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Biochemical composition and nutritional value of red-fleshed apple cultivars in the Ukrainian forest-steppe

Abstract. The study investigated the biochemical composition and nutritional value of 12 red-fleshed apple cultivars grown at the National University of Life and Environmental Sciences of Ukraine. The objective was to evaluate their phytochemical profile, including dry matter, soluble solids, total sugars, titratable acidity, pectins, and key bioactive compounds such as ascorbic acid, total polyphenols, anthocyanins, and chalcones. The research, conducted over two consecutive years (2023-2024), also aimed to identify correlations between these traits and to cluster cultivars with similar chemical profiles. The results noted a wide range of biochemical characteristics among cultivars. While their dry matter, soluble solids, and pectin content were comparable to modern white-fleshed varieties, their total polyphenol content was significantly higher, with an average of 335.69 mg/100 g. The cultivars 'Jurgen' and 'Firecracker' showed the highest polyphenol levels: 643.85 mg/100 g and 629.60 mg/100 g, respectively. The presence of anthocyanins in the flesh varied widely, ranging from 2.50 to 28.64 mg/100 g, with 'Dr Campbell' having the highest concentration. The study also found significant year-to-year variation in some traits, particularly hydropectin, total polyphenols, and chalcones, suggesting an environmental influence. A high positive correlation was observed between anthocyanins and chalcones ($r = 0.88$), as well as between total polyphenols and chalcones ($r = 0.72$). Hierarchical clustering analysis identified distinct groups of cultivars, with the highest content of biologically active substances in 'Dr Campbell', 'Cranberry', 'Jurgen', 'Firecracker', and 'Maypole'. These findings highlight the potential of red-fleshed apple cultivars as a rich source of health-promoting compounds, providing valuable data for future breeding programs and consumer use

Keywords: *Malus domestica* Niedzwetzkyana Group; ascorbic acid; polyphenolic compounds; anthocyanins; antioxidant activity

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INTRODUCTION

Fruits are one of central food sources for humanity. The apple tree (*Malus domestica* (Suckow) Borkh.) is one of the most significant fruit crops globally and in Ukraine. Apples are highly valued for their nutritional and biological properties, being a key source of nutraceuticals and biologically active substances. According to the Food and Agriculture Organisation (FAO) (2025), global apple production exceeds 97 million tonnes, with Ukraine producing over 1 million tonnes. Apples are the most popular fruit in Ukraine. They contain various compounds, such as polyphenols, which are responsible for the colour, taste, and aroma of the fruit, and also influence the metabolic activity of apples and processed products. These polyphenols also have a positive effect on human health. As U. Asma *et al*. (2023) highlighted, apples also contain ascorbic acid (vitamin C), which, similarly to polyphenols, have antioxidant properties. According to V. Mezhenskyj *et al.* (2024), among Ukrainian apple tree varieties, some red-fleshed apples belong to *Malus domestica* f. *niedzwetzkyana* (Dieck) Mezhenskyj. These cultivars are classified as the Niedzwetzkyana Group. In contrast to typical Ukrainian apple trees, where anthocyanins are found mainly in the skin of red apples, Niedzwetzkyana Group varieties also contain anthocyanins in the flesh, increasing their nutritional and biological value.

The State Register of Plant Varieties of Ukraine contains dozens of apple varieties with different ripening times that are suitable for fresh consumption and processing (Ministry of Agrarian Policy..., n.d.). However, red-fleshed varieties are not yet included, despite them already being grown by farms and small-scale gardeners. In the introduction of new varieties, consumer tastes and preferences are crucial to the positive reception of the product in the market, as P. Drkenda *et al.* (2021) noted. Many modern red-fleshed apple varieties are now commercialised under specific trademarks, transforming them into legally protected brands. This branding often exceeds the scope of traditional intellectual property rights, such as patents. Instead of developing a distinct brand for each individual cultivar, companies are increasingly marketing multiple varieties under a single master brand. This approach is evident in well-known examples such as Redlove®, Lucy™, Kissabel®, and Red Moon®.

A review by V. Mezhenskyj *et al.* (2024) of red-fleshed apples confirms the significant interest in their cultivation in various countries. This is determined by the the attractive original colour of the flesh and the specific biochemical composition caused by the accumulation of anthocyanins which provide the flesh its colour, as well as other biologically active substances. As shown by J. Juhart *et al.* (2022), a significant portion of the polyphenols in apples is concentrated in the peel, which also contains nearly all of the flavonols and anthocyanins. However, since consumers often eat considerably more of the flesh than the peel, they may not be receiving the full potential health benefits. According to study by N. Wang *et al.* (2018), red-fleshed apple varieties are a significant source of flavonoids. Therefore, incorporation of these apples into the diet can significantly increase flavonoid intake, which is crucial for promoting overall health and well-being. These findings suggest that red-fleshed apples are not just a visually appealing novelty but a valuable dietary component with substantial health benefits, therefore valuable for both consumers and agricultural development. D. Wang *et al.* (2024) established a significant varietal difference in the components of polyphenols. As evidenced by research by T. Xu *et al.* (2023), rsearch and enrichment of the regulatory network that controls flavonoid synthesis in red-fleshed apples is essential for growing high-quality fruit. Studies, including by P. Bouillon *et al.* (2024), utilise innovative methods such as image analysis and polyphenol profiling to analyse the complexity of these red-fleshed cultivars in greater detail. Furthermore, metabolomic research conducted by A. Ceci *et al.* (2021) has revealed the intricate structure of metabolites in these varieties, rendering them subject for further study.

The study aimed to analyse the biochemical composition of red-fleshed apple varieties in terms of their biologically active substance content, and to cluster genotypes to identify groups with similar chemical profiles.

MATERIALS AND METHODS

Plant Materials. The study used 12 cultivars: 'Circe' (Redlove®Circe), 'Cranberry', 'Dr Campbell' ('Simontornya Veralma'), 'Era' (Redlove®Era), 'Firecracker', 'Jurgen', 'Marisa' (Baya®Maria), 'Maypole', 'Mott`s Pink', 'Red Katty', 'Sirena' (Redlove®-Sirena), and 'Weirouge'. They were grown in the collection orchard of the Educational, Research and Productive Laboratory of Genetic Resources, Introduction and Breeding of Rare Fruits and Ornamental Plants at the Professor V.L. Symyrenko Department of Horticulture of the National University of Life and Environmental Sciences of Ukraine (NULES). This orchard is located at the Agronomic Research Station of NULES in Pshenychne village, Bila Tserkva district, Kyiv region, which is part of the forest-steppe natural zone.

According to the Köppen climate classification scheme, the region is characterised by a typical warm-summer humid continental climate. The research was conducted on soil classified as meadow chornozem. The adult trees were cultivated at a spacing of 5 × 4 m, with care involving standard agricultural practices such as inter-row cultivation and mechanical weed control. Irrigation was not used. Notably, the study fully adhered to the ethical standards established by the Convention on Biological Diversity (1992) and the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1976). Fruit harvesting was performed in mid-September over 2 consecutive years (2023 and 2024), with the fruits being picked upon reaching the stage of technical ripeness.

Dry matter content was determined using the sample drying method. Slices of fruit (3-4 g) were placed in a pre-weighed box containing river sand and dried to constant weight in an SNOL 58/350 (Ukraine) drying cabinet at 98-100°C. Results were expressed as a percentage. Soluble solids were measured with a PAL-1 portable refractometer (ATAGO, China). An analytical sample was prepared by homogenising 15-20 fruit pieces. A drop of juice was filtered through tissue onto the refractometer glass for measurement, with temperature error accounted for. Data were expressed as a percentage of the fresh mass.

Organic titrated acids. Of homogenised sample, 25 grams homogenised were transferred into a 250 ml volumetric flask and rinsed with ≤150 ml of hot distilled water. The flask was kept in a water bath at 80°C for 30 minutes, cooled, filled to the mark with distilled water, and filtered. Of extract, 20 millilitres of extract were pipetted into a conical flask, 3-4 drops of phenolphthalein were added, and the sample was titrated with 0.1 N NaOH until a pink endpoint (pH 7.0) appeared. Acid content was calculated using the titration data and a citric acid conversion factor. Results were expressed as a percentage of the fresh mass.

Sugars were extracted with hot distilled water, and proteins/pigments were removed by precipitation with lead acetate. Sucrose was hydrolysed to glucose and fructose with 10% HCl under heat. Reducing sugars were determined via Fehling's solution, and optical density was measured with a ULAB 102UV (China) spectrophotometer at 640 nm. Sugar content was calculated using standard glucose curves and expressed as a percentage of the fresh mass.

Pectin substances. Samples were freed from sugars and pigments using ethanol. Soluble pectin was extracted with water, and protopectin with 1 N H_2SO_4, then hydrolysed to galacturonic acid by heating. A 0.2% carbazole solution was added to acidified extracts, forming a coloured complex. Optical density was measured at 535 nm (ULAB 102UV). Pectin content was calculated using calibration graphs with galacturonic acid and expressed as a percentage of the fresh mass.

