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Assessment of the relation between the adaptive potential of oilseed radish varieties (*Raphanus sativus* l. var. *oleiformis* Pers.) and chlorophyll fluorescence induction parameters

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Abstract. The possibility of optimization of the system of varietal identification, particularly of cruciferous crops in the breeding programs an urgent task that needs a scientific solution. A system comparison of a complex model for assessing genotypes for plasticity and stability with indicative basic and derivative indicators of the chlorophyll fluorescence induction curve (CFI) is proposed as a possible solution to this problem. 14 varieties of oilseed radish of different ecological and geographical origin were chosen as the object of research. Widely tested indicators of both methodological approaches were applied, taking into account the agrotechnological aspects of the analysis of oilseed radish plants for uniformity and stability.
The varietal specificity of the basic indicators of the induction of chlorophyll fluorescence of oilseed radish in response to changes in the stress level of the years of the research period was established. The determined interval of correlation-regression dependencies at the level of -0.382–(-0.658) (p < 0.05–0.01) between the indicators of genotypic stability (G_p), adaptability (b_i), and selection value (S_v) and the basic indicators of the CFI curve such as minimal fluorescence (F_0), fluorescence of the 'plateau' zone (F_{pl}), maximal fluorescence (F_m) and fluorescence stationary level (F_{st}). Direct correlations were determined at the level of 0.652–0.745 (p < 0.01–0.001) in the same comparison system for maximal fluorescence (F_m), fluorescence rise (dF_{pl}), maximum variable fluorescence (F_v), photochemical efficiency (EP), leaf water potential (L_{wp}), plant viability index (RF_d), efficiency of the initial reactions of photosynthesis (K_{prp}), coefficient of decline of the fluorescence (K_{fd}). The indicated pair correlation dependences were confirmed by the results of multiple regression analysis for the value of multiple regression coefficients (R) in the interval of 0.793–0.833 (p < 0.05–0.01).
On the basis of the obtained data, an integrated version of the assessment of varieties of cruciferous crops is proposed, which allows optimization of the system of varietal identification, particularly of cruciferous crops, in the breeding programs of their pre- and post-registration study, as well as the system of searching for donors and sources of relevant traits in the breeding hybridization programs at various levels. In terms of further research, it will be promising to apply this variant of the analysis to wild species of cruciferous crops in a single complex with their cultural forms to assess the regularities of the formation of adaptations under the directed trait selection process.

Key words: adaptability, chlorophyll fluorescence, oilseed radish, plasticity, varieties.

INTRODUCTION

Modern approaches to the assessment of plant stress-adaptation are based on determining reliable criteria for assessing their ability to reduce sustainable levels of biological productivity when environmental factors change by a value that differs significantly from the biological optimum for a given plant species (Pandey et al., 2021). There has been a wide range of methodological approaches to identifying, recording, and applying such criteria over many years of research. This range included both indirect methods based on mediated plant responses to the stress factor and direct methods based on explicit morphological and physiological changes in plants caused by the relevant stress factor (Mable, 2019). For example, direct methods include germination of seeds in appropriate osmotic solutions of different concentrations, while associating the nature of liquid uptake and the speed of seed germination with the traits of drought tolerance of a species or genotype (Marcińska et al., 2013). Other methods include cultivation in special drying tanks (Marchin et al., 2020), the use of climatisation chambers, the creation of artificially created germination regimes in a phytotron or greenhouse system (Bartlett et al., 2016; Snowdon et al., 2021).

The range of indirect methods also includes a wide range of methodologies. The main and well-known ones include proline test (Signorelli, 2021; Berka et al., 2022), high and low temperature heat stress protein spectrum analysis (Jacob et al., 2017; Chi et al., 2019; Khan et al., 2021), thermal imaging study of plants with radiation spectral composition analysis using dedicated thermal imaging cameras (Pineda et al., 2020), and a method that has been used for a long time, but which has recently become increasingly popular due to the introduction of devices that give a new approach to its use in experimental work, namely, the chlorophyll fluorescence induction method (Kalaji et al., 2017a). This method is effective in assessing the state of plant stress reactions, which are displayed on the corresponding chlorophyll fluorescence induction curve (CFI) (Saglam et al., 2020). Under these conditions, the indicated reaction curve is effective in determining agrotechnological stress factors as well. The analysis of the dynamics of the curve allows to determine the mechanism of adaptations of the plant organism to changes in the edaphic environment (Kalaji et al., 2017b; Tsai et al., 2019; van Bezouw et al., 2019; Schuback et al., 2021; Valcke, 2021).

It is also noted the importance of identifying crop varieties and hybrids for stress tolerance in terms of plasticity and stability (Najafi et al., 2018; Macholdt et al., 2020; Tryhub et al., 2020; Prysiazhniuk et al., 2021). This will improve both the practical orientation of breeding and ensure food security in the world. An important aspect of modern approaches to genetically marker-assisted breeding with predictive identification is the identification of the relationships between the photosynthetic system of plants and their level of adaptability and stress tolerance (Mihaljevi´c et al., 2021; Hlahla et al., 2022).

Given the presentability of the chlorophyll fluorescence induction methodology in modern scientific research and the extensive approval of methodological approaches to assess varieties and hybrids for plasticity and stability, we considered it relevant to find out the effectiveness of comprehensive assessment of the oilseed radish varieties for adaptability based on a combination of the CFI curve indicators and the main indicators describing the plasticity and stability of the variety. This will make it possible to assess the potential of this approach and the effectiveness of its application in modern breeding practice.

MATERIALS AND METHODS

The six-year cycle of research (2015–2020) is based on dark gray forest soils (in the world soil classification Luvic Greyic Phaeozem soils (IUSS Working Group, 2015) typical for the region. The soil had the following properties: low humus content (2.02–3.20%), low content of mobile forms of nitrogen (67–92 mg kg^{-1}), high phosphorus content (149–220 mg kg^{-1}), average potassium content (92–126 mg kg^{-1}) and slightly acidic reaction of the soil solution (5.5–6.0).

The study covered 14 varieties of oilseed radish of different ecological and geographical origin and different breeding, obtained in cooperation with the National Center for Plant Genetic Resources of Ukraine.

The establishment and methodological support of the study was carried out in accordance with the cruciferous crop experimentation methodology (Sayko, 2011) with a recording plot area of 25 m^2 in a 4-fold replication. Sowing dates corresponded to the end of the first to the beginning of the second decade of April.

Seed productivity was calculated during the brown pod phase (BBCH 85-89) accordingly with the evaluation protocol on homogeneity and stability in oilseed radish (CPVO, 2017). The article presents the results of the different variants of line and wide-row sowing methods applied in the general layout of the experiment, when applying the wide-row sowing method (30 cm row-spacing) with the rate of 1.5 mln.pcs per ha of germinable seeds on the unfertilized soil according to the recommendations for the study of the features of chlorophyll fluorescence induction indicators (Kalaji et al., 2017a, 2017b). The specified variant under the conditions of the research region makes it possible to combine the implementation of the varietal potential of oilseed radish plants and the technology of its application, considering the combination of high levels of individual plant productivity and standing density, which ensures the achievement of potential yield levels (Tsytsiura, 2020).

The analysis of weather conditions and the level of their variability for the period 2015–2020 was carried out on the basis of the coefficient of significance of deviations (C_{sd}) of the elements of the agrometeorological regime of each of the studied years from the multi-year average according to formula 1:

$$C_{sd} = \frac{\left(X_i - X_{av}\right)}{S} \quad (1)$$

where X_{av} – an indicator of the average multi-year value; S – mean square deviation; X_i – an indicator for a particular year. The level of C_{sd}: 0÷ 1 – conditions close to normal; 1 ÷ 2 – the conditions were significantly different from the long-term averages; > 2 – conditions close to extreme.

The hydrothermal coefficient (*HTC*) was determined according to formula 2 (Evarte-Bundere & Evarts-Bunders, 2012):

$$HTC = \frac{\sum R}{0.1 \times \sum t_{>10}} \quad (2)$$

where ΣR (mm) – the amount of precipitation for period with temperatures above 10 °C; $\Sigma_{t>10}$ – the sum of effective temperatures for the same period.

According to the significance of the deviations of the average monthly value of HTC from the average multi-year data, the years of the research period according to the value of C_{sd} (Table 1) was classified as 2015 - extremely dry, 2016 - dry with significant differences from the average multi-year data, 2017–2020 - conditions close to those typical for the multi-year hydrothermal regime of the research area. The years of research in the order of increasing stress impact on the growth processes of oilseed radish plants were placed in the following order: 2017–2019–2018–2020–2016–2015.

