In an Iranian study, Alizadeh et al. (2020) assessed the yield stability of winter oilseed rape lines in cold regions, while Chen et al. (2014) evaluated the yield and agronomic traits of 488 global collections of *B. napus*. More recently, Holzenkamp et al. (2022) studied the effect of low lignin on yield and quality traits, and Yusuf and Möllers (2024) investigated the inheritance of cellulose, hemicellulose, and lignin content in relation to seed oil and protein content in oilseed rape.

The current study aimed to evaluate the yield and quality traits, as well as the *Sclerotinia* resistance, of 25 winter oilseed rape varieties (of which over one third were also registered in the Czech Republic). These varieties were grown over three seasons: 2020/21, 2021/22 and 2022/23. For this purpose, mixed model analyses and stability measures were employed to identify the varieties that performed best in terms of yield, fat content, and resistance to *Sclerotinia*. The adoption of molecular tools, such as marker-assisted selection and genomic prediction, by breeding companies has accelerated the identification of elite lines in Europe and worldwide (Spasibionek et al. 2020, Lin et al. 2024). The growing number of hybrid varieties registered with variety offices worldwide reflects this trend. In Poland, 13 varieties were registered in 2010, seven of which were hybrids. In 2024, only two of the 21 registered varieties were population varieties. By the end of 2024, a total of 147 oilseed rape varieties had been registered, of which only 17 were population varieties. Currently, over 85% of registered and cultivated oilseed rape varieties in Poland are hybrids, while population varieties account for less than 15% (COBORU Data 2024). For this reason, the performance of hybrids and population varieties has been examined using a unifying mixed model approach. Furthermore, stability analyses of yield and fat content were complemented by the genotypic confidence index introduced by Annicchiarico (1992), which enabled the identification of favourable and unfavourable environments. Using this index, we identified the agrometeorological factors that influence yield and fat content in the Polish post-registration field trial series conducted over three growing seasons. Finally, we demonstrated the application of the generalised exponential transformation to real data.

This study aimed to compare hybrid and population varieties in terms of yield, fat content and resistance to *Sclerotinia*, to assess their stability across environments, and to identify key environmental factors influencing these traits.

MATERIAL AND METHODS

Field experiments and data collection. The datasets comprised winter oilseed rape trials conducted during the 2020/21, 2021/22 and 2022/23 growing seasons. These trials were conducted at experimental stations affiliated with the Research Centre for Cultivar Testing (COBORU) and its partner institutions (Figure 1). A total of 30 distinct locations were included in the analysis. The sites were mainly located in the western part of Poland, where oilseed rape is grown (Figure 1). A list of the sites used in the present study, along with their geographical coordinates and the years they were used, is provided in Table 1.

Each trial was laid out in a 1-resolvable design with three replicates. Depending on the number of varieties tested, there were 5 or 6 blocks within each replicate. During the three growing seasons, the plot sizes varied from 10 m^2 to 16.5 m^2, depending on the site. At each site, the plots were harvested using a plot harvester. The oilseed rape varieties were sown according to best agricultural practice. The sowing dates for each site are provided in Table 1.

In each growing season, approximately 60 varieties from the National List (NL) and the Common Catalogue of Agricultural Plants (CCA) were tested. During the three growing seasons, 25 common varieties were observed. These were: Absolut, Advocat, Akilah, Ambassador, Artemis, Astana, Aurelia, Batis, Crotora, Derrick, DK Excited, DK Exima, Dominator, Duke, Dynamic, Gemini, Herakles, Kwazar, LG Anarion, LG Areti, LG Aviron, Mars, Temptation, Trezzor and Umberto KWS. Except for the five varieties of USA and Polish origin (DK Excited, DK Exima, Gemini, Kwazar and Mars), all the others were bred in Germany and France. Most of the varieties were registered in Poland between 2018 and 2020. Three of the tested varieties were registered elsewhere. Of the 25 varieties, only four were population varieties: Derrick, Gemini, Kwazar and Mars. The rest were hybrids.

According to the methodology used in post-registration trials, yield was observed in plots. For each

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trial, the plot yields were recalculated to contractual conditions, i.e., with a moisture content of 9%. The observed yields were expressed in tonnes per hectare (t/ha).

For each variety, the fat content is the mean of two samples. Each sample of fat content is expressed as a proportion of dry matter content (%). In each sample, fat content was determined using the Soxhlet method. Seed oil is extracted from dried seeds using a solvent such as ethyl ether. After the solvent has evaporated, alkaline hydrolysis takes place. The fatty acids released from the glycerides are then converted into methyl esters. The resulting esters are then analysed by gas chromatography. Fat content was measured only in chosen sites. The sites, in which fat content was measured, are marked with † in Table 1. This limitation arose from logistical and economic constraints, given that the Research Centre for Cultivar Testing has only one central laboratory equipped with the necessary facilities and staff trained in conducting standardised Soxhlet extractions.

Resistance to *Sclerotinia sclerotiorum* (Sclerotinia) was assessed by crop experts using the BBCH code (Hack et al. 1992). The measurements were taken at the BBCH 70–85 growth stage (when the first pods have reached their typical size, approximately 50% of the pods contain brown and hard seeds). Observations of pathogen infestation were made at several points in the canopy. To determine the percentage of diseased plants, those with heavily infested main shoots and first-order branching were considered the primary focus. Resistance to *Sclerotinia sclerotiorum* was measured as a percentage of plot area infected by the fungus.