Ascorbic acid. Samples were ground in a porcelain mortar with glass and transferred to a 100 ml volumetric flask with a 2% oxalic acid : 1% HCl mixture (80:20, v/v). The extract was filtered and titrated with 2.6-dichlorophenolindophenol (Tillmans' method). Results were expressed as mg/100 g fresh mass.

Total polyphenolic content. Samples were macerated with ethanol, filtered through a Büchner funnel, and washed with ethanol until colourless. Extracts were reacted with Folin-Denis reagent, followed by saturated sodium carbonate. Optical density was measured at 640 nm (ULAB 102UV) after 1 hour. Calibration was done using chlorogenic acid standards. Results were expressed as mg/100 g fresh mass.

Anthocyanidin and chalcone content. Alcoholic extracts from 3.5% HCl-acidified homogenates were analysed spectrophotometrically at 530 nm and 364 nm, respectively, using a ULAB 102UV. Results were expressed as mg/100 g fresh mass.

Statistical analyses. Descriptive statistics were applied to analyse the data and calculate mean values, standard deviation (SD), and coefficient of variation (CV%) for each indicator over 2 years. The percentage change between 2023 and 2024 for each biochemical trait was calculated, along with the fluctuation range. The effects of year and genotype on each selection parameter were evaluated using two-way analysis of variance (ANOVA) in Microsoft Excel. Fisher's least significant difference (LSD) test was used to identify significant differences between means at a 95% confidence level ($p \leq 0.05$). Results were reported as mean ± SD. Pearson correlation coefficients were calculated in Microsoft Excel to assess linear relationships among the measured parameters. Hierarchical clustering analysis was conducted using Euclidean distance and Ward's method. All clustering and data normalisation ("StandardScaler") were performed in "Python" using the scipy (hierarchical clustering) and scikit-learn (data normalisation) libraries. The dendrogram was visualised using "Matplotlib".

RESULTS AND DISCUSSION

The analysis of the biochemical composition of the cultivars, which is a key step in determining their unique properties and potential, is presented in this section. The obtained data, reflecting the content of various chemical components, is systematically organised in Tables 1 and 2.

Table 1. The biochemical composition of pomes

Cultivar	Dry matter, %	Soluble solids, %	Total sugar, %	Titratable acidity, %	Sugar-acid ratio	Hydropectin, %	Protopectin, %	Total pectin, %
'Circe'	17.37±0.06	14.26±1.48	9.56±0.29	0.95±0.01	10.06±0.45	0.04±0.02	0.87±0.16	0.90±0.13
'Cranberry'	17.44±0.73	11.96±0.49	7.44±0.12	2.24±0.14	3.33±0.16	0.12±0.02	1.20±0.07	1.32±0.09
'Dr Campbell'	20.40±0.18	15.96±3.32	11.00±0.72	1.29±0.38	8.82±2.05	0.06±0.07	1.12±1.18	1.18±0.31
'Era'	20.92±4.69	13.76±4.73	8.76±1.51	1.09±0.13	8.18±2.33	0.03±0.03	0.87±0.12	1.06±0.31
'Firecracker'	17.67±0.52	14.30±1.55	8.06±1.21	1.04±0.07	7.72±0.64	0.09±0.03	0.93±0.40	1.02±0.43
'Jurgen'	17.05±1.17	11.16±2.18	7.70±1.57	1.20±0.20	6.40±0.25	0.10±0.06	1.43±0.21	1.54±0.16
'Marisa'	16.80 ±1 .23	13.96±0.77	8.90±1.27	1.02±0.32	9.32±4.14	0.08±0.08	1.29±0.69	1.38±0.62
'Maypole'	17.34±0.70	14.96±0.77	9.93±0.96	1.62±0.05	6.10±0.40	0.12±0.09	0.93±0.03	1.06±0.05
'Mott`s Pink'	16.58±0.44	12.60±0.56	9.42±0.15	0.87±0.13	10.93±1.43	0.06±0.01	0.98±0.21	1.04±0.20
'Red Katty'	17.74±0.27	12.66±2.04	9.18±0.87	1.17±0.07	7.88±1.22	0.05±0.06	1.02±0.33	1.07± 0.40
'Sirena'	17.60±1.97	13.20±1.41	9.16±2.72	1.06±0.17	8.96±4.00	0.07±0.00	0.96±0.24	1.03±0.24
'Weirouge'	17.08±3.56	13.20±4.24	8.95±1.82	1.26±0.06	7.05±1.09	0.08±0.06	1.20±0.53	1.29±0.48

Note: the data represent average values for 2023-2024 ($x \pm SD$, $n = 2$), where SD – standard deviation and n – number of replicates

Source: compiled by the authors

A two-factor ANOVA revealed no statistically significant differences ($p \leq 0.05$) between genotypes for any of the studied biochemical parameters (dry matter, soluble solids, total sugars, titratable acidity, sugar-acid ratio, hydropectin, protopectin, and total pectin). The red-fleshed cultivars under study have characteristics similar to those of modern Ukrainian apple varieties grown in the same region regarding dry matter, soluble solids, and total pectin (Shevchuk *et al.*, 2021). These modern cultivars are characterised by a high sugar content (10.7%), low acidity (0.5%), and a high sugar-acid ratio (20); therefore, they have a sweet taste. The red-fleshed cultivars do not match them. Their apples are more likely to be used for culinary and technical purposes.

As noted by S. Gwanpua *et al.* (2014), pectin is a crucial component of apple structure, and its composition changes as the fruit ripens. According to E. Farzaliev & S. Ökten (2025), this is determined by pectin substances consisting of both protopectin, the cell walls material, and soluble hydropectin, which provides pectin the valued gelling properties for cooking. In red-fleshed apples, the hydropectin content ranges from 0.03% to 0.12%, and the protopectin/hydropectin index varies from 8 (in the 'Maypole') to 29 (in the 'Era').

Table 2. The biologically active compounds of RCH fruits, mg/100 g

Cultivar	Ascorbic acid	Total polyphenols	Antocyanins	Chalcones
'Circe'	7.44 ± 0.23	203.25 ± 52.68e	5.06 ± 1.65cd	7.95 ± 0.21bcd
'Cranberry'	12.02 ± 4.65	370.10 ± 139.87cd	17.42 ± 2.43b	12.90 ± 0.28b
'Dr Campbell'	6.38 ± 1.95	565.55 ± 20.06ab	28.64 ± 1.79a	18.00 ± 4.10a
'Era'	5.69 ± 1.82	219.25 ± 62.58de	4.50 ± 3.12cd	5.75 ± 0.35cd
'Firecracker'	8.12 ± 3.93	629.60 ± 68.73ab	2.50 ± 2.12d	9.95 ± 6.29bc
'Jurgen'	5.68 ± 1.17	643.85 ± 135.98a	6.91 ± 5.22cd	8.90 ± 2.55bcd
'Marisa'	8.30 ± 2.13	215.35 ± 40.52de	8.52 ± 3.08c	5.55 ± 2.76cd
'Maypole'	6.51 ± 0.02	483.05 ± 42.50abc	16.52 ± 1.24b	11.20 ± 6.65b
'Mott`s Pink'	7.64 ± 0.09	185.80 ± 39.32e	5.06 ± 1.18cd	4.95 ± .91d
'Red Katty'	4.74 ± 3.59	162.90 ± 36.91e	3.10 ± 0.28d	5.45 ± 3.04cd
'Sirena'	7.90 ± 2.63	176.70 ± 7.50e	4.10 ± 0.28cd	5.65 ± 2.19cd
'Weirouge'	4.19 ± 4.37	172.90 ± 18.53e	6.22 ± 1.58cd	4.75 ± 1.06d

Note: the data represent average values for 2023-2024 ($x \pm SD$, $n = 2$), where SD is the standard deviation and n is the number of replicates. Different letters indicate values that are significantly different within one column according to results of the LSD test ($p \leq 005$). Letters are assigned from the highest to the lowest mean value
Source: compiled by the authors

The ascorbic acid content of red-fleshed apples varied from 4.19 mg/100 g in 'Weirouge' to 12.02 mg/100 g in 'Cranberry', with an average value of 7.05 mg/100 g. Fruits of modern Ukrainian apple varieties contain an average of 5.7 mg/100 g, as found by L. Shevchuk *et al.* (2021). Apples are a rich source of total polyphenols with high antioxidant properties, a fact noted by D. Bars-Cortina *et al.* (2017) and S. Yuste *et al.* (2022). According to L. Shevchuk *et al.* (2021), sweet varieties of Ukrainian origin accumulate an average of 206 mg/100 g of total polyphenols. The highest levels were observed in the 'Solomiia', 'Askolda', and 'Kateryna' cultivars, with 262, 256, and 245 mg/100 g, respectively. Apples with red-fleshed pulp accumulate an average of 335.69 mg/100 g, which exceeds the maximum levels found in dessert apples and may influence their taste. The cultivars 'Jurgen' (643.85 mg/100 g) and 'Firecracker' (629.60 mg/100 g) have the highest accumulation of total polyphenols. M. Jalali *et al.* (2024) found that red-fleshed apple genotypes in Iran contain 449.6 mg/100 g of polyphenols. In contrast, D. Bars-Cortina *et al.* (2017) reported that the total polyphenol content in four red-fleshed varieties developed in Europe ranges from 298 to 522 mg/100 g.