Table 1. Significance of HTC during the growing season of oilseed radish, 2015–2020

Year of research	Months of the vegetation period										The mean value V–IX
	V		VI		VII		VIII		IX		
	X_i	C_{sd}	X_i	C_{sd}	X_i	C_{sd}	X_i	C_{sd}	X_i	C_{sd}	C_{sd}
2015	0.719	-2.637	0.613	-1.264	0.230	-3.693	0.061	-5.961	0.684	0.011	-2.708
2016	1.227	-2.096	0.893	-0.574	0.682	-0.739	0.486	-0.368	0.063	-2.359	-1.227
2017	0.645	-2.716	0.349	-1.914	0.806	0.072	0.563	0.645	1.983	4.969	0.211
2018	0.258	-3.128	3.124	4.921	1.349	3.621	0.349	-2.171	0.680	-0.004	0.648
2019	4.710	1.613	1.555	1.057	1.003	1.359	0.235	-3.671	0.945	1.008	0.273
2020	5.489	2.443	1.474	0.857	0.649	-0.954	0.474	-0.526	1.208	2.011	0.766
X_{av} (1990–2020)	3.195		1.126		0.795		0.514		0.681		–
S (2015–2020)	0.939		0.406		0.153		0.076		0.262		–

The obtained significant differences in the weather regimes of the years during the research period allowed us to apply the system of evaluating the productivity of varieties for plasticity and stability according to the basic indicator of the annual conditions index.

The portable chronofluorometer 'Floratest' with a functional measurement period of 90 seconds was used (Romanov et al., 2011).

The measurement was carried out after shade adaptation (10 minutes) of 25 leaves of the middle layer in 4 repetitions per flowering phase of plants (BBCH 61-63). The leaf plate was oriented with its upper part towards the exciting light source and did not contain first-order venation. The obtained fixation points of the chlorophyll fluorescence induction curve were fixed by the device with the processing of the received data and the construction of a curve based on each fixation point. The data was transmitted from the device unit in file format with the extension csv. In the process of analyzing the obtained curves, basic indicators (in relative fluorescence units) were analyzed in accordance with the recommended system of indicator analysis of CFI curves (Brestic & Zivcak, 2013; Kalaji et al., 2017a–c):

F_0 – minimal fluorescence (O level in the O-I-D-P-T nomenclature of CFI curve); F_{pl} – florescence of the 'plateau' zone (I level in the O-I-D-P-T nomenclature of CFI curve); F_m – maximal fluorescence (P level in the O-I-D-P-T nomenclature of CFI curve); F_{st} – fluorescence stationary level (T level in O-I-D-P-T nomenclature of CFI curve). The date of the records corresponded to the phenological phase of flowering, which for oilseed radish corresponds to the maximum activation of the assimilation apparatus and its photosystem (Tsytsiura, 2020).

Additionally, relative and calculated indicators to the defined basic indicators (F_0, F_{pl}, F_m, F_{st}) were analyzed (formulas 3–14).

Fluorescence rise (dF_{pl}) (Brestic & Zivcak, 2013; Korneev, 2002; Kalaji et al., 2017a–c):

$$dF_{pl} = F_{pl} - F_0 \quad (3)$$

Maximum variable fluorescence (F_v):

$$F_v = F_m - F_0 \quad (4)$$

An indicator of the influence of exogenous and endogenous factors (Stirbet & Govindjee, 2011; Stirbet et al., 2014, 2018; Sarahan, 2011):

$$\frac{dF_{pl}}{F_v} \quad (5)$$

Photochemical efficiency or quantum efficiency (EP):

$$EP = \frac{F_v}{F_m} \quad (6)$$

Photochemical extinguishing (Q_{ue}) (Larouk et al., 2021):

$$Q_{ue} = \frac{F_0}{F_v} \quad (7)$$

Leaf water potential (L_{wp}) (Larouk et al., 2021):

$$L_{wp} = \frac{F_m}{F_0} \quad (8)$$

Plant viability index (RF_d) (Korneev, 2002; Lichtenthaler et al., 2005; Stirbet & Govindjee, 2011; Stirbe & Govindjee, 2012; Derks et al., 2015):

$$RF_d = \frac{F_m - F_{st}}{F_{st}} \quad (9)$$

Indicator of endogenous stress factors (K_{ef}):

$$K_{ef} = \frac{F_{st}}{F_m} \quad (10)$$

Photochemical quenching of fluorescence (QP) (Korneev, 2002):

$$QP = \frac{F_m - F_{st}}{F_m - F_0} \quad (11)$$

Efficiency of the initial reactions of photosynthesis (K_{prp}):

$$K_{prp} = \frac{F_v}{F_0} \quad (12)$$

The coefficient of decline of the fluorescence (K_{fd}):

$$K_{fd} = \frac{F_m}{F_{st}} \quad (13)$$

Relative change in fluorescence at time t (V_t):

$$V_t = \frac{F_{st} - F_0}{F_m - F_0} \quad (14)$$

The relative value of comparison (%) ($k_{comparison}$) (formula 15) (Rumsey, 2016):

$$k_{comparison} = \frac{k_1}{k_2} \times 100 \quad (15)$$

where k_1 – the value of the indicator in the variant with which it is compared; k_2 – the value of a similar indicator in the variant being compared.

An average seed yield (g plant^{-1}) was calculated for the same plants on which the CFI curve indicators were determined. For this purpose, the specified plants were marked with labels with corresponding numbering.

The parameters of ecological plasticity and stability of oilseed radish varieties were calculated according to the methods of Eberhart & Russel (1966) and Tai & Young (1972).

The following model evaluation of plasticity and stability was considered (formula 16):

$$Y_{ij} = \mu_i + \beta_i I_j + \sigma_{ij} \quad (16)$$

where Y_{ij} – the variety mean of the i-th variety in the j-th environment ($i = 1, \ldots$ v; $j = 1, \ldots n$); μ_i – the mean of the i-th variety over all environments; β_i – the regression coefficient, that measures the response of the i-th variety to varying environments; δ_{ij} – the deviation from regression of the i-th variety at the j-th environment; I_j – the environmental index of the j-th environment, was calculated by the formula 17:

$$I_j = \frac{\sum_i Y_{ij}}{\nu} - \frac{\sum_i \sum_j Y_{ij}}{\nu n} \quad (17)$$

where n – number of years of observations; ν – the number of genotypes in the analysis system (at i = 1, … v; j = 1, … n).

The first parameter of genotype stability (regression coefficient) b_i (formula 18):

$$b_i = \frac{\sum_j Y_{ij} I_j}{\sum_j I_j^2} \quad (18)$$

The second parameter of stability (S_{di}^2) (deviation from the regression line) (formula 19):

$$s_{d_i}^2 = \frac{\sum_j \hat{\delta}_{ij}^2}{n-2} - \frac{s_e^2}{r} \quad (19)$$

where s_e^2 – the estimate of the pooled error; r – number of replications.

The following grouping was used to evaluate plasticity (b_i) and stability (S_{di}^2) (according to Eberhart & Russel, 1966; Tai, 1971; Pakudin & Lopatina 1984; Callaway et al., 2003): I $b_i < 1$, $S_{di}^2 > 0$ – had better results under unfavourable conditions, unstable type; II $b_i < 1$, $S_{di}^2 = 0$ – had better results under unfavourable conditions, stable type; III $b_i = 1$, $S_{di}^2 = 0$ – responded well to improving conditions, stable type; IV $b_i = 1$, $S_{di}^2 > 0$ – responded well to improving conditions, unstable type; V $b_i > 1$, $S_{di}^2 = 0$ – had the best results under favourable conditions, stable type; VI $b_i > 1$, $S_{di}^2 > 0$ – had the best results under favourable conditions, stable type. Genotypes with a coefficient of $b_i > 1$ are classified as highly plastic (group average), while $1 > bi = 0$ is classified as relatively low plastic.

The sum of the squares of deviations from the regression line was calculated by the formula 20 (Tai, 1971; Tai & Young, 1972):

$$\sum_j \hat{\delta}_{ij}^2 = (\sum_j Y_{ij}^2 - (\sum_J Y_{ij})^2/n) - (\sum_j Y_{ij} I_j)^2 / \sum_j I_j^2 \quad (20)$$

A model of analysis of variance with random effects of the environment was considered (formula 21):

$$y_{ijk} = \mu_i + d_i + \varepsilon_j + \gamma_{k(j)} + g_{ij} + e_{ijk} \quad (21)$$

where y_{ijk} (i = 1, …v, j = 1, … n, k = 1, … r) – the value of the trait of the i-th genotype in the j-th environment in the k-th replication; μ_i – the overall mean; d_i – the effect of the i-th genotype; ϵ_j – effect of the j-th environment; $\gamma_{k(j)}$ – the effect of replicates within environments; g_{ij} – the effect of genotype × environment interaction; e_{ijk} – the residual variation due to replications.

The linear response of the genotype to the effect of the environment (α_i) and the deviation from the linear response (λ_i) was calculated by the formulas 22 and 23 (Tai & Young, 1972):

$$a_i = \frac{MSL(b_i - 1)}{MSL - MSB} \quad (22)$$

$$\lambda_i = \left[\frac{\nu}{\nu - 1}\right]\left[\frac{n-2}{n-1}\right]\frac{s_{d_i}^{\ 2}}{MSE/r} - a_i\left[\frac{b_i - 1}{m-1}\right]\frac{MSB}{MSE} \quad (23)$$

where MSL, MSB, MSE – mean squares, due to environments, replicates within environments and error, respectively; r – number of replications; S_{di}^2 – the second parameter of stability; n – number of years of observations; ν – the number of genotypes in the analysis system; m – degrees of freedom for the error.

The graphical interpretation of the parameters α_i and λ_i according to Pakudin & Lopatina (1984) was made.