Statistical analysis. The observations in the Sclerotinia data set represented the proportions of plot area infected by the fungus *Sclerotinia sclerotiorum*. Such values can be treated as continuous proportions. In our dataset, the proportions ranged from 0 to 0.9. Continuous proportions, when they differ from 0 and 1, follow a Beta distribution (Stroup 2015). However, a problem arises when proportions take values equal to 0 and/or 1. To address this issue, we applied the generalised exponential transformation proposed by Malik and Piepho (2016):

$$y = \operatorname{sgn}(z) g(z, \phi) \tag{1}$$

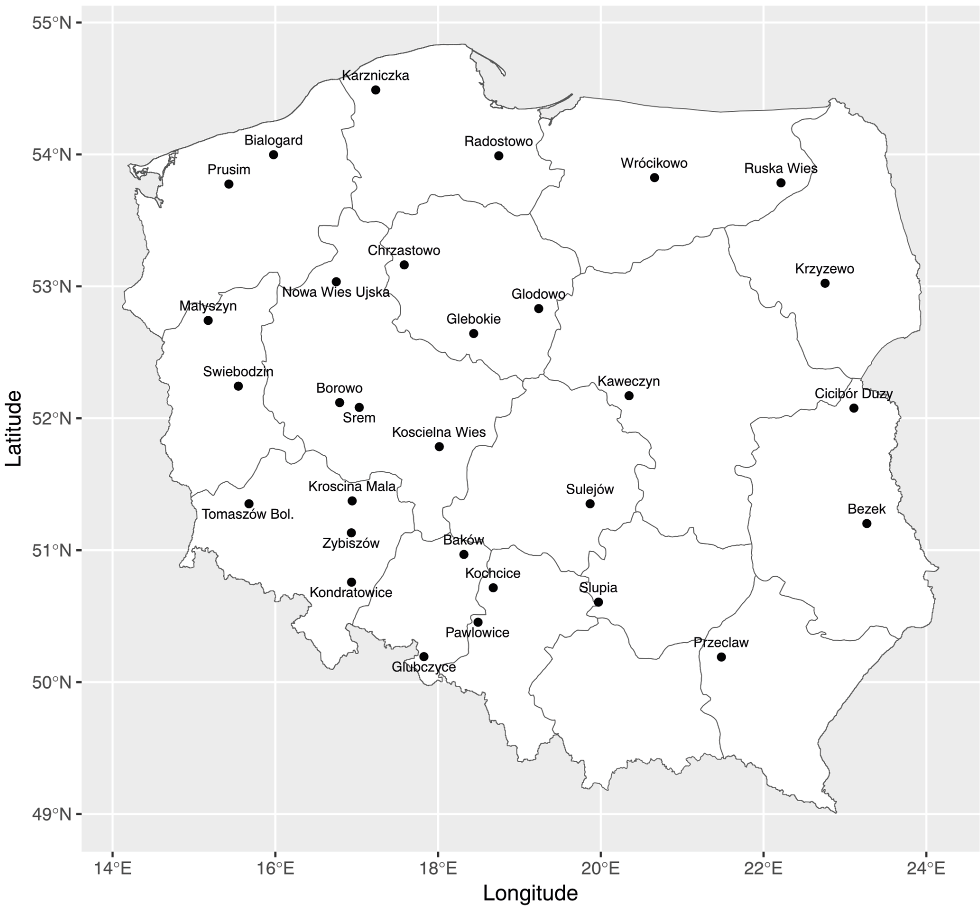

Figure 1. Map of Poland showing the locations of the experimental sites

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Table 1. Sowing dates and sites were used in the oilseed rape trials conducted in the growing seasons 2020/21–2022/23

Site	Sowing date			Geographical co-ordinates		
	2020/21	2021/22	2022/23	latitude	longitude	(m a.s.l.)
Bąków	26. 08	28. 08	30. 08	50°57'N	18°18'E	175–190
Bezek	31. 08	08. 09	26. 08	51°11'N	23°15'E	224
Białogard	01. 09	01. 09	30. 08	54°00'N	16°00'E	24
Borowo	09. 09	03. 09	31. 08	52°07'N	16°45'E	71
Chrząstowo	24. 08†	25. 08†	27. 08†	53°11'N	17°35'E	105
Cicibór Duży	02. 09	03. 09	01. 09	52°05'N	23°07'E	114
Głębokie	09. 09	06. 09	01. 09	52°39'N	18°27'E	85
Głodowo	08. 09	29. 08	30. 08	52°50'N	19°15'E	100
Głubczyce	28. 08†	14. 09†	31. 08†	51°11'N	16°50'E	280
Karżniczka	01. 09	01. 09	01. 09	54°29'N	17°14'E	80
Kawęczyn	26. 08	28. 08	31. 08	52°10'N	20°21'E	90
Kochcice	04. 09	08. 09	01.09	50°42'N	18°42'E	280
Kondratowice	24. 08	04. 09	02.09	50°46'N	16°56'E	167
Kościelna Wieś	04. 09	07. 09	01. 09	51°48'N	18°01'E	120
Krościna Mała	27. 08	25. 08	31. 08	51°22'N	16°57'E	106
Krzyżewo	09. 09	25. 08	31. 08	53°01'N	22°46'E	135
Małyszyn	29. 08	29. 08	02. 09	52°44'N	15°10'E	19–105
Nowa Wieś Ujska	29. 08	25. 08	26. 08	53°02'N	16°45'E	105
Pawłowice	26. 08	03. 09	31. 08	50°28'N	18°29'E	240
Prusim	04. 09	01. 09	02. 09	53°46'N	15°26'E	55
Przecław	28. 08	06. 09	26. 08	50°11'N	21°29'E	185
Radostowo	09. 09	27. 08	30. 08	53°59'N	18°45'E	40
Ruska Wieś	26. 08†	24. 08†	30. 08†	53°53'N	22°28'E	130
Słupia	26. 08†	08. 09†	27. 08†	50°38'N	19°58'E	290
Sulejów	05. 09	04. 09	01. 09†	51°21'N	19°52'E	188
Śrem	28. 08	07. 09	30. 08	52°05'N	17°02'E	76
Świebodzin	27. 08	06. 09	29. 08	52°14'N	15°35'E	90
Tomaszów Bol.	05. 09	01. 09	01. 09	51°17'N	15°41'E	200
Wrócikowo	26. 08	25. 08	25. 08	53°49'N	20°40'E	142
Zybiszów	28. 08†	27. 08†	31. 08	51°04'N	16°55'E	130