The red colour of the flesh is determined by the presence of anthocyanins. Apples of common varieties do not contain anthocyanins in their flesh. The cultivars studied vary greatly in this aspect, ranging from 2.50 mg/100 g ('Firecracker') to 28.64 mg/100 g ('Dr Campbell'), with an average value of 9.05 mg/100 g across all varieties. Data are consistent with results obtained by other researchers. For example, a study of a large hybrid population of red-fleshed apple trees in France by P. Bouillon *et al.* (2024) demonstrated that anthocyanin content varied within the range of 0.2-30.9 mg/100 g. In Spain, D. Bars-Cortina *et al.* (2017) found that four red-fleshed cultivars consisted of 0.93-4.93 mg/100 g of anthocyanins. Similarly, M. Jalali *et al.* (2024) reported that red-fleshed genotypes in Iran also exhibit significant variability in anthocyanin content, ranging from 2.1 to 18.9 mg/100 g. Lastly, a study by A. Ceci *et al.* (2021) reported an anthocyanin content of 7.5 mg/100 g.

D. Bars-Cortina *et al.* (2017) demonstrated that red-fleshed apples contain higher amounts of phenolic acids, anthocyanins, dihydrochalcones, and organic acids in their flesh or peel compared to white-fleshed apples. However, the study determined that red-fleshed apples have a lower amount of flavan-3-ols. The authors suggested that these quantitative differences could be correlated with the up-regulation of anthocyanins, dihydrochalcones, and malic acid, and a corresponding down-regulation of flavan-3-ols (which are precursors to anthocyanins) in red-fleshed varieties. Regarding the taste of anthocyanins, F. Brossaud *et al.* (2008) suggested that they are astringent, despite having no tasteF. Brossaud *et al.* (2008). In contrast, research by R. Espley *et al.* (2013) demonstrated that elevated levels of anthocyanins in red-fleshed apples were not associated with any negative taste attributes. Table 3 provides a summary of the statistics for each chemical trait across the two growing years (2023 and 2024), demonstrating the mean values, variability, and dynamic changes in the chemical composition of the fruit among the studied genotypes.

Table 3. Statistics describing the chemical composition of the fruits for each trait (n = 9)

Trait	Year	x ± SD	CV, %	Min – max	Change, % (2024 compared to 2023)
Dry matter	2023	17.11 ± 1.58	9.3	13.57-20.27	8.9
	2024	18.63 ± 2.10	11.3	16.89-24.24	
Soluble solids	2023	12.11 ± 1.52	12.6	15.62-24.22	22.9
	2024	14.88 ± 1.79	12.0	14.10-21.80	
Total sugar	2023	8.51 ± 1.40	16.4	6.59-10.61	11.7
	2024	9.50 ± 1.14	12.0	7.53-11.50	
Titratable acidity	2023	1.20 ± 0.37	30.5	0.80-2.14	6.0
	2024	1.27 ± 0.42	32.9	0.78-2.34	
Sugar-acid ratio	2023	7.62 ± 2.43	31.9	3.44-12.25	7.2
	2024	8.17 ± 2.55	31.3	3.22-11.94	
Hydropectin	2023	0.10 ± 0.04	40.8	0.07-0.14	-51.8
	2024	0.05 ± 0.04	70.8	0.01-0.11	
Protopectin	2023	0.95 ± 0.24	25.4	0.75-1.28	24.1
	2024	1.18 ± 0.31	26.0	0.79-1.78	
Total pectin	2023	1.06 ± 0.26	24.9	0.57-1.08	19.3
	2024	1.26 ± 0.31	24.6	0.58-1.10	
Ascorbic acid	2023	6.87 ± 1.07	15.6	4.85-8.73	5.4
	2024	7.23 ± 3.92	54.2	1.10-15.30	
Total phenolics	2023	340.67 ± 204.68	60.1	158.00-740.00	-2.9
	2024	330.72 ± 192.86	58.3	136.80-678.20	
Anthocyanins	2023	8.67 ± 7.91	91.3	19.60-131.56	-8.7
	2024	9.43 ± 8.15	86.5	20.60-115.00	
Chalcones	2023	6.63 ± 11.74	57.8	20.30-52.70	56.9
	2024	10.21 ± 4.81	47.2	21.40-43.50	

Source: compiled by the authors

The CV is used to estimate the variability of different traits. V. Mezhenskyj (2017) suggested that the inherent variability of plants can be described as the "lower" norm (CV = 5-24%), "upper" norm (CV = 25-44%, large variation (CV = 45-63%), very large variation (CV = 65-84%), and extremely large variation (CV = 85-105%). Most of the phytochemical composition of the fruit exhibits normal variation. Dry matter, soluble solids, total sugar, and total pectin are characterised by a "lower" norm, while titratable acidity, sugar-acid ratio, and protopectin are characterised by an 'upper' norm. Ascorbic acid had a "lower" norm of variability in 2023 and large variability in 2024. For hydropectin, there were fluctuations from the "upper" norm in 2023 to a significant decrease in content by -51% and a large variation in 2024. Characteristics associated with phenolic metabolites varied the most: polyphenols and chalcones showed large variation, with the latter increasing significantly in content by 56.9% in 2024. The content of anthocyanins showed large variation. These fluctuations suggest that the stability of the expression of chemical components across different cultivars is influenced by annual environmental conditions.

According to the two-factor ANOVA, the effect of the year of cultivation was statistically significant ($p \leq 0.05$) for hydropectin, total polyphenols, and chalcones. According to D. Bars-Cortina *et al.* (2018) and L. Yu *et al.* (2022), there is a significant interaction with the season in total phenolic content, flavonols, triterpenes, and organic acids. The total phenolic content in the apple flesh was higher in years with lower rainfall during the harvest period, which could have favoured hydric stress in the apple trees. Anthocyanin concentration in the flesh of the red-fleshed apples showed no clear relation to the season, and each variety showed an individual pattern. The linear relationships between the measured biochemical parameters of the fruit are shown in Table 4.

Table 4. Pearson correlation coefficients between traits (r)

Trait	Dry matter	Soluble, solids	Total sugar	Titratable acidity	Sugar-acid ratio	Hydropectin	Protopectin	Total pectin	Ascorbic acid	Total polyphenols	Antocyanines	Chalcones
Dry matter	1.00											
Soluble solids	0.47	1.00										
Total sugar	0.34	0.76	1.00									
Titratable acidity	0.00	-0.16	-0.29	1.00								
Sugar-acid ratio	0.04	0.33	0.55	-0.90	1.00							
Hydropectin	-0.48	-0.21	-0.40	0.69	-0.74	1.00						
Protopectin	-0.30	-0.47	-0.38	0.26	-0.37	0.46	1.00					
Total pectins	-0.20	-0.47	-0.45	0.33	-0.47	0.50	0.97	1.00				
Ascorbic acid	-0.22	-0.12	-0.37	0.49	-0.29	0.42	0.03	0.03	1.00			
Total polyphenols	0.14	0.15	-0.14	0.26	-0.40	0.53	0.28	0.31	0.10	1.00		
Antocyanidines	0.37	0.46	0.44	0.57	-0.31	0.33	0.23	0.23	0.22	0.44	1.00	
Chalcones	0.39	0.44	0.26	0.53	-0.38	0.36	0.11	0.11	0.31	0.72	0.88	1.00

Source: compiled by the authors

The relationship between the traits is considered weak with a correlation coefficient of 0.1-0.29, moderate with a coefficient of 0.3-0.49, noticeable with a coefficient of 0.5-0.69, high with a coefficient of 0.7-0.89, and very high with a coefficient of 0.9-0.99 (Mezhenskyj, 2017). A high correlation was found between total pectin content and protopectin content ($r = 0.97$), as protopectin is the primary component of pectic substances. The relationship between total pectin and hydropectin was noticeable ($r = 0.50$). The high correlation coefficient between anthocyanin and chalcone content ($r = 0.88$) is explained by the fact that chalcones are anthocyanin precursors. Chalcones also have a high correlation coefficient with total phenols ($r = 0.72$). Similarly, there is a high correlation between total sugars and soluble solids ($r = 0.76$), possibly due to sugars contributing to a significant proportion of soluble solids.