The coefficient of homeostaticity (H_{omi}) (stability index) (formula 24) (Khangildin et al., 1979):

$$H_{omi} = \frac{\bar{Y}^2_i}{\sigma_i(\bar{Y}_{i(opt)} - \bar{Y}_{i(lim)})} \quad (24)$$

where σ_i – the standard deviation of the trait for the i-th genotype; $\bar{Y}_i$, $\bar{Y}_{i(opt)}$, $\bar{Y}_{i(lim)}$ – the mean values of the trait for the i-th genotype in all environments, in the optimal and limited environment, respectively.

Agronomic stability coefficient (A_s) was determined as the residual of the difference between the total stability of the genotype and the level of its variation during the evaluation period (Bacsi & Hollósy, 2019; Reckling et al., 2021).

The selection value indicator (S_v) was calculated according to the formula 25 (De Jong, 1994):

$$S_v = \bar{Y}_i \frac{\bar{Y}_{i(min)}}{\bar{Y}_{i\,(max)}} \quad (25)$$

where $\bar{Y}_i$ – average yield over the evaluation period for a given genotype, $\bar{Y}_{i(min)}$, $\bar{Y}_{i(max)}$ – respectively, the minimum and maximum recorded yields for a given genotype during the evaluation period.

Coefficient of dryness (C_d) was determined as the percentage ratio of the yield of the respective variety in the driest year to its yield in the year with maximum moisture (Becker & Léon, 1988).

Coefficient of stress resistance (C_{sr}) and genetic plasticity (G_p) was determined according to the recommendations of Pakudin & Lopatina (1984).

The coefficient of productivity (C_p) was determined as percentage ratio of the average yield of the variety during the study period to the maximum potential yield shown by the variety during the period of variety production in the conditions of the zone of research (Fernandez, 1991; Fikere et al., 2014).

The evaluation of the variation was carried out according to the gradation of the coefficient of variation (CV_i,%) according to the methodological guidelines (Temesgen et al., 2015; Urruty et al., 2016): up to 10% – low, 11–20% – medium and > 21% – high.

The coefficient of variation of the i-th genotype is actually determined by a standard formula 26 (Snedecor, 1989):

$$CV_i = \frac{\sigma_i}{\bar{Y}_i} \times 100\% \qquad (26)$$

where σ_i – the standard deviation of the trait for the i-th genotype; $\bar{Y}_i$ – the mean value of the trait for the i-th genotype in all environments. Genotypes with yield above overall mean yield and CV_i below overall coefficient of variation was considered as more stable than the others.

The degree of integrated connection of plant morphological features was assessed using the weight correlation graph method (Kakade & Foster, 2007; Hajjar et al., 2022) using the formula 27:

$$G = \sum_{|r_{ij}| \geq \alpha} |r_{ij}| \qquad (27)$$

where r_{ij} – correlation coefficient between i-th and j-th indicator. Reliable correlation coefficients was considered.

The percentage dependence of the variation of the performance indicator on the influence of the selected factor is determined through the coefficient of determination (d_{xy}) according to formula 28 (Davide et al., 2021):

$$d_{yx} = r_{ij}^2 \times 100 \qquad (28)$$

where r_{ij} – correlation coefficient between i-th and j-th indicator.

The periodization of the phenological development of oilseed radish varieties corresponds to the BBCH periodization scale (CPVO, 2017).

To compare the average data in the experimental variants, the indicator of the least significant difference ($LSD_{0.5}$) was used (for the lower limit of the permissible level of significance $p < 0.05$) (Marques de Sá, 2007; Hinnkelmann & Kempthorne, 2019). Standard methods of regression and correlation analyzes using the Statistica 10 framework were also applied (StatSoft – Dell Software Company, USA).

RESULTS AND DISCUSSION

The identification of oilseed radish varieties by plasticity (b) and stability (S_{di}^2) (Table 2) allowed to divide the studied genotypes by the corresponding rank gradations. The first rank includes varieties ‘Alfa’, ‘Iveia’, ‘Pryhazhunia’, ‘Raiduha’, ‘Snizhana’, ‘Nika’, ‘Liniia IRHSHI’, ‘Tambovchanka’, ‘Sabina’. The VI rank includes varieties ‘Olha’, ‘Ramonta’, ‘Zhuravka’, ‘Lybid’, ‘Fakel’. Varieties of I rank according to the classification given in the methodology section are classified as unstable type with possible manifestation of maximum productivity in years with unfavorable environmental conditions. Varieties of VI rank are referred to a stable type with a positive increase in productivity (in our case, the resulting value of seed yield (SY)) under optimized environmental conditions. Thus, the influence of selective origin of oilseed radish varieties in the expression of their adaptive potential can be traced. This is essentially correct, as most of the varieties under study belong to the Eur asian selection group with the inclusion of local source forms of oilseed radish from the territories of northern and central Ukraine, Russia and Belarus with a certain recombination of breeding forms from Poland and Germany (Blume et al., 2020).

Table 2. Parameters of stability, plasticity, resistance and yield potential of varieties of oilseed radish, (average for 2015–2020)

Variety	SY, t ha^{-1}	C_P, %	CV_i, %	C_{st}	G_p	C_d	A_s	H_{omi}	S_v	b_i	S_{di}^2	a_i	λ_i
Olha	1.81	88.13	23.59	-1.23	1.83	0.70	89.14	2.79	8.96	1.10	2.29	0.46	0.84
Alfa	1.28	69.00	19.58	-0.77	1.26	0.66	89.68	3.81	6.81	0.39	1.56	-0.64	-1.22
Ramonta	2.08	87.62	15.63	-1.00	2.10	0.76	90.97	5.94	12.72	1.09	0.10	-0.13	0.15
Iveia	1.71	67.06	23.25	-1.24	1.67	0.61	86.93	2.65	7.84	0.57	4.23	0.37	-0.47
Pryhazhunia	2.03	78.44	18.84	-1.12	1.91	0.65	88.05	4.31	11.10	0.95	0.48	0.23	0.45
Raiduha	1.82	86.83	17.77	-0.95	1.72	0.63	88.91	4.93	10.32	0.71	1.04	-0.24	0.82
Zhuravka	2.12	87.76	17.37	-1.06	2.05	0.68	88.41	5.19	12.46	1.11	2.39	0.01	2.07
Lybid	1.77	87.71	22.60	-1.23	1.71	0.57	88.62	2.88	8.32	1.08	0.50	0.35	-0.22
Fakel	1.88	88.60	18.08	-1.06	1.82	0.68	92.53	4.39	10.31	1.01	0.69	-0.06	0.68
Snizhana	1.96	82.98	19.50	-1.17	1.94	0.69	83.96	3.84	10.49	1.24	0.26	0.25	0.04
Nika	1.86	73.94	19.35	-1.07	1.93	0.82	89.94	4.10	10.53	0.81	3.17	0.004	1.15
Liniia IRHSHI	1.45	81.10	24.78	-1.06	1.35	0.54	88.87	2.48	6.33	0.65	1.53	0.06	0.77
Tambov-chanka	1.70	69.11	18.09	-0.91	1.58	0.67	87.05	4.62	9.38	0.51	0.95	-0.32	0.83
Sabina	1.72	66.54	17.00	-0.89	1.71	0.72	91.19	5.10	10.10	0.366	3.426	-0.34	-0.23

Parameters (Fisher criterion) for SY (yield, t ha^{-1})	F_f	F_{t05}	*LSD*$_{05}$ (yield, t ha^{-1})
Variety	284.23	1.82	0.041
Year conditions	111.36	2.46	0.029
Interaction of variety x conditions of the year	9.82	1.48	0.049

Thus, the varieties of Ukrainian selection 'Raiduha', 'Zhuravka', 'Lybid', 'Fakel' were created by repeated individual selection from earlier varieties of German (Skletta) and Polish selection (Bashta, Snopkowska), which in turn were created by population selection from local species forms of oilseed radish common in Central and Eastern Europe (Tsitsiura & Tsitsiura, 2015). The use of positive selection contributed to the selection of genotypes with stable adaptive potential, increasing against the background of optimization of plant growth and development conditions. Oilseed radish varieties of Belarusian selection 'Iveia', 'Pryhazhunia', 'Snizhana', 'Nika', 'Sabina' were created on the basis of hybridization of such varieties as 'Raiduha', 'Tambovchanka', as well as varieties of own selection of an earlier period with varieties of the already mentioned Polish and German selection and subsequent multiple individual selection.

The variety of German selection 'Ramonta' was also created by hybridization. The use of hybridization allowed to increase the overall heterozygous state of the initial population with subsequent stabilizing positive multiple selection. As a result, this contributed to the formation of an unstable type in terms of the ratio of plasticity and stability with a potentially positive reaction of yield growth under the appropriate combination of environmental conditions and genotypic characteristics of the variety. Thus, the use of hybridization in oilseed radish breeding complicates the rank reaction of varieties in the tested model of Eberhart & Russell (1966) with the expansion of the adaptive response of genotypes and at the same time reducing the predictability of such a reaction (increasing the probability of $S_{di}^2 > 0$). This conclusion was confirmed by graphical interpretation of the spatial relationship of the linear response of the genotype to the effect of the environment a_i and the deviation from the linear response λ_i (Fig. 1).