†Fat content was measured

where: x – observed proportion; $z = x - 0.5$, sgn(z), ϕ – sign-function taking value 1 if $z > 0$, 0 if $z = 0$ and 1 if $z < 0$, and g(z,ϕ) is defined as:

$$g(z,\phi) = \begin{cases} \frac{(\exp(\phi|z|-1))}{\phi} & \phi \neq 0 \\ |z| & \phi = 0 \end{cases}$$

Since the parameter ϕ is generally unknown, we used the R function provided by Malik and Piepho (2016) to estimate its optimal value. To obtain means in the original scale, the following back-transform was used:

$$x = 0.5 + (\text{sgn}(y)\log(1 + \phi|y|))/\phi \qquad (2)$$

where: $\log(a)=\log_e(a)$.

In the literature, such data are analysed either by taking 0 for continuous data at [0,1] by left censoring a latent random variable at 0 (Chib 1992), or by using the zero-inflated beta model Ospina and Ferrari (2010, 2012) or Tang et al. (2023). Both approaches are difficult to implement. The main advantage of the approach used in this study was that it is relatively simple and attractive to non-statisticians who are familiar with linear models, but less familiar with the various extensions of generalised linear mixed models. In addition, Malik and Piepho (2016) pro-

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vided a function for finding the optimal ϕ, which facilitates the implementation of this transformation in R. They also demonstrated that this transformation can be applied to binomial data as an alternative to the often-criticised arcsine transformation (Warton and Hui 2011).

All three data sets were modelled using mixed models, depending on whether a given trait was plot-based or variety-based (i.e., a single measurement for a variety in a given environment). Let y_{ijkl} be the value of the observed trait f or the i-th (i = 1,..., I) variety at the j-th (j = 1,...,J) environment (a combination of year and location) in the k-th (k = 1, ..., K) replicate and the l-th (l = 1,..., L) block, whereas y_{ij} denote the observed trait for the i-th variety in the j-th environment. Then, the model for plot data can be written as:

$$y_{ijkl} = \mu + \alpha_i + u_j + v_{ij} + \\ + w_{jk} + z_{jkl} + e_{ijkl} \quad (3)$$

where: μ – general mean and α_i – fixed variety effect. By u_j, v_{ij}, w_{jk}, z_{jkl} and e_{ijkl}, we denote in (3) the random effect of environments (E), of variety × environment interaction (G × E), of replicates (E × Rep) nested within environments, of blocks nested within replicates and environments (E × Rep × Block), and of errors, respectively. Using the same notation as in model (3), the model for y_{ij} can be written as:

$$y_{ij} = \mu + \alpha_i + u_j + e_{ij} \quad (4)$$

In both models, we assumed that all random effects follow a normal distribution with zero mean and variance σ_m^2 ($m = u, v, w, z, e$), i.e. $u_j \sim N(0, \sigma_u^2)$, $v_{ij} \sim N(0, \sigma_v^2)$, $w_{jk} \sim N(0, \sigma_w^2)$, $z_{jkl} \sim N(0, \sigma_z^2)$, $e_{ijkl} \sim N(0, \sigma_e^2)$ and $e_{ij} \sim N(0, \sigma_e^2)$.

Model (3) included all random effects. For fat content, the reduced model (4) was applied, since for this trait, a single measurement per variety and environment was taken (not in all environments; Table 1). This specification better reflected the data structure and ensured model identifiability.

In both models, variance components were estimated using the restricted maximum likelihood algorithm (REML) (Searle et al. 2006) under the restriction alpha sub 1 equals 0 (numerical implementation of the lme4 package, Bates et al. 2015). Next, using these estimates, the fixed effects were estimated by generalised least squares. To test a null hypothesis

$$H_0: \alpha_1 = \alpha_2 = ... = \alpha_I = 0 \quad (5)$$

An approximate F-test was used. The test statistic has an approximate P distribution with numerator degrees of freedom (*ndf*) equal to $I - 1$ and denominator degrees of freedom (*ddf*) calculated using the Kenward-Roger approximation (1997) (numerical implementation 'pbkrtest', Halekoh and Højsgaard 2014). To obtain all pair-wise comparisons at significance level α, we used functions emmeans from 'emmeans' package (Lenth 2024) and cld from 'multcomp' package (Hothorn et al. 2008) with letters display Piepho (2004). To adjust critical probability values for the t-statistic that account for the number of comparisons being made, we used the Bonferroni multiple testing procedure (Shaffer 1986). For this purpose, we set in the cld function Letters = letters and p.adjust = "Shafer", and default significance level α = 0.05. For *Sclerotinia*, all pair-wise comparisons were performed on the transformed data.

Among the 25 tested varieties, there were two groups: hybrid and population varieties. The latter group included varieties such as Derrick, Gemini, Kwazar, and Mars. In this study, we aim to compare these two groups. Therefore, after fitting models (3) and (4), the difference between the two group means was tested with a simple contrast hypothesis, i.e. for each trait, the following null hypothesis was tested:

$$H_0: \frac{\sum_{i=1}^{4} \mu_i}{4} = \frac{\sum_{i'=1}^{21} \tilde{\mu}_{i'}}{21} \quad (6)$$

where: μ_i – population variety means, whereas $\tilde{\mu}_i$' denote variety means of the hybrid varieties. The significance of the null hypothesis (6) was assessed using a t-test. For *Sclerotionia*, the t-test was performed on transformed data.

To assess the variety stability of each study trait, Shukla's stability variances (Shukla 1972) were calculated using the Shukla function implemented in the 'metan' R package (Olivoto and Lúcio 2020). Varieties with the smallest Shukla's stability variance tend to be more stable.