The calculated sugar-acid index exhibits a high negative correlation with titratable acidity ($r = -0.90$) and a noticeable positive correlation with total sugars ($r = 0.55$). The sugar-acid index also has a high correlation coefficient with hydropectin content (-0.74). There is a noticeable correlation between titratable acidity and hydropectin content ($r = 0.69$), anthocyanins ($r = 0.57$), and chalcones ($r = 0.53$). There is also a moderate correlation between titratable acidity and ascorbic acid content (r = 0.44). In addition to a high correlation coefficient with chalcones and total polyphenols, and a noticeable correlation with titrated acidity, anthocyanins have a moderate correlation with soluble solids (r = 0.44). Overall, the correlation analysis not only confirmed established biochemical relationships but also elucidated specific associations within the studied cultivars. Hierarchical clustering analysis, visualised through the dendrograms (Figs. 1 and 2), highlights the biochemical diversity and relationships among the studied cultivars.

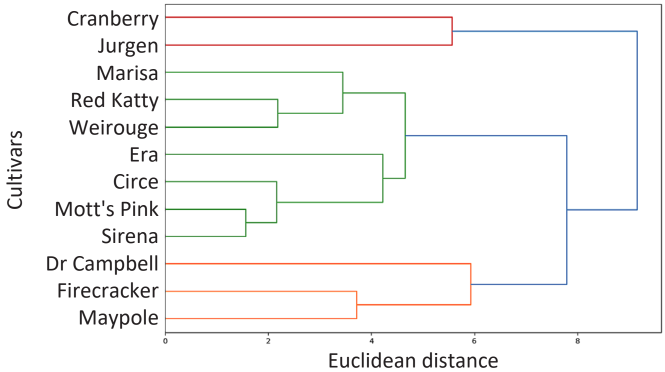

Figure 1. Dendrogram of cultivars clustering based on all biochemical characteristics
Source: compiled by the authors

A large cluster encompasses most of the cultivars studied: 'Marisa', 'Red Katty', 'Weirouge', 'Era', 'Circe', and 'Mott's Pink'. They are characterised by their relative biochemical similarity. This cluster can be divided into several subgroups connected at different stages. 'Dr Campbell', 'Firecracker', and 'Maypole' form a separate group, while 'Cranberry' and 'Jurgen' have the most different phytochemical profiles of all the varieties. When considering only varieties according to indicators of biologically active substances with antioxidant activity in cluster analysis, the cultivars will be grouped differently (Fig. 2).

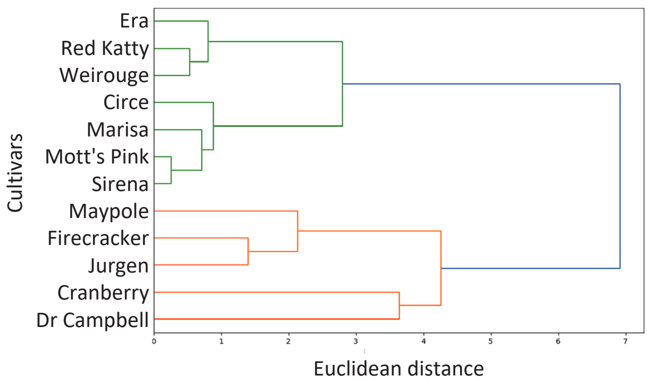

Figure 2. Dendrogram of cultivars clustering based on antioxidant traits
Source: compiled by the authors

The large cluster contains the same varieties as the previous dendrogram, but groups them differently into two subclusters. The first subcluster comprises 'Red Katty', 'Weirouge', and 'Era', while the second comprises 'Mott's Pink' and 'Sirena', alongside 'Marisa' and 'Circe'.

Varieties with a higher content of biologically active substances form another cluster, which has two subclusters. The first subcluster contains 'Firecracker' and 'Jurgen', which have the highest polyphenol content, and 'Maypole'. 'Cranberry' and 'Dr Campbell' are the most distinct in terms of the complex of bioactive substances, forming the second subcluster connected to the first at a distance of about 4.2.

CONCLUSIONS

This research, conducted over two years (2023-2024), aimed to analyse the nutritional and biochemical composition of 12 red-fleshed apple cultivars grown in Ukraine. The study demonstrated that red-fleshed apples are a significantly richer source of phytochemicals than typical dessert varieties, therefore highly promising for dietary use and processing. Red-fleshed apples were found to far surpass conventional sweet apples in their total polyphenol content. Specifically, cultivars such as 'Jurgen' and 'Firecracker' demonstrated exceptionally high concentrations of these antioxidants, highlighting their potential as functional foods. The amount of anthocyanins, which are responsible for the flesh's red colour, varied considerably among the cultivars. The cultivar 'Dr Campbell' was noted for the highest concentration of these beneficial pigments, making it particularly valuable for breeding and consumption. The study also revealed that environmental factors, such as weather conditions and the harvest year, significantly influenced the levels of certain compounds. For example, the content of hydropectin, total polyphenols, and chalcones fluctuated depending on the year, indicating the crucial role of the environment in shaping the fruit's chemical composition. This underscores the need for long-term studies to obtain stable and reliable data. The analysis of biochemical profiles revealed strong relationships between different compounds. A strong positive correlation was found between high levels of anthocyanins and their precursor compounds, chalcones. This suggests efficient metabolic pathways leading to the synthesis of these beneficial substances in certain cultivars. Clustering the cultivars based on their biochemical profiles identified several unique and promising cultivars. The 'Dr Campbell', 'Cranberry', 'Jurgen', 'Firecracker', and 'Maypole' were identified as valuable and with distinct chemical compositions. These cultivars can be recommended for further breeding programs aimed to improve the nutritional value of apples, as well as to produce functional foods.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

[1] Asma, U., Morozova, K., Ferrentino, G., & Scampicchio, M. (2023). Apples and apple by-products: Antioxidant properties and food applications. *Antioxidants,* 12(7), article number 1456. doi: 10.3390/antiox12071456.

[2] Bars-Cortina, D., Macià, A., Iglesias, I., Garanto, X., Badiella, L., & Motilva, M.-J. (2018). Seasonal variability of the phytochemical composition of new red-fleshed apple varieties compared with traditional and new white-fleshed varieties. *Journal of Agricultural and Food Chemistry,* 66(38), 10011-10025. doi: 10.1021/acs.jafc.8b03950.

[3] Bars-Cortina, D., Macià, A., Iglesias, I., Romero, M.P., & Motilva, M.J. (2017). Phytochemical profiles of new red-fleshed apple varieties compared with traditional and new white-fleshed varieties. *Journal of Agricultural and Food Chemistry*, 65(8), 1684-1696. doi: 10.1021/acs.jafc.6b02931.

[4] Bouillon, P., Fanciullino, A.-L., Belin, E., Bréard, D., Boisard, S., Bonnet, B., Hanteville, S., Bernard, F., & Celton, J.-M. (2024). Image analysis and polyphenol profiling unveil red-flesh apple phenotype complexity. *Plant Methods*, 20, article number 71. doi: 10.1186/s13007-024-01196-1.

[5] Brossaud, F., Cheynier, V., & Noble, A.C. (2008). Bitterness and astringency of grape and wine polyphenols. *Australian Journal of Grape and Wine Research,* 7, 33-39. doi: 10.1111/j.1755-0238.2001.tb00191.x.

[6] Ceci, A.T., Bassi, M., Guerra, W., Oberhuber, M., Robatscher, P., Mattivi, F., & Franceschi, P. (2021). Metabolomic characterization of commercial, old, and red-fleshed apple varieties. *Metabolites,* 11(6), article number 378. doi: 10.3390/metabo11060378.

[7] Convention on Biological Diversity. (1992, June). Retrieved from https://www.cbd.int/doc/legal/cbd-en.pdf.

[8] Convention on the Trade in Endangered Species of Wild Fauna and Flora. (1976, March). Retrieved from https://surl.li/pzwcxf.

[9] Drkenda, P., Ćulah, A., Spaho, N., Akagić, A., & Hudina, M. (2021). How do consumers perceive sensory attributes of apple? *Foods*, 10(11), article number 2667. doi: 10.3390/foods10112667.

[10] Espley, R.V., *et al.* (2013). Analysis of genetically modified red-fleshed apples reveals effects on growth and consumer attributes. *Plant Biotechnology Journal,* 11(4), 408-419. doi: 10.1111/pbi.12017.

[11] Farzaliev, E.B., & Ökten, S. (2025). Pectin as a functional food ingredient in jelly marmalade. *Natural Product Research*, 1-6. doi: 10.1080/14786419.2025.2455461.

[12] Food and Agriculture Organization (FAO). (2025). Retrieved from https://www.fao.org/faostat/.

[13] Gwanpua, S.G., Buggenhout, S.V., Verlinden, B.E., Christiaens, S., Shpigelman, A., Vicent, V., Kermani, Z.J., Nicolai, B.M., Hendrickx, M., & Geeraerd, A. (2014). Pectin modifications and the role of pectin-degrading enzymes during postharvest softening of Jonagold apples. *Food Chemistry,* 158, 283-291. doi: 10.1016/j.foodchem.2014.02.138.

[14] Jalali, M., Abedi, M., Tabarsa, M., & Moreno, D.A. (2024). Morphological and biochemical characteristics of wild red-fleshed apples (*Malus sieversii* f. *niedzwetzkyana*) in the North and Northeast of Iran. *BMC Plant Biology,* 24, article number 899. doi: 10.1186/s12870-024-05608-1.