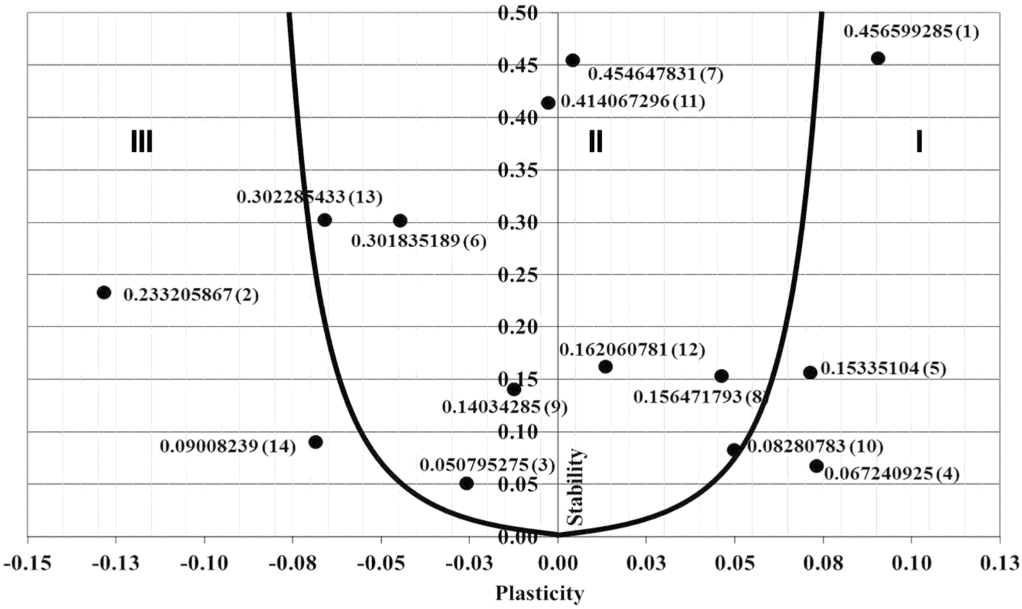

Figure 1. Distribution of varieties of oilseed radish into classes by plasticity (a_i) and stability (λ_i) at a 5% significance level, 2015–2020 (indexation of varieties: 1 – 'Olha'; 2 – 'Alfa'; 3 – 'Ramonta'; 4 – 'Iveia'; 5 – 'Pryhazhunia'; 6 – 'Raiduha'; 7 – 'Zhuravka'; 8 – 'Lybid'; 9 – 'Fakel'; 10 – 'Snizhana'; 11 – 'Nika'; 12 – 'Liniia IRHSHI'; 13 – 'Tambovchanka'; 14 – 'Sabina').

It was found that the varieties of the first (I) zone ('Olha', 'Iveia', 'Pryhazhunia') belong to genotypes with high response to changes in growing conditions. That is, such varieties should be recommended for cultivation in conditions of high culture of agriculture. However, on a low agricultural background, their yields are sharply reduced. In contrast, the varieties whose coordinates are located in the second (II) zone ('Ramonta', 'Raiduha', 'Zhuravka', 'Lybid', 'Fakel', 'Snizhana', 'Nika', 'Liniia IRHSHI', 'Tambovchanka') are more conservative in response to changing environmental conditions. Ecological plasticity of varieties placed coordinately in the third (III) zone ('Alfa', 'Sabina') is at the level of average plasticity, typical for the studied set of varieties. This distribution is consistent with the level of realization of the genetic potential of the variety (productivity coefficient (C_p)) of oilseed radish varieties, which are the result of Ukrainian breeding, in particular 'Raiduha', 'Zhuravka', 'Lybid', 'Fakel' showed the highest levels of this indicator, which is evidence of their adaptation to local conditions and hydrothermal regime of the territory. On the contrary, varieties of the most geographically distant selection 'Alpha', 'Tambovchanka' showed the lowest value of C index in the group. These levels of adaptability for varieties 'Raiduha', 'Zhuravka' and 'Fakel' were confirmed by the values of the coefficient of variation (C_v) at the level of 17.37–18.08 and the coefficient of stress resistance (C_{st}) at the level of -0.95– -1.06 in relation to the effective indicator of seed yield in the applied analysis system. The maximum indices of genetic plasticity (Gp) were determined in varieties Ramonta' and 'Zhuravka', which, taking into account the statements of a number of researchers (Ghanem et al., 2015; Subira et al., 2015), indicates significantly higher values of breeding value of these varieties (Sv) and the level of their homeostasis (H_{omi}) in the general comparison group. As for the level of homeostasis, according to Xu (2016), its value indicates the level of adaptive adaptations of the genotype to the given environmental conditions of the territory of its cultivation. On the basis of this, it was found that for the varieties of oilseed radish 'Olha' and 'Liniia IRHSHI', the breeding centers of which belong to the zone of central Siberia, the level of these adaptations is minimal. At the same time, among the varieties selected in geographically close to the research area, the level of homeostasis is also low, in particular in the varieties 'Lybid' and 'Iveia'. Such results are explained from the point of view of certain properties of the genotype, which are the resultant in the formation of its productivity, as confirmed by Brouziyne et al. (2018). In our case, this is the value of the drought tolerance index by the value of the aridity coefficient (C_d), which for the varieties 'Lybid', 'Iveia' and 'Liniia IRHSHI' was minimal among the studied varieties 0.57, 0.61 and 0.54, respectively.

According to the general combinatorics of indicators characterizing the adaptive properties of the variety, its breeding value and agronomic stability (A_s), the studied varieties of oilseed radish were placed in the following order 'Ramonta', 'Zhuravka', 'Pryhazhunia', 'Nika', 'Snizhana', 'Raduha', 'Sabina', 'Tambovchanka', 'Olha', 'Lybid', 'Iveia', 'Alfa', 'Liniia IRHSHI'. Each of these genotypes according to additional criteria a_i and λ_i showed additional features that determine the variety-specific response to the combination effect of genotype and environmental conditions. This is confirmed by the nature of placement of the studied varieties in the cordinal plane of the ratios of stability and plasticity of varieties (Fig. 1). There are significant differences ($p < 0.05$–0.01) in the ratio of Fisher's criterion ($F_f/F_{t05\text{-}01}$) for the main parameter of determination of varieties - seed yield (SY) allowed to interpret the results from the point of view of genotypic expression of adaptations of varieties and compare them with physiological aspects of growth and photoassimilation processes, in particular with the induction of chlorophyll a florescence. The possibility and feasibility of such a comparison is substantiated in a number of studies (Olivoto et al., 2019; Pour-Aboughadareh, 2022).

The results of accounting of the basic and derivative calculated parameters of the CFI curve (Table 3) showed their significant (at $p < 0.5$) differences within the studied varieties of oilseed radish. At the same time, the share of the influence of environmental factors in the dispersion analysis system was from 21 to 28% for the basic indicators of the CFI curve. Taking into account the share of the year conditions for the seed yield at the level of not less than 25% (Table 2), the significant role of the annual variation in the formation of stability and plasticity of varieties on the resulting trait and in the formation of the CFI curve indicators was proved. Taking into account the results of studies by Hoffmann & Woods (2003), Auld et al. (2010), Mohammadi (2014), Klingenberg (2019), the comparison of varieties evaluation indicators by classical breeding indicators and indicators of chlorophyll a fluorescence induction was applied.

Table 3. The value of the CFI curve indicators for oil radish varieties (relative fluorescence units for flowering phase BBCH 65–67), 2015–2020

Variety	Basic indicators				Estimated indicators and indices											
	F_0	F_{pl}	F_m	F_{st}	dF_{pl}	F_v	dF_{pl}/F_v	EP	L_{wp}	Q_{ue}	RF_d	K_{ef}	QP	K_{prp}	K_{fd}	V_t
Olha	438	619	1,655	523	181	1,217	0.149	0.735	3.78	0.360	2.164	0.316	0.930	2.779	3.164	0.070
Alfa	495	607	1,608	553	112	1,113	0.101	0.692	3.25	0.445	1.908	0.344	0.948	2.248	2.908	0.052
Ramonta	454	681	1,814	518	227	1,360	0.167	0.750	4.00	0.334	2.502	0.286	0.953	2.996	3.502	0.047
Iveia	520	674	1,578	623	154	1,058	0.146	0.670	3.03	0.491	1.533	0.395	0.903	2.035	2.533	0.097
Pryhazhunia	460	633	1,592	525	173	1,132	0.153	0.711	3.46	0.406	2.032	0.330	0.943	2.461	3.032	0.057
Raiduha	522	626	1,534	596	104	1,012	0.103	0.660	2.94	0.516	1.574	0.389	0.927	1.939	2.574	0.073
Zhuravka	438	691	1,808	509	253	1,370	0.185	0.758	4.13	0.320	2.552	0.282	0.948	3.128	3.552	0.052
Lybid	506	623	1,690	570	117	1,184	0.099	0.701	3.34	0.427	1.965	0.337	0.946	2.340	2.965	0.054
Fakel	454	597	1,644	537	143	1,190	0.120	0.724	3.62	0.382	2.061	0.327	0.930	2.621	3.061	0.070
Snizhana	455	617	1,734	526	162	1,279	0.127	0.738	3.81	0.356	2.297	0.303	0.944	2.811	3.297	0.056
Nika	482	641	1,598	529	159	1,116	0.142	0.698	3.32	0.432	2.021	0.331	0.958	2.315	3.021	0.042
Liniia IRHSHI	463	605	1,412	532	142	949	0.150	0.672	3.05	0.488	1.654	0.377	0.927	2.050	2.654	0.073
Tambov-chanka	483	654	1,563	565	171	1,080	0.158	0.691	3.24	0.447	1.766	0.361	0.924	2.236	2.766	0.076
Sabina	497	667	1,619	606	170	1,122	0.152	0.693	3.26	0.443	1.672	0.374	0.903	2.258	2.672	0.097