Next for each trait, all varieties were ranked based on the estimated variety means and Shukla's stability variances. To combine the two rankings, a simultaneous selection index was used:

$$SSI_i = RM_i + RS_i \quad (7)$$

where: RM_i – rank of the trait mean and RS_i – rank of Shukla's stability score for the i-th genotype. The varieties with the lowest rank sum are the most desirable. For each trait, the top ten varieties in terms of the SSI index were selected, and a Venn diagram was used to select the best-performing variety according to all studied traits.

Finally, a risk analysis was conducted to assess the yield and fat content. These two traits are the most important for farmers and industry. For this

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purpose for each trait, first the variety means $\bar{y}_{ij}$ in the j-the environment were expressed as a percentage of the environmental mean $\bar{y}_i$ (Y_{ij}), from which the mean Y_i and the standard deviation S_i (stability) of the i-th variety were calculated. Then, using the values Y_i and S_i, the genotypic confidence index (GCI, Annicchiarico 1992) was calculated as:

$$GCI_i = Y_i + Z(1 - \alpha)S_i \quad (8)$$

where: Z(1 – α) – quantile of order 1 – α from the standard normal distribution. In this study, the GCI index values were calculated for α = 0.05. This index has a similar form to Eskridge's safety-first rule (Eskridge 1990). As in Eskridge (1990), varieties with the highest GCI index values are preferred. Moreover, for each trait, environments were classified as favourable (GCIf) or unfavourable (GCIu) depending on whether their environmental index was positive or negative. The environmental index was defined as the difference between the mean yield in a given environment and the overall mean yield across all environments ($\bar{y}_j - \bar{y}_{...}$). If the environmental index was negative, the environment was classified as unfavourable; otherwise, it was classified as favourable. This classification reflects relative environmental productivity and was used in calculating the genotypic confidence index (GCI) for yield and fat content. The classification and GCI values were obtained using the *Annicchiarico*() function implemented in the 'metan' R package (Olivoto and Lúcio 2020), with a significance level of α = 0.05.

RESULTS AND DISCUSSION

The optimal ϕ value was estimated at 4.14 using the R function of Malik and Piepho (2016),

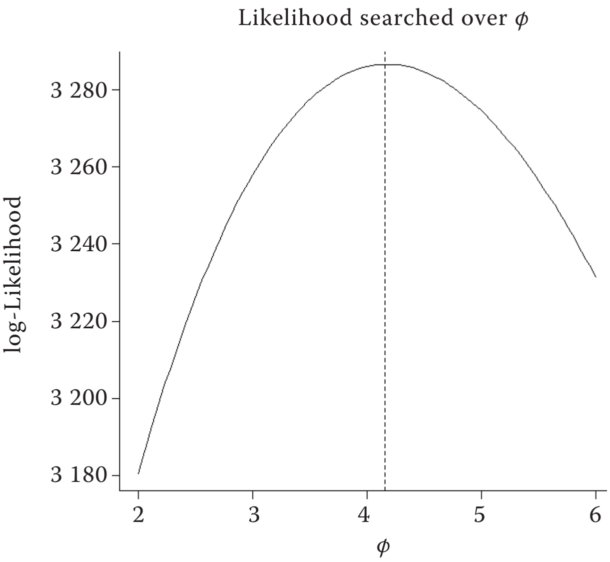

Figure 2. Profile log-likelihood (log(L)) with the generalised exponential transformation

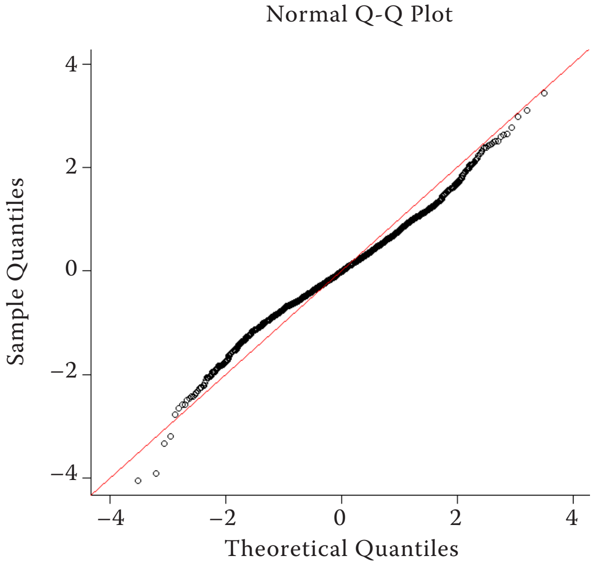

Figure 3. Diagnostic plot for transformed *Sclerotinia* data set

as indicated by the profile likelihood in Figure 2, where the vertical dashed line marks the optimum. This value was then applied to transform the *Sclerotinia* data using the generalised exponential transformation (1).

All traits were subjected to models (3) and (4). The analyses provided several estimated parameters and statistics (Tables 1–5). The estimates of variance components for each trait are reported in Table 1.

For all analysed traits, the highest estimates of variance components were obtained for environments. This means that environments explain most of the observed variability in all datasets. Furthermore, for plot traits, the variance components for G × E interaction were the second highest. Moreover, one can observe that for all plot traits, the variance components for replicates nested within environments and block nested within replicates and environments were approximately equal. Finally, we checked the normality of the errors assumption for the trans-

Table 1. Estimated variance components for analysed traits

Variance component	Yield	Fat content	*Sclerotinia*
E	0.819	3.387	0.167
G × E	0.091	–	0.027
E × Rep	0.014	–	0.001
E × Rep × Block	0.016	–	0.005
Error	0.063	0.526	0.033

E – environment; G – variety; Rep – replicates

https://doi.org/10.17221/337/2025-PSE

Table 2. Significance of variety effects

Trait	MS	*ndf*	*ddf*	*F*-stat	*P*-value
Yield	5.30	24	1 894.7	83.676	< 0.001
Fat	13.93	24	336.0	26.502	< 0.001
Sclerotinia	0.25	24	694.4	7.758	< 0.001

MS – mean square; *ndf* – numerator degrees of freedom; *ddf* – denominator degrees of freedom

Table 3. Comparisons of hybrids *vs*. population varieties

Trait	Mean		*P*-value
	hybrid varieties	population varieties	
Yield (t/ha)	4.84	4.13	< 0.001
Fat content (%)	48.24	47.03	< 0.001
Sclerotinia (%)	12.68	12.70	0.995

formed *Sclerotinia* data set. For this purpose, the expected normal quantiles were plotted against the standardised residuals (Figure 3). It can be seen that most of the points on the plot are located along the = *x*-axis. Only a few points in the lower left corner deviated slightly from this line. This means that the assumption of normality of errors was quite well met.