[15] Juhart, J., Medic, A., Veberic, R., Hudina, M., Jakopic, J., & Stampar, F. (2022). Phytochemical composition of red-fleshed apple cultivar ‘Baya Marisa’ compared to traditional, white-fleshed apple cultivar ‘Golden Delicious’. *Horticulturae,* 8(9), article number 811. doi: 10.3390/horticulturae8090811.

[16] Mezhenskyj, V.M. (2017). *Fundamentals of scientific research in horticulture. Calculations in Microsoft Excel: Study guide*. Kyiv: Lira-K.

[17] Mezhenskyj, V.M., Pyshcholka, D.V., Mezhenska, L.O., & Havryliuk, O.S. (2024). An overview of the red-fleshed apple: History and its importance for horticulturists, gardeners, nurserymen, and consumers. *Biosystems Diversity*, 32(1), 158-167. doi: 10.15421/012416.

[18] Ministry of Agrarian Policy and Food of Ukraine. (n.d.). *State register of plant varieties suitable for distribution in Ukraine*. Retrieved from https://minagro.gov.ua/file-storage/reyestr-sortiv-roslin.

[19] Shevchuk, L., Grynyk, I., Levchuk, L., Babenko, S., Podpriatov, H., & Kondratenko, P. (2021). Fruit quality indicators of apple (*Malus domestica* Borkh.) cultivars bred in Ukraine. *Journal of Horticultural Research,* 29(2), 95-106. doi: 10.2478/johr-2021-0019.

[20] Wang, D., *et al.* (2024). Dynamic changes in polyphenols in fruit development of red flesh apple ‘Hongxun 2’. *Horticulturae*, 10(11), article number 1125. doi: 10.3390/horticulturae10111125.

[21] Wang, N., Jiang, S., Zhang, Z., Fang, H., Xu, H., Wang, Y., & Chen, X. (2018). *Malus sieversii*: The origin, flavonoid synthesis mechanism, and breeding of redskinned and red-fleshed apples. *Horticulture Research,* 5, article number 70. doi: 10.1038/s41438-018-0084-4.

[22] Xu, T., *et al.* (2023). The regulatory role of MdNAC14-Like in anthocyanin synthesis and proanthocyanidin accumulation in red-fleshed apples. *Plant Physiology and Biochemistry*, 204, article number 108068. doi: 10.1016/j.plaphy.2023.108068.

[23] Yu, L., Sun, Y., Zhang, X., Chen, M., Wu, T., Zhang, J., Xing, Y., Tian, J., & Yao, Y. (2022). ROS1 promotes low temperature-induced anthocyanin accumulation in apple by demethylating the promoter of anthocyanin-associated genes. *Horticulture Research*, 9, article number uhac007. doi: 10.1093/hr/uhac007.

[24] Yuste, S., Ludwig, I.A., Romero, M.-P., Motilva, M.-J., & Rubió, L. (2022). New redfleshed apple cultivars: A comprehensive review of processing effects, (poly)phenol bioavailability and biological effects. *Food and Function*, 13(9), 4861-4874. doi: 10.1039/D2FO00130F.

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Біохімічний склад і харчова цінність червоном’якушних сортів яблуні в Лісостепу України

Анотація. Це дослідження було присвячене вивченню біохімічного складу та поживної цінності 12 сортів червоном’якушних яблук, вирощених у Національному університеті біоресурсів і природокористування України. Метою було оцінити їхній фітохімічний профіль, включаючи суху речовину, розчинні сухі речовини, загальні цукри, титровану кислотність, пектини та ключові біоактивні сполуки, такі як аскорбінова кислота, загальні поліфеноли, антоціани та халкони. Дослідження, яке проводилося протягом двох років поспіль (2023-2024), також мало на меті виявити кореляції між цими показниками та кластеризувати сорти зі схожими хімічними профілями. Результати показали, що сорти демонструють широкий спектр біохімічних характеристик. Хоча вміст сухої речовини, розчинних сухих речовин та пектинів був порівнянний із сучасними білом’якушними сортами, вміст загальних поліфенолів був значно вищим, у середньому 335,69 мг/100 г. Найвищі рівні поліфенолів було виявлено в сортів ‘Jurgen’ (643,85 мг/100 г) та ‘Firecracker’ (629,60 мг/100 г). Присутність антоціанів у м'якуші значно варіювалася, від 2,50 до 28,64 мг/100 г, причому найвища концентрація була у сорту ‘Dr Campbell’. Дослідження також виявило значні коливання деяких показників, зокрема гідропектину, загальних поліфенолів та халконів, залежно від року, що свідчить про вплив навколишнього середовища. Було виявлено високу позитивну кореляцію між антоціанами та халконами ($r = 0,88$), а також між загальними поліфенолами та халконами ($r = 0,72$). Ієрархічний кластерний аналіз визначив окремі групи сортів, причому найвищий вміст біологічно активних речовин був у ‘Dr Campbell’, ‘Cranberry’, ‘Jurgen’, ‘Firecracker’ та ‘Maypole’. Ці результати підкреслюють потенціал червоном’якушних сортів яблук як багатого джерела корисних для здоров'я сполук, надаючи цінні дані для майбутніх селекційних програм та для споживачів

Ключові слова: *Malus domestica* Niedzwetzkyana Group; аскорбінова кислота; поліфенолові речовини; антоціани; антиоксидантна активність

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Quality indicators of introduced strawberry varieties (*Fragaria × ananassa* Duch.) grown in the Polissya region of Ukraine

Abstract. Strawberries are among the earliest fruits of the season and represent a valuable dietary product due to their high content of nutrients and bioactive compounds. New strawberry varieties are added to the assortment each year and require systematic evaluation, particularly in relation to their adaptability to specific growing conditions. This study examined the suitability of introduced garden strawberry varieties for cultivation under the conditions of the Polissya region of Ukraine. Yield and average berry weight were determined by gravimetric methods, while sugar content and polyphenolic compounds were assessed using spectrophotometry. Titratable acidity and vitamin C content were determined by titration. The obtained data were analysed statistically using the STATISTICA software package and analysis of variance (ANOVA). The results indicate that the

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varieties 'Sensation' and 'Symphony' exhibit the highest yields. These varieties also show the greatest average fruit weight, exceeding 30.0 g, whereas 'Clery' records the lowest values. The analysed fruits show a dry matter content of 11.1% and a soluble solids content of 8.5%. The 'Clery' and 'Jolly' varieties accumulated significantly higher sugar levels than the other studied varieties, while 'Elsanta', 'Asia', and 'Malvina' demonstrated lower sugar accumulation. The favourable sensory properties of the 'Clery' variety, reflected by a sugar-acid index of 8.4, were associated with its high sugar content and low titratable acidity of 0.91%. The concentration of bioactive compounds in the studied fruits ranged from 31.0 to 68.3 mg of vitamin C per 100 g and from 150.0 to 307.3 mg of polyphenolic compounds per 100 g of fresh weight. The 'Sensation' variety was distinguished by a high phytochemical content, with a vitamin C concentration of 51 mg/100 g. The findings are of practical relevance for breeders selecting parental material for the development of new varieties and for producers choosing cultivars for the establishment of industrial plantations in the Polissya region of Ukraine

Keywords: fruits; yield; sugars; vitamin C; polyphenolic substances

INTRODUCTION

The strawberry (*Fragaria × ananassa*) is an early-ripening fruit characterised by a rich biochemical composition. Together with blue honeysuckle, it marks the beginning of the season for the consumption of fresh berry products in Ukraine. This crop is valued for its relatively simple cultivation technology, rapid onset of fruiting, and the preventive and therapeutic properties of its fruits, which exhibit high sensory quality indicators. At present, the strawberry assortment is expanding through the introduction of new varieties, which do not always demonstrate sufficient adaptability to the growing conditions of different regions of Ukraine.