LSD_{05}	F_0	F_{pl}	F_m	F_{st}	The share of influence of experimental factors				
					factors	F_0	F_{pl}	F_m	F_{st}
LSD_{05} factor A (year)	5.96	6.83	5.91	5.25	A	21.369	23.551	28.129	27.884
LSD_{05} factor B (plant species)	6.84	7.92	6.18	4.29	B	48.369	45.274	51.369	49.139
LSD_{05} interaction AB	8.92	10.12	9.24	8.87	AB	30.262	31.175	20.502	22.977

Tukey HSD Test (Signifscant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1)

	Df	Sum Sq	Mean Sq	F value	Pr (>F)
F_0 RE	13	27,197	2,092	6.75	**
Residuals	84	26,027	310		
F_{pl} RE	13	42,030	3,233	10.80	***
Residuals	84	25,137	299		
F_m RE	13	29,434	2,264	24.74	***
Residuals	84	7,686	92		
F_{st} RE	13	11,450	881	15.08	***
Residuals	84	4,905	58		

The obtained range of values of the basic indicators of the CFI curve (F_0, F_{pl}, F_m, F_{st}) had extremely close intervals of values, which corresponded to a close numerical interval. This is confirmed by graphical interpretation of CFI curves (Figs 2a–2b) in oilseed radish varieties. Based on this, it was concluded that chlorophyll fluorescence induction indices can be used in the processes of genomic identification of plants. In addition to the conclusions of Kalaji & Guo (2008), Flood et al. (2011), Driever et al. (2014) and Flexas & Carriqu´ı (2020), the presented graphical data proved the similarity of the formation of dynamic changes in the process of chlorophyll fluorescence induction in terms of general formation and established the specific nature of the curve sections in terms of ordinal placement and specific formation features in the corresponding sections.

At the same time, with the general similarity of the curves, specific features were noted. This specificity is defined as a factor of special adaptive reactions of the assimilation apparatus of oilseed radish plants due to appropriate responses to environmental stress factors. For example, comparison of CFI curves for significantly different by the established parameters of breeding value varieties of oilseed radish 'Ramonta' (Fig. 2a) and 'Liniia IRHSHI' (Fig. 2b). For the variety 'Ramonta' high maximum ordinate position up to the level of 1800 relative units of fluorescence standard (F_0), intensive decrease of the curve in the area of 33–60 second fixation, complex microrelief character of the curve in the area of 61 second fixation to the level of stationary fluorescence F_{st}.

For the variety 'Liniia IRHSHI' the minimum ordinal position up to the level of 1400 relative units of the fluorescence standard (F_0), slower decrease of the curve in the 33–60 second fixation, smoothed character of the curve in the 61 second fixation to the level of F_{st} were noted.

Taking into account the fact that the photosynthetic apparatus of plants has certain idiosyncratic mechanisms of adaptation to stress, as noted in the studies of Ajigboye et al. (2016) and Araus & Cairns (2014) and genotypic features of the variety determine both the formation of the plant photosystem and the mechanisms of its functioning (Strasser et al., 2004), the obtained data confirm the conjugation of the formation of plasticity and stability of the genotype and the efficiency of its photosystem. In support of this, such a mechanism of formation was noted already at the early stages of formation of juvenile elements of the photosystem of cruciferous crops (Jalink et al., 1998). The possibility of such evaluation approaches was confirmed in the variants of drought tolerance, salinity tolerance and general stress tolerance of rapeseed genotypes (Kauser et al., 2006; Jafarinia & Shariati, 2012; Ayyaz et al., 2021), mustard (Irfan et al., 2015) and radish subspecies (Guo et al., 2005).

A high value of the initial fluorescence index F_0 at the level of 500 relative units of the fluorescence standard was noted, taking into account the results of studies by Gu et al. (2017), according to which the growth of F_0 in the comparison of plant species indicates its sensitivity to an increase in plant density. On the basis of this, the studied varieties of oilseed radish are predictably attributed to those responding to thickening by reducing the level of individual bioproductivity with increasing planting density. Different gradations of the F index$_0$ allowed to hypothetically determine the varieties of oilseed radish with different degrees of agrotechnological response to changes in the range of planting density. Thus, for the varieties 'Raiduha', 'Iveia', 'Lybid', 'Sabina', the optimum standing density should be predicted in a narrower agrotechnological interval than for the varieties 'Olha', 'Zhuravka', 'Fakel', 'Ramonta'.

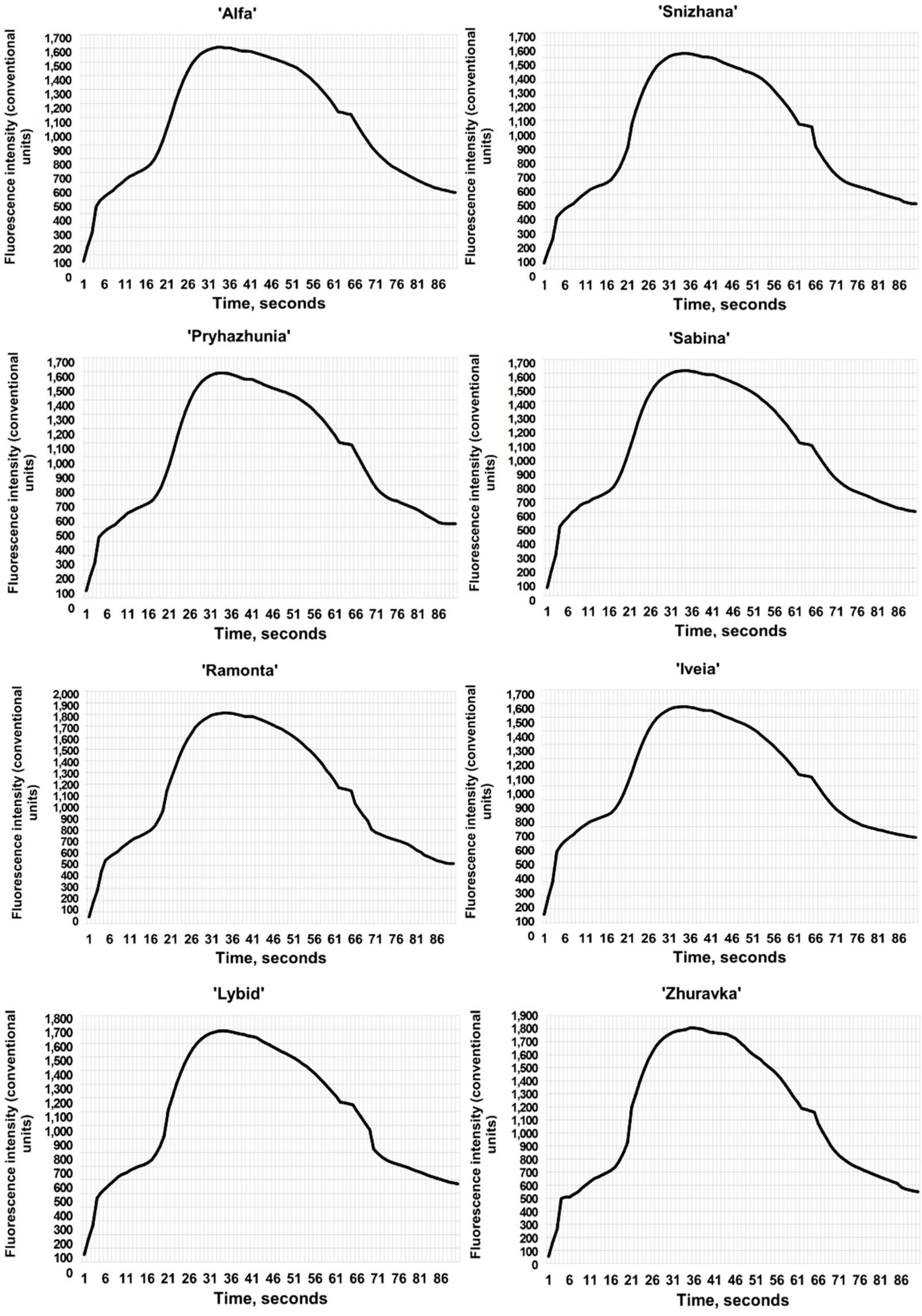

Figure 2a. CFI curves (adjusted for the average multi-year values of the indicator at each fixation point) for oilseed radish varieties based on averaged data from fixation points in the 90 second interval over the 2015–2020 period.