Yield and fat content

Yield and fat content were analysed using models (3) and (4), respectively. The values of the approximate *F*-statistics used to test the significance of variety effects are reported in Table 2. It can be observed that for both traits, the null hypothesis (5) was rejected ($P < 0.001$). This means that for each trait, the variety means differed significantly.

Among the 25 tested varieties, there were two groups: hybrid and population varieties. Therefore, after fitting models (3) and (4), the differences between the two-group means were tested. The results are given in Table 3.

The grain yield was approximately 0.7 t/ha lower for population varieties than for hybrids. This finding is consistent with the results obtained for winter rye (Ghafoor et al. 2024) and winter wheat (Buczek et al. 2016). In a long-term study on winter rye, Laidig et al. (2017) have shown that the mean yields for hybrids were three times higher than the mean for population varieties. Furthermore, hybrid varieties outperformed population varieties in terms of fat content, indicating their higher agronomic and production potential (Table 3). However, to confirm this trend, a larger dataset with a greater number of varieties and a longer time horizon is required. In the UK study (Mackay et al. 2011), the annual genetic gain amounted to 0.091% between 1979 and 2007. In contrast, a German study (Laidig et al. 2014) reported an annual genetic gain of 27.2 kg/ha for oil yield between 1983 and 2012. In the latter study, the genetic trend was estimated without distinction between hybrid and population varieties.

In columns 2 and 8 of Table 4, variety means for yield and fat content are reported, respectively. One can observe that DK Excited variety was the highest yielding variety among the tested varieties (column two of Table 4). This variety was also the highest-yielding variety among the hybrid varieties. The second-best yielding variety was LG Aviron. On the other hand, variety Derrick was the highest yielding variety among the population varieties and was ranked 22nd overall. The highest fat content was obtained for the variety Duke. This variety was also the best among the hybrid varieties. The second-highest fat content was observed for the variety Dynamic. The highest-yielding variety (DK Excited) was ranked seventh. For population varieties, the highest fat content was observed for variety Kwazar. This variety was ranked 11th overall, whereas the highest-yielding population variety was ranked 13th.

In columns three and nine of Table 4, the values of Shukla's stability variances for yield and fat content are reported, respectively. For the yield, the lowest value of Shukla's stability variance was obtained for the variety Dynamic. This means that this variety was the most stable among the tested varieties. For population varieties, Gemini was the best in terms of Shukla's stability variance and was ranked 12 overall. The highest-yielding variety (DK Excited) was ranked seventh, whereas the second-yielding variety (LG Aviron) was ranked fourth. Comparing the Shukla's stability variances for fat content, one can observe that the highest yielding variety, Derrick, was the most stable among the tested varieties. Varieties Duke (variety with the highest fat content among the tested varieties) and Kwazar (variety with the highest fat content among the population varieties) were ranked seventh and eleventh in terms of Shukla's stability variance. Variety, with the second-highest fat content, was ranked 19.

The values of the simultaneous selection index for yield, fat content, *Sclerotinia*, TGW and plant height are reported in columns four, ten of Table 4,

https://doi.org/10.17221/337/2025-PSE

Table 4. Estimated variety means, Shukla's stability variances, simultaneus selection indices (SSI), and genotypic confidence indices (GCI) values for yield and fat content