Owing to their biological characteristics, strawberries are cultivated across a wide range of climatic zones, including cool, temperate, subtropical, and Mediterranean climates. Nevertheless, careful selection of highly adaptable and productive varieties remains necessary under specific regional growing conditions. According to Z. Liu *et al.* (2023), the high adaptability of strawberries, together with their elevated vitamin, fibre, and antioxidant content, contributes to their status as one of the most popular berry crops worldwide. Data from the Food and Agriculture Organization of the United Nations (FAO) (n.d.) indicate that the global area under strawberry cultivation increased by approximately 80,000 hectares between 2013 and 2023, while gross production rose by more than 3 million tonnes. As of 2023, China ranked as the global leader in strawberry production, with an estimated gross output of approximately 27 million tonnes. In Ukraine, the State Statistics Service of Ukraine (n.d.) reports that strawberries occupied 0.9 thousand hectares in 2024, with a gross harvest of 5.2 thousand tonnes. N. Kilic *et al.* (2021) report that strawberries have gained increasing recognition among consumers due to their distinctive flavour, extended market availability, and health-promoting properties. M. Sarıdaş (2021) and J. Newerli-Guz *et al.* (2023) emphasise the rich content of biologically active compounds in strawberry fruits, which influence metabolic and physiological processes in the human body. Other researchers, including Z. Fan *et al.* (2021) in Florida, United States, indicate that consumer quality attributes of strawberries are closely associated with the concentration of key components, particularly sugars and organic acids. Spanish researchers M. Navarro-Hortal *et al.* (2022) demonstrate that these quality parameters contribute to a reduced risk of cardiovascular disease, type 2 diabetes, neurodegenerative disorders, and certain forms of cancer. According to R. Qaderi (2023), the biochemical composition of strawberries depends on multiple factors, including genotype and environmental conditions. Berry size and weight also represent critical determinants of strawberry quality, alongside colour and flavour. Based on these attributes, strawberries are classified as suitable for fresh consumption or intended for processing, despite possessing acceptable sensory characteristics. Climate change exerts a substantial influence on strawberry yield and quality. N. Khammayom *et al.* (2022) note that the selection of strawberry varieties for cultivation in different countries is shaped not only by climatic and environmental factors, but also by agricultural traditions and agronomic capacity. A considerable proportion of agricultural land in Ukraine lies within a temperate climatic zone, which is favourable for open-field strawberry cultivation. Consequently, the selection of varieties that demonstrate high adaptability to specific natural and climatic zones and produce high yields meeting commercial and consumer quality standards remains a priority for scientific research. Given the nutritional and therapeutic value of strawberries and their sensory attributes, breeding programmes worldwide focus on the development of new varieties. The introduction of these varieties into diverse regions, including Ukraine, necessitates comprehensive evaluation of their adaptability to local climatic conditions.

The purpose of the study was to identify the most adaptable introduced strawberry varieties for industrial plantations in the Polissya region of Ukraine and to provide breeders with scientifically grounded information on varieties exhibiting superior commercial, sensory, and bioactive quality indicators.

MATERIALS AND METHODS

The study was conducted during the period 2022-2024 at the Educational and Scientific Laboratories (ESL) of the Department of Horticulture of the National University of Life and Environmental Sciences of Ukraine named after V.L. Simirenko. The ESL is located in the Polissya region of Kyiv on medium podzolic soils formed from glacial deposits. Strawberry plantations were established in 2022 using frigo seedlings. The planting scheme was defined as 0.9 × 0.20 × 0.25 m, corresponding to a planting density of 71,400 plants per hectare. The plantations are equipped with drip irrigation systems, and mulch is applied annually between the rows. Grain straw serves as the mulching material. Before strawberry planting, optimal rates of nitrogen, potassium, and phosphorus fertilisers were applied to the soil. From May onwards, plants received four foliar fertiliser treatments at monthly intervals. Protection of the strawberry plantations followed the Syngenta protection scheme (n.d.).

The optimal ripeness stage of strawberries was determined through visual assessment. Strawberry ripening is characterised by the development of varietal red colouration. Average berry weight and yield were determined through weighing. Within the study, berries were harvested from five reference plants, counted, and weighed. The total berry mass from each plant was divided by the number of plants sampled. Strawberry yield was determined by weighing berries harvested at each picking stage, after which individual weights were summed to obtain the total yield. Plant density per hectare was established, and yield per hectare was calculated accordingly. Berry firmness was measured using a stationary Chatillon penetrometer (United States) and expressed in newtons, employing a 3 mm probe. Medium-sized berries were selected for analysis, with five fruits sampled from each variety.

Before analytical determination, samples were obtained from 30 strawberries and homogenised using a laboratory homogeniser. Sample mass was measured using Axis AD 200R analytical scales (Poland) with an accuracy of two decimal places. Dry matter content was determined by drying samples at a temperature of 98-100°C. For this purpose, 5 g of homogenised fresh strawberry material was mixed with dry river sand. Samples were weighed before and after drying. Drying was conducted in an SP-30 drying oven manufactured in Ukraine until a constant mass was achieved. Dry matter content was calculated as the difference between the initial sample mass and water mass, recalculated per 100 g, and expressed as a percentage. Soluble solids content was determined using the refractometric method with a portable Atago PAL-1 refractometer (Japan). Ten ripe strawberries were homogenised, and a drop of juice was filtered through fabric and placed on the refractometer prism. Measurements were recorded with correction for laboratory temperature variation. Soluble solids content was expressed as a percentage of fresh weight per 100 g.

Sugar content in strawberry fruits was determined using a colorimetric method. Sugars were extracted with hot water, after which proteins and pigments were removed by precipitation with lead acetate. Sucrose hydrolysis into glucose and fructose was achieved by heating with the addition of 10% hydrochloric acid. Hydrolysis products were oxidised using Fehling solution. Optical density was measured using a ULAB 102UV spectrophotometer (China) at a wavelength of 640 nm. Sugar concentration in strawberry fruits was calculated using a formula and a calibrated graphical method. A calibration curve representing the relationship between optical density and glucose concentration (mg/ml) was constructed using standard glucose solutions of varying concentrations. Sugar content results were expressed as a percentage of fresh weight (% per 100 g).

The titration method was used to determine the organic acid content of strawberry fruits. A 25 g sample of homogenised fruit from each variety was transferred to a 250 ml volumetric flask and diluted with 150 ml of hot distilled water. Extraction proceeded in a water bath at 80°C for 30 minutes, after which the sample was cooled. The volume was then adjusted to the calibration mark with distilled water, filtered, and transferred to a 250 ml conical flask. A 20 ml aliquot of the extract was transferred to a conical flask, and 3-4 drops of phenolphthalein indicator were added. Titration was performed with 0.1 N sodium hydroxide solution until the appearance of a stable pink colour corresponding to a pH of 7.0. Titratable acidity in strawberry fruits was calculated using the volume of 0.1 N sodium hydroxide solution consumed and a conversion factor to citric acid. The content of titratable acids was expressed as a percentage of fresh weight (% per 100 g).

The sugar-acid index of strawberry fruits was determined as the ratio of total sugar content to titratable acidity. Ascorbic acid content in strawberry fruits was determined by titration. Fruit pulp was ground in a porcelain mortar with the addition of crushed glass and an extracting mixture of 2% oxalic acid and 1% hydrochloric acid (80:20, v/v). The homogenised sample was transferred to a 100 ml volumetric flask, and the volume was adjusted to the mark using the same extracting mixture. The solution was filtered and titrated with 2,6-dichlorophenolindophenol solution (Tillman's reagent). Ascorbic acid concentration was calculated using the standard Tillman's titration formula. Results were expressed as milligrams per 100 g of fresh fruit weight (mg/100 g).

Polyphenol content in strawberry fruits was determined using a spectrophotometric method. Fruit samples were homogenised in a porcelain mortar with the addition of ethyl alcohol. The homogenate was filtered through blue-band paper into a Bunsen flask using a VF-15S vacuum filtration system. Residual material on the filter was washed with small portions of ethyl alcohol until complete discolouration occurred, and the total volume of alcohol used was recorded. Subsequently, 7.9 ml of distilled water, 0.1 ml of extract, and 1 ml of Folin-Denis reagent were mixed, and after 3 minutes, 1 ml of saturated sodium carbonate solution was added and mixed thoroughly. Absorbance was measured at a wavelength of 640 nm using a ULAB 102UV spectrophotometer (China). The control solution consisted of 8 ml of distilled water, 1 ml of Folin-Denis reagent, and 1 ml of saturated sodium carbonate solution. Polyphenol content was calculated using a calibration curve and expressed as milligrams per 100 g of fresh weight (mg/100 g).

Statistical analysis was performed using STATISTICA 13.1 (StatSoft, Inc., United States). Results were presented as mean values with standard errors, expressed as mean ± standard error ($x \pm SE$). Differences between varieties were assessed using analysis of variance (ANOVA). Statistical significance was accepted at $p < 0.05$. Pairwise comparisons were applied to identify significant differences among means. The study complies with the ethical principles of the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1976).

RESULTS AND DISCUSSION

The yield of the strawberry varieties under study ranged from 10.3 t/ha in the 'Clery' cultivar to 21.7 t/ha in the 'Symphony' cultivar. Mean yield for this group of varieties amounted to 15.3 t/ha. With the exception of the 'Sensation' and 'Asia' varieties, yields exceeded this average value. The mean yield corresponds closely to the maximum yield reported by S. Chowhan *et al.* (2016), which reached 15.83 t/ha. The yields of the 'Romina', 'Flair', 'Sonata', 'Joly', and 'Elsanta' varieties were below the group average and amounted to 11.9, 10.5, 12.4, and 12.5 t/ha, respectively. The yield of the 'Clery' variety exceeded the group average. This value remains lower than the minimum yield of 6.15 t/ha reported by the same authors and by researchers in Norway in Valdal and Trondheim, where yields of 9.4 and 5.7 t/ha were recorded, respectively (Døving & Måge, 2001). Average yield values were observed for the 'Kimberly' (14.0 t/ha) and 'Malvina' (14.5 t/ha) varieties (Table 1).