The formation of the ‘plateau’ zone F_{pl} fluorescence also has few generic as well as varietal differences. Regarding varietal features, oilseed radish was characterized by a dynamically increasing level of formation of this index with a little expressed form of ‘plateau’ zone at the level of 11–15 seconds of registration with a portable fluorimeter, followed by intensive increase of index of CFI curve up to the value of maximum fluorescence (F_m) (Figs 2a–2b). The varietal specificity of indicator formation should also be noted. Thus, in the varieties ‘Alfa’, ‘Raiduha’, ‘Iveia’, on average over a multi-year period of evaluation, the achievement of the ‘plateau’ zone in the intensively growing area F_0–F_{pl} was noted. For the varieties ‘Zhuravka’, ‘Fakel’, ‘Olha’, ‘Pryhazhunia’, the angular slope of the CFI curve in the F_0–F_{pl} area was less.

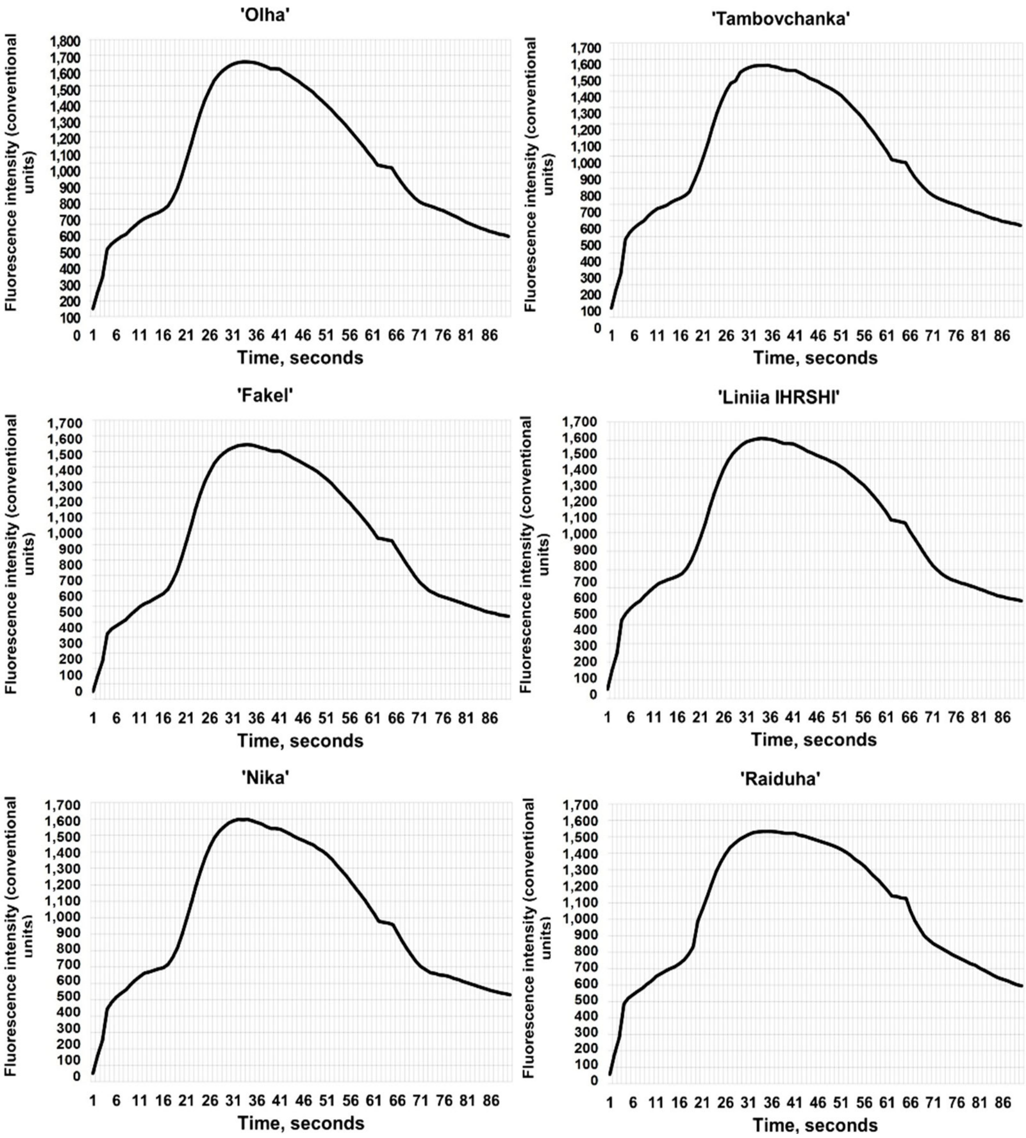

Figure 2b. CFI curves for oilseed radish varieties based on averaged data from fixation points in the 90 second interval over the 2015–2020 period.

Under these conditions, the formation of the F_{pl} indicator was noted on the intensively increasing segment of the CFI curve. At the same time, the nature of such formation was varietal specific. This indicates certain differences in the functioning of the photosystem of different oilseed radish genotypes and similarity in the reaction to a change in the area of plant nutrition. By the way, similar results were obtained in winter wheat (Brestič et al., 2012) and spring barley (Kalaji & Guo, 2008).

A number of peculiarities of oilseed radish varieties in comparison with other cruciferous crops were also found in the area of the CFI curve between F_{pl} and F_m (Figs 2a–2b). The character of the graph in this area had the highest level of visual genotypic differences, which further proved the possibility of varietal identification of oilseed radish on the basis of basic indicators of chlorophyll fluorescence induction. In all years of research, a special area on the CFI curve in the period 61–65 seconds of registration was also recorded, which was typical for all studied varieties of oilseed radish. Similar analogies with different expression of the duration of this area were noted in our studies on spring rape, white mustard and spring rape (Tsytsiura, 2022). The presence of this area is explained by the fact that the nature of the curve formation in the area F_m–F_{st} indicates certain physiological mechanisms of pre-adaptation of the PSII photosystem in the transition to stationary fluorescence, which characterizes the stress sensitivity of the species. The low expression of this activity on the CFI curve of individual cultivars is explained by the higher rate of physiological aging of leaves than in other cruciferous species in the analyzed group, as indicated in the publications of Ward et al. (1995) and Hasanuzzaman (2020).

It was found that the graphical altitudinal position of this transition area for different varieties of oilseed radish was significantly different. Over the long-term study period, it was recorded at the level of 997 relative fluorescence units in the variety 'Olha', 1,020 relative fluorescence units in the variety 'Fakel', and 1125 units in the variety 'Raiduha', respectively (Table 3). In general, with these varietal differences in varieties of oilseed radish, a rather narrow niterval of fixation of this transition in the range of 950–1,150 relative fluorescence units was noted. The very nature of the CFI curve in the area from F_m to the marked characteristic plateau at 61–65 seconds of registration has a pronounced varietal difference from a wide stretched character in the varieties 'Raiduha' and 'Alfa' to a narrow one with an intense decline in the varieties 'Zhuravka', 'Ramonta', 'Nika'. Thus, this section of the curve in cruciferous plant species should be considered as an indicator of appropriate levels of stress resistance. This possibility by the nature of the CFI curve segment F_m–F_{st} in determining the species response to high or low temperatures, drought, soil salinity, heavy metal concentration, lack of nutrients is indicated in a number of studies on different plant species, in particular, Huner et al. (1993), Flexas et al. (2002), Adams & Demmig-Adams (2004), Gonçalves & dos Santos (2005), Urban et al. (2018), Khazaei et al. (2019), McAusland et al. (2019). At the same time, under intense stress, as well as under the conditions of natural stage aging of leaves, the value of F_{st} was significantly higher than F_0 and vice versa under optimal conditions with a shorter time interval for reaching the level of F_{st} on the CFI curve. These generalizations are confirmed by the nature of the plot F_m–F_{st} (Figs 3a–3b). Thus, for the varieties 'Snizhana', 'Fakel', 'Lybid' a consistent slow character of its formation was noted, and for the varieties 'Ramonta', 'Zhuravka', 'Lybid' an intense downward character was observed when reaching the stationary level of F_{st}.

The index dF_{pl} also had significant differences within the studied varieties based on statistically significant difference for the values F_{pl} and F_0 (Table 3). In this case, the value of the indicator between the limit values was 141 conventional units of fluorescence, respectively 253 units in the variety 'Zhuravka' to 112 units in the variety 'Alfa'. It is proved for many plant species that induced stresses (herbicides, thickening, diseases, etc.) reduce the dF_{pl} with simultaneous growth of both F_0 and F_{pl}. However, the growth rate of initial fluorescence outpaces the growth rate of fluorescence of the 'plateau' zone. This has been noted in a number of studies (Goltsev & Yordanov (1997); Lazár et al. (1997); Morales et al. (2000), Klinkovsky & Naus (2004); Papageorgiou & Govindjee (2004); Lazár & Schansker (2009); Rapacz et al. (2015); Ripoll et al. (2016); Østrem et al. (2018); Sánchez-Moreiras et al. (2020). However, the data presented in the case of oilseed radish varieties showed the lack of stable compliance with these patterns. Thus, varieties with different breeding value (S_v) such as 'Pryhazhunia', 'Tambovchanka', 'Snizhana' had similar values of dF_{pl}. Based on this, it was concluded that different varieties of oilseed radish have certain peak values of F_{pl} and F_0, according to the level of physiological capacity of their photosystem. That is, for oilseed radish as for the species as a whole, a narrowed interval of possible genotypic stress response was determined, which is expressed in the formation of an adaptive niche of the reaction of its photosystem.