Variety	Yield						Fat content					
	mean (t/ha)	Shukla's var	SSI	GCI	GCIf	GCIu	mean (%)	Shukla's var	SSI	GCI	GCIf	GCIu
Absolut	5.00^{cdef} [8]	0.107 [8]	16	93.1 [7]	93.5 [8]	92.8 [7]	46.8^{fgh} [23]	0.411 [10]	33	95.3 [20]	95.7 [21]	95.3 [19]
Advocat	4.74^{gh} [17]	0.089 [3]	20	87.8 [15]	89.9 [15]	85.4 [16]	48.3^{abcd} [12]	0.365 [9]	21	98.5 [10]	98.2 [12]	98.6 [13]
Akilah	5.00^{cdef} [7]	0.113 [14]	21	92.5 [8]	94.2 [7]	90.3 [10]	48.9^{ab} [8]	0.462 [12]	20	99.5 [9]	98.4 [11]	101.0 [2]
Ambassador	5.12^{abcd} [5]	0.101 [6]	11	95.3 [5]	96.8 [4]	94.2 [5]	47.7^{defg} [18]	0.292 [5]	23	96.7 [16]	98.4 [10]	96.3 [16]
Artemis	5.18^{abc} [4]	0.117 [16]	20	95.8 [4]	96.1 [5]	95.8 [4]	48.3^{bcde} [13]	0.355 [8]	21	98.4 [11]	98.9 [7]	98.6 [12]
Astana	4.60^{hi} [18]	0.089 [2]	20	84.9 [18]	88.4 [17]	81.4 [19]	49.2^{ab} [3]	0.621 [14]	17	99.6 [7]	98.7 [9]	**101.1 [1]**
Aurelia	5.06^{bcde} [6]	0.100 [5]	11	94.2 [6]	94.7 [6]	93.4 [6]	47.4^{cdefg} [17]	0.633 [15]	32	96.0 [18]	96.6 [17]	95.4 [18]
Batis	4.96^{def} [9]	0.141 [21]	30	90.7 [11]	92.3 [11]	88.7 [12]	49.2^{ab} [4]	0.174 [3]	**7**	100.9 [2]	100.9 [2]	100.7 [5]
Crotora	4.46^{ij} [21]	0.127 [19]	40	80.6 [21]	81.3 [21]	79.6 [20]	49.0^{ab} [6]	0.098 [2]	8	100.8 [3]	100.7 [3]	100.8 [4]
Derrick	4.34^{jk} [22]	0.126 [18]	40	77.7 [22]	80.4 [22]	74.7 [22]	46.2^{h} [25]	0.483 [13]	38	93.7 [25]	94.8 [23]	93.1 [25]
DK Excited	**5.30^{a} [1]**	0.103 [7]	8	**99.7 [1]**	**100.0 [1]**	**99.8 [2]**	49.0^{ab} [7]	**0.048 [1]**	8	**101.1 [1]**	**101.1 [1]**	101.0 [3]
DK Exima	4.96^{def} [10]	0.124 [17]	27	91.8 [9]	91.2 [14]	92.6[8]	47.2^{fg} [20]	0.633 [16]	36	95.6 [19]	96.6 [18]	95.1 [21]
Dominator	4.84^{fg} [16]	0.109 [9]	25	87.8 [16]	93.0 [10]	82.7 [17]	49.1^{ab} [5]	0.653 [17]	22	99.5 [8]	99.2 [6]	99.6 [9]
Duke	4.89^{efg} [11]	0.109 [11]	22	90.2 [12]	92.3 [12]	87.9 [13]	49.3^{a} [1]	0.348 [7]	8	100.5 [4]	100.4 [5]	100.4 [7]
Dynamic	4.88^{efg} [12]	**0.083 [1]**	13	91.4 [10]	93.1 [9]	89.2 [11]	**49.3^{a} [2]**	0.664 [19]	21	99.7 [6]	98.8 [8]	100.5 [6]
Gemini	4.16^{kl} [24]	0.114 [15]	39	74.6 [24]	76.4 [23]	72.4 [25]	47.6^{cdefg} [16]	0.684 [20]	36	96.3 [17]	96.2 [19]	96.2 [17]
Herakles	4.59^{hi} [19]	0.158[25]	44	82.0 [19]	81.7 [20]	82.5 [18]	48.9^{ab} [9]	0.215 [4]	13	100.1 [5]	100.5 [4]	99.7 [8]
Kwazar	4.13^{l} [25]}	0.112 [12]	37	74.7 [23]	76.3 [24]	72.8 [24]	47.7^{cdef} [15]	0.460 [11]	26	97.0 [15]	97.4 [16]	96.8 [15]
LG Anarion	4.86^{fg} [13]	0.113 [13]	26	89.4 [13]	91.6 [13]	86.8 [15]	47.3^{efg} [19]	1.11 [25]	44	94.9 [21]	95.9 [20]	94.0 [24]
LG Areti	5.24^{ab} [3]	0.109 [10]	13	98.7 [3]	98.4 [3]	99.2 [3]	47.7^{cdef} [14]	0.306 [6]	20	97.4 [14]	97.5 [15]	97.6 [14]
LG Aviron	5.27^{a} [2]	0.092 [4]	**6**	99.4 [2]	98.6 [2]	**101.0 [1]**	46.9^{fgh} [21]	0.653 [18]	39	94.8 [22]	95.6 [22]	94.3 [23]
Mars	4.17^{kl} [23]	0.151[23]	46	74.3 [25]	74.3 [25]	74.1 [23]	46.6^{gh} [24]	0.908 [23]	47	93.9 [24]	92.7 [25]}	95.2 [20]
Temptation	4.84^{fg} [15]	0.142 [22]	37	88.7 [14]	87.3 [18]	90.4 [9]	48.7^{ab} [10]	0.979 [24]	34	98.1 [12]	97.9 [13]	99.2 [11]
Trezzor	4.57^{hi} [20]	0.155 [24]	44	81.6 [20]	83.4 [19]	79.4 [21]	48.4^{abc} [11]	0.705 [21]	32	98.0 [13]	97.5 [14]	99.2 [10]
Umberto KWS	4.84^{fg} [14]	0.141 [20]	34	87.1 [17]	89.0 [16]	87.5 [14]	46.9^{fgh} [22]	0.877 [22]	44	94.4 [23]	94.7 [24]	94.8 [22]

[a]Means not sharing any letter are significantly different at the 5% level of significance. Bold values indicate the best-performing varieties, while italicised values denote the poorest-performing ones. GCIf – genotypic confidence index for favorable environments; GCIu – genotypic confidence index for unfavorable environments

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respectively. One can observe that the variety LG Aviron had the lowest value of the SSI index. This means that this variety was the highest-yielding and most stable among the tested varieties. The SSI index for the highest-yielding amount was 8 and was the second lowest. This means that these two varieties were the most desirable for cultivation in terms of yield. For the most stable variety, the index was equal to 13. For fat content, the lowest value of the SSI index was obtained for variety Batis. Furthermore, it can be seen that for Crotora, DK Excited and Duke varieties, the values of the SSI index were equal and were the second lowest.