Table 1. Yield, weight and firmness of strawberries, average 2023-2024

Varieties	Yield t/ha	Average weight of berries, g	Firmness of berries, N
'Clery'	10.3 ± 0.6[b]	14.5 ± 0.3[b]	6.0 ± 0.3[a]
'Romina'	11.9 ± 0.5[b]	16.6 ± 0.4[b]	6.2 ± 0.2[a]
'Kimberly'	14.0 ± 0.4[ab]	19.6 ± 0.4[ab]	4.5 ± 0.3[b]
'Flair'	10.5 ± 0.4[b]	14.7 ± 0.5[b]	5.9 ± 0.2[a]
'Sonata'	12.4 ± 0.4[b]	17.4 ± 0.5[b]	6.2 ± 0.2[a]
'Joly'	10.6 ± 0.5[b]	14.8 ± 0.3[b]	5.9 ± 0.3[ab]
'Elsanta'	12.5 ± 0.8[b]	17.5 ± 0.6[ab]	4.6 ± 0.2[b]
'Asia'	15.3 ± 0.7[a]	21.4 ± 0.9[ab]	6.1 ± 0.3[a]
'Sensation'	21.6 ± 0.5[a]	30.3 ± 0.7[a]	5.6 ± 0.3[ab]
'Malvina'	14.5 ± 0.9[ab]	20.3 ± 1.3[ab]	3.7 ± 0.3[b]
'Symphony'	21.7 ± 0.7[a]	30.4 ± 0.9[a]	4.6 ± 0.2[b]
Mean ± SE	14.1 ± 0.2	19.8 ± 0.3	5.4 ± 0.2
Min	10.3 ± 0.2	14.5 ± 0.3	3.7 ± 0.1
Max	21.7 ± 0.7	30.4 ± 0.9	6.2 ± 0.1
V, %	29	29	17

Note: [a] and [b] – indicate values that differ significantly from the mean; values marked [ab] do not differ significantly from the mean; the results of the comparison were obtained using Tukey's test with the Bonferroni correction
Source: developed by the authors

As noted by K. Simkova *et al.* (2023), berry weight, together with other physical attributes such as size and colour, represents one of the most important indicators of strawberry quality. The data demonstrate that fruits can be classified according to their suitability for fresh market sale, rejection, or use in technical processing. This classification applies regardless of the ability of the fruit to provide acceptable taste and colour characteristics.

The weight of strawberries grown in the Polissya region of Ukraine ranged from 14.5 g for the 'Clery' variety to 30.4 g for the 'Symphony' variety, with a mean value of 19.8 g for the group. L. Antunes *et al.* (2010) reported an average berry weight of 20.28 g for the 'Camarosa' variety and 16.83 g for the 'Festival' variety, which corresponds closely to the results obtained for the 'Romina' and 'Malvina' varieties, where average berry weights amounted to 16.6 and 20.3 g, respectively. Although the mean berry weight of 'Romina' was lower than the group average, the values recorded for the 'Kimberly' (19.6 g), 'Elsanta' (17.5 g), and 'Malvina' (20.3 g) varieties did not differ significantly from the mean. The 'Symphony' and 'Sensation' varieties exhibited berry weights exceeding 30.0 g, representing the maximum values recorded. The lowest berry weights were observed for the 'Clery', 'Fleur', and 'Joly' varieties, amounting to 14.5, 14.7, and 14.8 g, respectively (Table 1). The berry weight values obtained in this study substantially exceed those reported by C. Menzel (2021), who indicates that strawberries weighing 4-12 g are considered unsuitable for market sale. According to E. Krüger *et al.* (2012), fruit size may vary within the same variety depending on the cultivation location.

Fruit firmness represents another important physical indicator of strawberry quality (Sykalo & Shpak, 2024). Firmness determines transportability, as higher firmness reduces mechanical damage during handling and transportation. The firmness of the strawberry fruits analysed ranged from 3.7 N for the 'Malvina' variety to 6.2 N for the 'Romina' and 'Sonata' varieties. The 'Clery' variety exhibited a firmness of 6.0 N, while the 'Asia' variety reached 6.1 N. These values exceed the group average. With the exception of the 'Malvina' variety, firmness values of 4.5 N were recorded for 'Kimberly', 'Elsanta', and 'Symphony', while 'Elsanta' and 'Symphony' showed values of 4.6 N (Table 1). Intermediate firmness values were observed for the 'Sensation' and 'Joly' varieties, amounting to 5.6 N. J. Lee *et al.* (2024) reported firmness values of 36.2 g·mm^{-2} for the 'Mika' variety and 10.1 g·mm^{-2} higher values for the 'Goha' variety, corresponding to 3.6 and 4.03 N, respectively, which represent some of the lowest firmness levels among the varieties examined in that study.

Dry matter content in the analysed strawberry fruits averaged 11.0%. Mean dry matter values were recorded for the 'Malvina' (10.4%), 'Sensation' (10.7%), 'Asia' (10.5%), and 'Clery' (10.5%) varieties. Significantly higher dry matter content was observed in the 'Sonata', 'Joly', and 'Symphony' varieties, amounting to 12.3, 12.4, and 11.7%, respectively, while lower values were recorded for 'Romina' and 'Kimberly', at 10.3 and 10.4% (Table 2).

Table 2. Organic matter content and sugar-acid index of strawberry fruits, average 2023-2024

Varieties	Dry matter, %	Dry soluble substances	Sugars	Titratable acids	Sugar-acid index
		% of fresh weight			
'Clery'	10.5 ± 0.3^{ab}	8.5 ± 0.2^{ab}	7.6 ± 0.1^{a}	0.91 ± 0.03^{b}	8.4
'Romina'	10.3 ± 0.2^{b}	8.1 ± 0.2^{ab}	5.6 ± 0.2^{ab}	0.80 ± 0.05^{b}	7.0
'Kimberly'	10.4 ± 0.2^{b}	8.5 ± 0.3^{ab}	5.5 ± 0.3^{ab}	1.06 ± 0.05^{a}	5.2
'Flair'	11.7 ± 0.4^{ab}	9.2 ± 0.2^{a}	5.6 ± 0.3^{ab}	0.86 ± 0.03^{b}	6.5
'Sonata'	12.3 ± 0.3^{a}	9.4 ± 0.4^{a}	6.1 ± 0.3^{ab}	1.12 ± 0.03^{a}	5.4
'Joly'	12.4 ± 0.2^{a}	8.8 ± 0.3^{ab}	8.5 ± 0.2^{a}	1.26 ± 0.04^{a}	6.7
'Elsanta'	10.4 ± 0.3^{ab}	8.2 ± 0.1^{ab}	5.1 ± 0.2^{b}	0.89 ± 0.02^{b}	5.7
'Asia'	10.5 ± 0.2^{ab}	7.8 ± 0.3^{b}	4.9 ± 0.2^{b}	1.02 ± 0.03^{a}	4.8
'Sensation'	10.7 ± 0.3^{ab}	8.5 ± 0.2^{ba}	4.6 ± 0.4^{b}	1.08 ± 0.01^{a}	4.3
'Malvina'	10.4 ± 0.3^{ab}	8.1 ± 0.5^{ab}	4.4 ± 0.2^{b}	0.79 ± 0.02^{b}	5.6
'Symphony'	11.7 ± 0.2^{a}	8.5 ± 0.4^{ab}	5.3 ± 0.3^{ab}	0.82 ± 0.02^{b}	6.5
Mean ± SE	11.0 ± 0.3	8.5 ± 0.3	5.8 ± 0.3	0.98 ± 0.02	6.0
Min	10.3 ± 0.2	7.8 ± 0.2	4.4 ± 0.2	0.79 ± 0.02	4.8
Max	12.4 ± 0.2	9.4 ± 0.2	8.5 ± 0.2	1.26 ± 0.04	8.4
V, %	8.6	5.8	21.5	15.7	

Note: ^{a} and ^{b} – indicate values that differ significantly from the average; values marked ^{ab} do not differ significantly from the mean; the results of the comparison were obtained using Tukey's test with the Bonferroni correction
Source: developed by the authors

According to Serbian researchers, strawberry fruits accumulate soluble solids in the range of 6-12% (Akšić *et al.*, 2019). S. Pădureț *et al.* (2017) reported even higher values, ranging from 8.4 to 14.2%. Among the varieties examined in the present study, the highest soluble solids content was recorded in the 'Sonata' variety, at 9.4%. This value exceeded the inter-varietal mean and was slightly higher than that observed for the 'Flair' variety (9.2%), while remaining below the maximum values reported by M. Akšić *et al.* (2019) and S. Pădureț *et al.* (2017). The lowest soluble solids content was observed in fruits of the 'Asia' variety (7.8%). In the remaining varieties included in the study, soluble solids content did not differ significantly and remained close to the group mean of 8.5% (Table 2). This value exceeds the minimum levels reported in the literature and corresponds to the lower range of published data. C. Menzel (2022) reported a mean soluble solids content of 7.6% for the varieties analysed in his study, which is 0.9 percentage points lower than the mean value recorded in the present research.