The results of the correlation analysis between the studied parameters (Table 4) allowed to confirm the previously made conclusions and identify a number of features in the expression of adaptive varietal strategies of oilseed radish in the functioning of their photosystem.

It was determined that the indicator F_m had a close relationship of a direct nature with the parameters SY, G_p, b_i, S_v and H_{omi} and the inverse of CV_i S_{di}^2. For the indicators F_o and F_{st}, the nature of the correlation between the same indicators had the opposite nature of formation. And for the F_{pl} indicator, a heterogeneous impact with a productive direct character was determined.

At the same time, the effective significance of the dependencies of the indicators F_o, F_{pl}, F_m and F_{st} on the size of the correlation graph (G) in the interval of indicators SY–S_v had corresponding differences. According to the size of this correlation graph, the indicators of the impact on the certainty of the main criteria for evaluating varieties for adaptability and stability can be placed in the following ascending order: F_{st} (G = -1,732) – F_0 (-1,925) – F_{pl} (1,946) – F_m (2,459). Thus, the basic criteria for the induction of chlorophyll fluorescence are recommended as predicted for the evaluation and determination of adaptive properties of oilseed radish varieties at the corresponding already announced optimized ratio of b_i and S_{di}^2, according to the grouping ranks of their ratio. It was proved that the oilseed radish variety with higher plasticity and stability will be characterized by higher levels of maximum chlorophyll fluorescence (F_m), lower values of initial fluorescence (F_0) and, as a result, higher values of F_v. At the same time, the indication of dependence was significantly higher for the parameter b_i than for the parameter S_{di}^2. This is explained by the levels of adaptive responses of varieties to environmental stress factors and genotypic features that determine the physiological and anatomical features of the structure and functioning of the plant photosystem. The presence of these physiological and anatomical features in other plant species is reported in the studies of Strasser & Tsimilli-Michael (2001), Lascano et al. (2003), Lepeduš et al. (2012) and Herritt et al. (2020). It should be noted that for the studied varieties of oilseed radish, the range of F_m values was 402 conventional units of fluorescence (1,814 in the variety 'Ramonta' and 1,412 in the variety 'Liniia IRHSHI') (Table 3). In relation to the average long-term value for the studied varieties of 1630 conventional units of fluorescence, it was 24.7%. Taking into account the results of studies by Middleton et al. (2019), Dechant et al. (2020), Quero et al. (2020), Jushkov et al. (2021), where it is noted that the increase in the range of values of basic indicators of fluorescence in a certain species population of plants at a very high gradation indicates its heterogeneity and significantly differentiated physiological stability of plant stress responses. In view of this, the genetically determined mechanisms of adaptive adaptability of oilseed radish varieties to changing environmental conditions was obviously due to the involvement of the original local populations and wild forms of oilseed radish well adapted to reactions to various changes in hydrothermal and edaphic conditions. The effectiveness of breeding to improve varieties in this way is noted in particular in the studies of Li et al. (2006), Long et al. (2006, 2015), Rapacz et al. (2015), Kromdijk et al. (2016), Khazaei et al. (2019) and Zhuang et al. (2020).

Taking into account the direct nature of the relationship between the parameters b_i, S_v and H_{omi} and the inverse relationship between S_{di}^2 and F_m and the inverse relationship with a smaller value of the correlation coefficients with respect to F_0 – the value of ER (F_V/F_m) can be successfully used in breeding programs for evaluating oilseed radish varieties for stability and plasticity. At the same time, given the multidirectional correlation dependencies of ER components, the importance of the criterion F_m in the predicted assessment of the adaptive potential of varieties will be the main one.

Based on the established in studies of varietal characteristics of the CFI curve section F_0–F_{pl}–F_m, it was determined that the correctness of identification of oilseed radish varieties by varietal adaptability will be determined by the physiological response of the genotype at the initial stages of induction of chlorophyll fluorescence in the F_0–F_{pl} section and the speed and intensity of the recovery of the acceptor mechanism of electrons of the PS II photosystem. The tendency of both ratios to the identical reduction reaction at the growth of stress factors causes a less significant level of dependence than in single correlation comparisons between dF_{pl} and F_v, which is clearly confirmed by the data of Table 4.

Genotypic differences in oilseed radish by the rate of change in the induction of chlorophyll fluorescence by V_t were also determined. On the basis of this, in oilseed radish varieties where this indicator was lower, the possibility of expanding the interval of the boundary limits of the corresponding stress factor was established, which provides a wider range of plasticity of the variety and its adaptations. This is confirmed by the inverse relationship between V_t and such criteria as b_i (-0.561, at $p < 0.05$) and the indicator of breeding value of the variety (S_v) (-0.382, $p < 0.05$) and a direct relationship with the indicator of variant stability of the trait, Sdi^2 (0.490, at $p < 0.01$) (Table 4).

The potential possibility of using the vitality index RF_d, (an indicator of the threshold level of exogenous stress (Korneev, 2002)) in identifying the adaptability of oilseed radish varieties on the basis of direct correlations (at $p < 0.01$) with such indicators as seed yield (SY) (0.649), genetic flexibility (G_p) (0.703), breeding value of the variety (S_v) (0.662) and regression coefficient b_i (0.774). At the same time, inverse relationships of medium strength (at $p < 0.05$) were determined with the stability variant Sdi^2 (-0.409) and the coefficient of genotypic variation of the variety CV_i (-0.397).

Table 4. Correlation analysis of dependencies of the system of chlorophyll fluorescence induction indices and adaptive potential of oilseed radish varieties (comparing 28 correlation pairs by averaged indices for the pair of incompatible repeats from the total scheme of 56 observations during 2015–2020 (for Snedecor, 1989))

Indicator	F_{pl}	F_m	F_{st}	dF_{pl}	F_v	dF_{pl}/F_v	EP	L_{wp}	Q_{ue}	RF_d	K_{ef}	QP
F_0	0.031	-0.431*	0.890**	-0.672***	-0.612***	-0.551**	-0.824***	-0.817***	0.824***	-0.777***	0.786***	-0.419*
F_{pl}		0.453*	0.155	0.719***	0.390*	0.702***	0.242	0.284	-0.227	0.225	-0.154	-0.132
F_m			-0.396*	0.635***	0.977***	0.254	0.863***	0.871***	-0.858***	0.858***	-0.836***	0.465*
F_{st}				-0.504**	-0.556**	-0.348	-0.739***	-0.730***	0.741***	-0.810***	0.832***	-0.764***
dF_{pl}					0.714***	0.903***	0.752***	0.778***	-0.741***	0.707***	-0.660***	0.194
F_v						0.352	0.950***	0.955***	-0.945***	0.934***	-0.917***	0.505**
dF_{pl}/F_v							0.445*	0.479**	-0.435*	0.381*	-0.335	-0.058
EP								0.995***	-0.999***	0.964***	-0.960***	0.522**
L_{wp}									-0.991***	0.966***	-0.954***	0.512**
Q_{ue}										-0.960***	0.960***	-0.525**
RF_d											-0.995***	0.712***
K_{ef}												-0.740***

Indices	K_{prp}	K_{fd}	V_t	SY	G_p	CV_i	b_i	S_{di}^2	H_{omi}	S_v
F_0	-0.817***	-0.777***	0.419*	-0.449*	-0.466*	0.096	-0.632***	0.381*	-0.147	-0.413*
F_{pl}	0.284	0.225	0.132	0.461*	0.473*	-0.517**	-0.059	0.440*	0.501**	0.532**
F_m	0.871***	0.858***	-0.465*	0.662***	0.726***	-0.580**	0.638***	-0.231	0.478**	0.689***
F_{st}	-0.730***	-0.810***	0.764***	-0.507**	-0.410*	0.105	-0.658***	0.503**	-0.141	-0.378*
dF_{pl}	0.778***	0.707***	-0.194	0.654***	0.674***	-0.476*	0.396*	0.061	0.473*	0.681***
F_v	0.955***	0.934***	-0.505**	0.685***	0.745***	-0.443*	0.707***	-0.292	0.454*	0.701***
dF_{pl}/F_v	0.470*	0.381*	0.058	0.456*	0.450*	-0.204	0.114	0.248	0.420*	0.467*
EP	0.995***	0.964***	-0.522**	0.658***	0.710***	-0.449*	0.749***	-0.359	0.391*	0.652***
L_{wp}	0.997***	0.966***	-0.512**	0.674***	0.722***	-0.387*	0.762***	-0.343	0.387*	0.680***
Q_{ue}	-0.991***	-0.960***	0.525**	-0.649***	-0.703***	0.385*	-0.744***	0.362	-0.358	-0.643***
RF_d	0.966***	0.967***	-0.712***	0.649***	0.703***	-0.397*	0.777***	-0.409*	0.391*	0.668***
K_{ef}	-0.954***	-0.995***	0.740***	-0.621***	-0.678***	0.388*	-0.775***	0.442*	-0.360	-0.632***

Table 4 (continued)

Indices	K_{prp}	K_{fd}	V_t	SY	G_p	CV_i	b_i	S_{di}^2	H_{omi}	S_v
QP	0.512^{**}	0.712^{***}	-0.995^{***}	0.303	0.352	-0.217	0.561^{**}	-0.490^{*}	0.207	0.350
K_{prp}		0.966^{***}	-0.512^{**}	0.674^{***}	0.722^{***}	-0.383^{*}	0.752^{***}	-0.343	0.387^{*}	0.670^{***}
K_{fd}			-0.712^{***}	0.649^{***}	0.703^{***}	-0.391^{*}	0.774^{***}	-0.409^{*}	0.391^{*}	0.662^{***}
V_t				-0.303	-0.352	0.217	-0.561^{**}	0.490^{**}	-0.207	-0.382^{*}
YS					0.972^{***}	-0.487^{**}	0.731^{***}	-0.225	0.519^{**}	0.914^{***}
G_p						-0.571^{**}	0.734^{***}	-0.145	0.501^{**}	0.906^{***}
CV_i							-0.016	0.175	$-0,978^{***}$	-0.777^{***}
b_i								-0.540^{**}	0.038	0.524^{**}
S_{di}^2									-0.168	-0.204
H_{omi}										0.809^{***}

* – reliable at 5% significance level; ** – reliable at 1% significance level; *** – reliable at 0.1% significance level.