The values of the genotypic confidence indices for yield and fat content are shown in columns five and eleven of Table 4. In addition, for each trait, the environments were divided into two distinct groups: favourable and unfavourable environments. The GCI indices were then calculated for each group and trait. For yield, the results are presented in columns 6 to 7 of Table 4, and for fat content, in columns 12 to 13. In the case of yield, the highest value of the GCI index was obtained for variety DK Excited. This variety was also the best in terms of GCI in favourable environments and the second best in unfavourable environments. The opposite was observed for the variety LG Aviron. This variety was the second best in all environments, the best in favourable environments, and the worst in unfavourable environments. On the other hand, the most stable variety (Dynamic) obtained similar ranks in both favourable and unfavourable environments as in the initial ranking. Furthermore, it can be noted that the varieties Aurelia, Derrick, and LG Areti were ranked the same, regardless of whether the GCI index was calculated for all environments, favourable environments, or unfavourable environments. A different pattern was observed for fat content. Variety DK Excited had the highest value of the GCI index. This variety was also the best in favourable environments and third in unfavourable environments. The highest value of the GCI index in unfavourable environments was obtained for variety Astana. Furthermore, for both traits, the estimates of the genotypic confidence indices were supplemented by the lists of the names of the favourable and unfavourable environments. The environments were classified into one of two groups based on the value of the environmental index. If the environmental index was negative, the environment was classified as unfavourable; otherwise, it was classified as favourable. For clarity, only the classification of environments for fat content and the corresponding classification of environments for yield are shown in Table 5.

For yield, among 80 environments, 35 were classified as unfavourable. Depending on the environment, the yields in unfavourable environments were less than the overall mean, and the difference varied from –2.35 t/ha (23KW) to –0.04 t/ha (21Gle). For favourable environments, the difference varied from 0.02 t/ha (21Sr) to 1.94 t/ha (22RW). In the case of fat content, eight out of 15 environments were classified as unfavourable (Table 6). The rest was classified as favourable. In unfavourable environments, the difference between environmental means and the general mean varied from –4.05% (22Zyb) to –0.17% (21RW). In favour, the difference varied from 0.21% to 3.2%. Now, when we compare the environments in which fat content was assessed, we can see that environment 22Zyb was classified as unfavourable for both yield and fat content. In contrast, environments 22Glu, 22RW, 23Glu, 23RW, 23Slu and 23Sul were classified as favourable for both traits (Table 5). A different pattern emerges for environments 21Ch, 21Glu, 21RW, 21Slu, 21Zyb, 22Ch, 22Slu and 22Zyb (Table 5). These environments were classified as

Table 5. Classification of environments for fat content, and corresponding classification of environments for yield

Trait	Favourable environment	Unfavourable environment
	21Ch, 21Glu, 21RW, 21Slu, 21Zyb	–
Yield	22Ch, 22Glu, 22RW, 22Slu	22Zyb
	23Glu, 23RW, 23Slu, 23Sul	23Ch
	–	21Ch, 21Glu, 21RW, 21Slu, 21Zyb
Fat content	22Glu, 22RW	22Ch, 22Slu, 22Zyb
	23Ch, 23Glu, 23RW, 23Slu, 23Sul	–

[a]Abbreviations for environments refer to the year (e.g., 21 means 2021) and to the following sites: Ch – Chrzastowo; Glu – Głubczyce; RW – Ruska Wieś; Slu – Słupia; Zyb – Zybiszów

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Table 6. Estimated variety means, Shukla's stability variances, and simultaneus selection indices (SSI) values for *Sclerotinia*

Variety	Mean[a]	Back-transformed mean (%)	Shukla's var	SSI
Absolut	–0.729[ab] [24]	16.5	0.047 [19]	43
Advocat	–0.995[fg] [6]	10.6	0.041 [14]	20
Akilah	–0.980[efg] [9]	10.9	0.038 [12]	21
Ambassador	–0.743[ab] [23]	16.1	0.024 [2]	25
Artemis	–0.838[abcdef] [19]	13.9	0.042 [15]	34
Astana	–0.998[fg] [5]	10.6	0.053 [23]	28
Aurelia	–0.868[abcdefg] [18]	13.3	0.047 [20]	40
Batis	–0.952[defg] [10]	11.5	0.042 [16]	26
Crotora	–0.999[fg] [4]	10.6	0.026 [4]	**8**
Derrick	**–1.032[g] [1]**	**9.9**	0.035 [9]	10
DK Excited	–0.884[bcdefg] [15]	12.9	0.075 [25]	40
DK Exima	–0.939[cdefg] [11]	11.8	0.035 [10]	21
Dominator	–1.028[g] [2]	10.0	0.032 [7]	9
Duke	–0.893[bcdefg] [13]	12.7	0.026 [3]	16
Dynamic	–1.016[fg] [3]	10.2	0.043 [17]	20
Gemini	–0.881[abcdefg] [16]	13.0	0.039 [13]	29
Herakles	–0.983[efg] [8]	10.9	0.033 [8]	16
Kwazar	–0.892[bcdefg] [14]	12.7	0.028 [5]	19
LG Anarion	–0.694[a] [25]	17.4	0.049 [21]	46
LG Areti	–0.806[abcde] [20]	14.6	0.028 [6]	26
LG Aviron	–0.762[abc] [22]	15.7	0.059 [24]	46
Mars	–0.787[abcd] [21]	15.1	0.051 [22]	43
Temptation	–0.986[efg] [7]	10.8	0.045 [18]	25
Trezzor	–0.871[abcdefg] [17]	13.2	0.038 [11]	18
Umberto KWS	–0.908[bcdefg] [12]	12.4	**0.021 [1]**	13

[a]Means not sharing any letter are significantly different at the 5% level of significance. Bold values indicate the best-performing varieties, while italicised values denote the poorest-performing ones

favourable for yield, but unfavourable for fat content. The opposite was observed for 23Ch. A detailed inspection of the meteorological conditions revealed that the oilseed rape yield was affected by high temperatures and a lack of rainfall in March, June and July. Additionally, some environments experienced a reduction in yield due to disease. The main limiting factor for fat content was the lack of rainfall in July. Similar conclusions were obtained in Zając et al. (2016). They demonstrated that environmental factors have a significant impact on the growth of winter rapeseed in a temperate climate, particularly during critical stages of development, which affects the final yield. Similar conclusions regarding fat content were obtained in Gharechaei et al. (2019). In a soybean study, Sobko et al. (2020) demonstrated a positive correlation between seed yield and solar radiation and precipitation. This suggests that these environmental factors may promote higher productivity. Furthermore, a detailed analysis of the current study's results showed that yield and fat content were negatively affected by soil conditions and fertilisation. Zając et al. (2016) indicated that nitrogen deficiency in the early growth stages further limited plant development, emphasising the importance of an optimal nitrogen supply. Béreš et al. (2019) showed that, given the local conditions and weather, and the low mineral nitrogen content in the soil, the most suitable nitrogen dose for autumn fertilisation was 40 kg N/ha. Stepien et al. (2017) demonstrated the importance of crop rotation in improving both seed and fat yield. In contrast, the impact of agricultural technology intensity on seed fat content was limited. They also showed that nitrogen fertilisation increased both seed yield and protein content, but that increased