Table 5. The system of regression dependencies of basic indicators of chlorophyll fluorescence induction and the main criterion estimates of the adaptive value of oilseed radish varieties (based on the combined 2015–2020 data set)

Indexes	Parameters		Dependence equation	The coefficient of multiple regression (R/R^2)	Assessment of the significance of dependence
	x	y			
F_m	b_i	S_v	$F_m = 2{,}223.9895 – 678.4613x – 3{,}448.9904y + 744.578x^2 – 1{,}395.8739xy + 7{,}748.952y^2$	$0.793^{*}/0.629$	$F/SS_{total} = 5.18$ ($F_{t05} = 4.67$), ($p < 0.05$)
F_v	b_i	S_v	$F_v = 1{,}671.6984 – 1{,}388.0067x – 57.2714y + 807.98x^2 + 32.3023xy + 3.1041y^2$	$0.808^{*}/0.653$	$F/SS_{total} = 5.37$ ($F_{t05} = 4.67$), ($p < 0.05$)
EP	b_i	S_v	$EP = 0.8332 – 0.294x – 0.0172y + 0.1742x^2 + 0.0081xy + 0.0008y^2$	$0.813^{*}/0.661$	$F/SS_{total} = 5.98$ ($F_{t05} = 4.67$), ($p < 0.05$)
L_{wp}	b_i	S_v	$L_{wp} = 5{,}2719 – 3{,}3971x – 0.2887y + 1{,}9941x^2 + 0.0984xy + 0.0148y^2$	$0.823^{*}/0.677$	$F/SS_{total} = 6.29$ ($F_{t05} = 4.67$), ($p < 0.05$)
Q_{ue}	b_i	S_v	$Q_{ue} = 0.185 + 0.5931x + 0.0289y – 0.3511x^2 – 0.0163xy – 0.0014y^2$	$0.803^{*}/0.645$	$F/SS_{total} = 5.22$ ($F_{t05} = 4.67$), ($p < 0.05$)
RF_d	b_i	S_v	$RF_d = 3.7205 – 2.7856x – 0.2888y + 1.2207x^2 + 0.1583xy + 0.0115y^2$	$0.833^{*}/0.694$	$F/SS_{total} = 6.51$ ($F_{t05} = 4.67$), ($p < 0.05$)
K_{ef}	b_i	S_v	$K_{ef} = 0.1805 + 0.3186x + 0.0232y – 0.1401x^2 – 0.0182xy – 0.0007y^2$	$0.819^{*}/0.671$	$F/SS_{total} = 6.14$ ($F_{t05} = 4.67$), ($p < 0.05$)
K_{prp}	b_i	S_v	$K_{prp} = 4.2627 – 3.4087x – 0.2853y + 1.9895x^2 + 0.1008xy + 0.0145y^2$	$0.821^{*}/0.674$	$F/SS_{total} = 6.23$ ($F_{t05} = 4.67$), ($p < 0.05$)
K_{fd}	b_i	S_v	$K_{fd} = 4.7205 – 2.7856x – 0.2888y + 1.2207x^2 + 0.1583xy + 0.0115y^2$	$0.831^{*}/0.691$	$F/SS_{total} = 6.42$ ($F_{t05} = 4.67$), ($p < 0.05$)

* Significant at 5% level.

Indirectly, the physiological state of oilseed radish varieties was assessed by the leaf water potential (L_{wp}), since, according to van der Tol et al. (2009), Vialet-Chabrand et al. (2017) and Zhang et al. (2020), the activity and efficiency of the plant photosystem depends on the total water content of the assimilation surface, its turgor state and water balance. Considering the already mentioned general physiological peculiarity of oilseed radish to intensive reduction of plant leafiness and its different tier physiological stages according to stem height (Tsytsiura, 2022), leaf water potential for oilseed radish cultivars is an important aspect of its photosystem functioning. According to our estimates, the highest value of this indicator in the range of 3.81–4.13 was established for varieties with high breeding value and adaptive properties such as 'Ramonta', 'Zhuravka', 'Snizhana' and confirmed by direct correlations (at $p < 0.01$) with such indicators as seed yield (SY) (0.674), genetic flexibility (G_p) (0.722), breeding value of the variety (S_v) (0.670) and regression coefficient b_i (0.752). That is, the indicators of effective water consumption of plants, the physiological state of the assimilation surface in the vertical profile of leaf placement determine the physiological mechanisms of adaptation of oilseed radish varieties.

Taking into account the calculated derivative of the basic indicators of the CFI curve such as Q_{ue}, K_{ef}, QP, K_{prp}, K_{fd}, its application in the process of evaluating oilseed radish varieties for adaptability, plasticity and stability correlates with the already indicated features of application in terms of basic indicators and certain indices based on them.

The results of multiple regression analysis confirm earlier conclusions and the most statistically significant results are shown in Table 5. Thus, the possibility of effective use of both basic and derivative indicators determined by estimating the chlorophyll fluorescence induction curve for the predicted assessment of both genotypic stability of the variety (b_i) and its breeding value in the system of complex interaction of stressful and non-stressful growing years (S_v) with the level of multiple regression coefficient in the range of 0.793–0.833 (at $p < 0.05$) was proved. The determined level of significance in combination with the results of pairwise correlation (Table 4) according to Pour-Aboughadareh (2022) is sufficient to apply the criteria of the CFI curve of the corresponding variety to identify its adaptive properties.

The established degree nature of the dependence in view of the study by Vaezi et al. (2019) indicates a complex configurational interaction of environmental factors both in relation to the physiological aspects of the photosynthetic activity of oilseed radish plants and in relation to the realization of the genetic yield potential of each variety.

CONCLUSIONS

It was determined that the complex indices of chlorophyll fluorescence induction F_0, F_{pl}, F_m, F_{st} had genotypic differences with the possibility of identifying stress resistance and adaptability of oilseed radish varieties to limiting exogenous environmental factors in the process of determining its breeding value. The possibility of using a comparable systematic analysis of the characteristic areas of the chlorophyll fluorescence induction curve (CFI) of the photosystem of oilseed radish varieties during the period of its maximum activity and identifiers of its plasticity and stability (coefficient of genetic plasticity (G_p), coefficient of agronomic stability (A_s), coefficient of stress resistance (C_{st}), coefficient of homeostaticity (H_{omi})) has been proved. The use of this variant of evaluation is confirmed by the coefficient of determination (d_{xy}) for the inverse nature of the pair correlation (at $p < 0.05–0.01$) at the level of 14.6–53.3% in the comparison of genetic plasticity (G_p), regression coefficient of genetic stability of the variety (b_i), breeding value of the variety (S_v) with such indicators as initial fluorescence (F_0), stationary fluorescence (F_{st}), rate of change of fluorescence in time (V_t). Direct pairwise correlation dependences (at $p < 0.01–0.001$) for the same parameters of genotypic evaluation and a number of CFI curve parameters in the following order of increasing d_{xy} were determined: fluorescence rise (dF_{pl}, d_{xy} = 15.6–46.4%) – maximum fluorescence (F_m, 40.7–52.7%) – photochemical efficiency (EP, 42.5–56.1%) – efficiency of the initial reactions of photosynthesis (K_{prp}, 44.9–56.6%) – maximum variable fluorescence (F_v, 49.1–55.5%) – leaf water potential (L_{wp}, 46.2–58.1%) – coefficient of decline of the fluorescence (K_{fd}, 43.8–59.9%) – plant viability index (RF_d, 44.6–60.4%). Predictability and applicability of these comparisons was confirmed by multiple regression analysis between genotypic stability (b_i), breeding value (S_v) and CFI curve parameters such as F_m, F_v, EP, L_{wp}, Q_{ue} (photochemical extinguishing), RF_d, K_{prp}, K_{ef} (indicator of endogenous stress factors), K_{fd} with the value of multiple regression coefficient (R) in the range 0.793–0.833 (at $p < 0.05$).

From the point of view of prospects for further research, this system of evaluation of initial breeding material should be studied for the possibility of application to other types of cruciferous crops, including its wild forms. This will improve the process of selection of source material and search for an effective variant of its genetic recombination.

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