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nitrogen rates had a detrimental effect on oil content. Sienkiewicz-Cholewa and Kieloch (2015) noted that sulphur deficiency significantly reduced yields, whereas rates above 40 kg S/ha increased yields by 11–12%. Similar effects were noted for boron and copper fertilisation, which also improved seed oil content (Jankowski et al. 2016). Conversely, excess sulphur had a detrimental effect on fat content, emphasising the importance of balanced nutrient management, particularly in maintaining the correct balance of essential elements.

Resistance to *Sclerotinia*

Scleortinia data set was analysed using models (3). The values of the approximate *F*-statistics used to test the significance of variety effects are reported in Table 2. It can be observed that for both traits, the null hypothesis (5) was rejected ($P < 0.001$). This means that for each trait, the variety means differed significantly. Furthermore, it can be seen that no significant differences were observed between the groups for *Sclerotinia* resistance (Table 3). This means that these two groups included both resistant and susceptible varieties.

In columns two and three of Table 6, the means and the back-transformed means are reported, respectively. It can be seen that variety Derrick was the most resistant. This variety was also the most resistant of the population varieties. The second-best variety was Dominator, which was also the most resistant among the hybrids.

Shukla's stability variances are reported in column four of Table 6. The lowest value of Shukla's stability variance was obtained for Umberto KWS. This means that this variety was the most stable in terms of resistance to *Sclerotinia*. It was also the most stable of the hybrid varieties. The Kwazar variety was the most stable among the population varieties and was ranked fifth overall. The most resistant varieties, Derrick and Dominator, were ranked 9th and 7th overall, respectively.

The values of the simultaneous selection index are reported in the final column of Table 4. It can be seen that the lowest value of the index was obtained by variety Crotora. This means that it was the most resistant and stable of the tested varieties. The values of the SSI index for varieties Derrick and Umberto KWS were 10 and 13, respectively.

The presence of resistant cultivars among both hybrid and population varieties suggests that genetic resistance to *Sclerotinia* is not solely determined by breeding type, but instead by the presence of specific resistance loci. These may include known genes such as *AtGDSL1* or *BnaA07.MKK9*, as reported in previous studies (Ding et al. 2020, Lin et al. 2024). In addition, polygenic resistance and minor QTLs likely contribute to partial resistance. Environmental modulation of resistance responses and expression of defence-related genes may further explain the observed variation. Future molecular profiling of these cultivars could elucidate the underlying mechanisms.

Multi-trait selection

To select the best variety in terms of all analysed traits, we identified the top ten varieties in terms of the SSI index for each trait, as shown in Table 7. For fat content, the values of the SSI index for varieties Advocat, Artemis, and Dynamic were equal; therefore, we included Table 5, which lists the top 11 varieties for this trait.

Based on the results in Table 7, the best variety was selected using a Venn diagram (Figure 2). It can be seen that the Advocat (2) and Dynamic (15) varieties were the best in terms of yield, fat content and resistance to *Sclerotinia*. This means that this variety should be promoted for cultivation. Considering the traits of yield and fat content, two varieties emerged as the best: Advocat (2), Artemis (5), Astana (6), DK Excited (11), Dynamic (15) and LG Areti (20). However, Venn diagrams can be used for up to four traits. For more than four traits, they only show the number of varieties that are common to all of them. This can be a valuable tool for plant breeders. More reliable multi-trait selection indices, irrespective of the number of traits, were implemented in 'metan' (Olivoto and Lúcio 2020).

Table 7. Top ten varieties in terms of simultanous selection index (SSI) for the analysed traits

No.	Yield	Fat content	*Sclerotinia*
1	LG Aviron	Batis	Crotora
2	DK Excited	Crotora	Dominator
3	Ambassador	DK Excited	Derrick
4	Aurelia	Duke	Umberto KWS
5	LG Areti	Herakles	Duke
6	Dynamic	Astana	Herakles
7	Absolut	Akilah	Trezzor
8	Advocat	LG Areti	Kwazar
9	Artemis	Advocat	Advocat
10	Astana	Artemis	Dynamic
11	–	Dynamic	–

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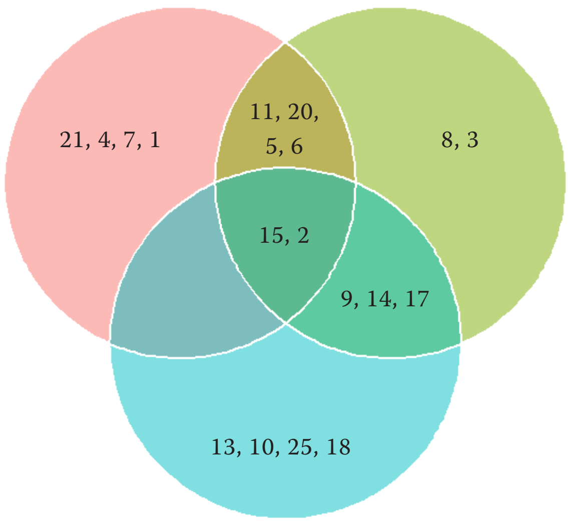

Figure 4. Venn diagrams showing common varieties for major traits used in the recommendation process

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