Sweetness in strawberries depends primarily on sugar content. Sugars, together with titratable acidity and the concentration of volatile compounds, constitute the main determinants of strawberry flavour, as reported by M. Schwieterman *et al.* (2014), and vary depending on cultivar characteristics (Haynes, 2024). Sugar content among the analysed varieties ranged from 4.4 to 8.5%, with an inter-varietal mean of 5.8%. The proportion of sugars in soluble solids ranged from 54% in the 'Sensation' variety to 96% in the 'Joly' variety. The sugar content of 'Joly' fruits exceeded the group average and reached 8.5%, while the 'Malvina', 'Sensation', and 'Asia' varieties exhibited values below the mean, amounting to 4.4, 4.6, and 4.9%, respectively. In the remaining varieties, sugar content ranged from 5.3% in 'Symphony' to 6.1% in 'Sonata' (Table 2). These values correspond closely to the level of 57.4 mg/g (5.7%) reported by C. Menzel (2022).

Titratable acidity represents another key indicator influencing strawberry taste. The highest acidity was recorded in the 'Joly' variety (1.26%), while the lowest value was observed in 'Malvina' (0.79%). Mean inter-varietal acidity was observed in fruits of the 'Asia' variety (1.02%). Titratable acid content in the 'Symphony', 'Elsanta', 'Romina', and 'Clery' varieties amounted to 0.82, 0.89, 0.80, and 0.91%, respectively. These values exceed those reported by C. Menzel (2022) by at least 0.21 percentage points and those reported by J. Lee *et al.* (2024) by 0.17 percentage points. Elevated titratable acidity levels were also recorded in the 'Kimberly' (1.06%), 'Sonata' (1.12%), and 'Sensation' (1.08%) varieties, all exceeding 1.0% (Table 2).

The characteristic taste of strawberries is largely determined by the sugar-to-acid ratio (Schwieterman *et al.*, 2014), which is widely regarded as a reliable indicator of fruit flavour quality (Antunes *et al.*, 2010). Superior strawberry quality is associated with high sugar content and an elevated sugar-to-acid ratio (Yan *et al.*, 2018). These principles explain the results obtained in the present study, particularly the combination of high sugar content (7.6%) and relatively low titratable acidity (0.91%), which resulted in the maximum sugar-acid index of 8.4 for the 'Clery' variety. Sugar-acid index values exceeding the group mean (6.0) were also observed in the 'Romina' (7.0), 'Flair' (6.5), and 'Joly' (6.7) varieties. In the first two cases, elevated sugar-acid index values resulted primarily from reduced titratable acidity below 1.0%, while in 'Joly', high sugar content of 8.5% constituted the decisive factor. Sugar-acid index values below 5.0 were recorded for the 'Asia' (4.8) and 'Sensation' (4.3) varieties, reflecting the combination of low sugar content, at 4.9 and 4.6%, respectively, and elevated titratable acidity, amounting to 1.08 and 1.02% (Table 2).

Vitamin C plays a pivotal role in determining the nutritional value of strawberries, as this fruit represents one of the most important natural sources of this essential micronutrient (Zhong *et al.*, 2017). The strawberry varieties analysed accumulated vitamin C in the range from 31.0 mg per 100 g in the 'Elsanta' variety to 68.3 mg per 100 g in the 'Clery' variety, with a mean content of 45.9 mg per 100 g. Strawberries cultivated in Poland exhibit an average vitamin C content of 73.24 mg per 100 g, which exceeds the mean value observed in the present study and corresponds to the upper range of reported values. Among the analysed varieties, elevated vitamin C levels were recorded not only in 'Clery', but also in the 'Sonata', 'Joly', and 'Sensation' varieties, amounting to 57.9, 55.5, and 51.2 mg per 100 g, respectively. Strawberries examined by M. Stürtz *et al.* (2011) accumulated 58.8 mg per 100 g of vitamin C, which falls within the upper range of values recorded for the varieties investigated. A. Selamovska (2014) reported a vitamin C content of 50 mg per 100 g in strawberries cultivated in Macedonia, which slightly exceeds the mean value established for the analysed group of varieties, at 45.9 mg per 100 g. Fruits of the 'Romina', 'Asia', and 'Symphony' varieties exhibited intermediate vitamin C contents of 44.0, 47.9, and 45.9 mg per 100 g of fresh weight, respectively, as presented in Table 3. The lowest vitamin C concentrations were observed in the 'Kimberly' (39.1 mg per 100 g), 'Flair' (31.8 mg per 100 g), and 'Malvina' (35.3 mg per 100 g) varieties. Nevertheless, these values exceed those reported for strawberry varieties cultivated in Turkey, where vitamin C content ranges from 13.90 to 25.08 mg per 100 g of fresh weight (Agehara & Nunes, 2021) (Table 3).

Table 3. Content of biologically active substances in strawberry fruits, average for 2023-2024

Varieties	Vitamin C	Polyphenolic substances
	mg/100 g of raw weight	
‘Clery’	68.3 ± 2.8[a]	240.3 ± 7.3[ab]
‘Romina’	44.0 ± 3.2[ab]	233.0 ± 8.8[b]
‘Kimberly’	39.1 ± 1.6[b]	245.5 ± 12.8[ab]
‘Flair’	31.8 ± 1.7[b]	228.8 ± 13.1[ab]
‘Sonata’	57.9 ± 1.8[a]	300.0 ± 10.4[a]
‘Joly’	55.5 ± 2.4[a]	255.3 ± 13.4[ab]
‘Elsanta’	31.0 ± 1.1[b]	296.3 ± 9.7([a])
‘Asia’	47.9 ± 8.1[ab]	150.0 ± 10.3[b]
‘Sensation’	51.2 ± 1.7[a]	307.3 ± 6.1([a])
‘Malvina’	35.3 ± 1.4[b]	296.0 ± 9.7([a])
‘Symphony’	45.9 ± 1.6[ab]	202.7 ± 16.2[b]
Mean ± SE	46.2 ± 1.5	250.2 ± 10.7
Min	31.0 ± 1.1	150.0 ± 10.3
Max	68.3 ± 2.8	307.3 ± 6.1
V, %	25.2	19

Note: [a] and [b] – indicate values that differ significantly from the average; values marked [ab] do not differ significantly from the mean; the results of the comparison were obtained using Tukey’s test with the Bonferroni correction
Source: developed by the authors

Polyphenols constitute a significant group of secondary metabolites accumulated in strawberry fruits, where they perform multiple physiological functions, including the formation of berry colour, taste attributes, and protection against pathogenic microorganisms. The highest content of polyphenolic substances was recorded in fruits of the ‘Sensation’ variety, reaching 307.3 mg per 100 g of raw weight, followed by the ‘Sonata’, ‘Malvina’, and ‘Elsanta’ varieties, with values of 300.0, 296.0, and 296.0 mg per 100 g of raw weight, respectively. These values are close to the lower limit of the range reported for strawberries cultivated in the Forest-Steppe zone of Ukraine, where the minimum polyphenol content is approximately 303 mg per 100 g of raw weight. Average polyphenol levels for the studied group, amounting to 250.2 mg per 100 g of raw weight, were observed in the ‘Clery’ (240.3 mg), ‘Kimberly’ (245.5 mg), ‘Flair’ (228.8 mg), and ‘Joly’ (255.3 mg per 100 g of raw weight) varieties. With the exception of the ‘Asia’ variety, the lowest accumulation of polyphenolic substances was detected in fruits of the ‘Symphony’ variety, at 202.7 mg per 100 g of raw weight, which remains within the lower range of values reported for strawberries, at approximately 189.2 mg per 100 g. The variability of polyphenol content among the analysed varieties was moderate and amounted to 19.3%.

CONCLUSIONS

The study demonstrated that the ‘Sensation’ and ‘Symphony’ varieties produce the highest yields, exceeding 20 tonnes per hectare, when cultivated in the Polissya region of Ukraine. The mean berry weight reaches 21.4 g in the ‘Sensation’ variety and 30.4 g in the ‘Symphony’ variety. The ‘Clery’, ‘Romina’, ‘Sonata’, and ‘Asia’ varieties are characterised by high transportability, which is associated with increased pulp firmness. Pulp firmness ranges from 4.3 N in the ‘Sensation’ variety to 5.6 N in the ‘Malvina’ variety. The highest sugar content is observed in the ‘Joly’ variety, where sugars account for 9.6% of soluble dry matter, with total soluble solids reaching 8.5%. Alongside ‘Joly’, the ‘Clery’ variety also exhibits a high sugar content of 7.6%, according to the results obtained over two years of research. This sugar concentration positively influences the sensory quality of ‘Clery’ fruits, which are characterised by a titratable acid content of 0.91% and a sugar-acid index of 8.4. High taste quality is also characteristic of fruits of the ‘Romina’, ‘Flair’, ‘Joly’, and ‘Symphony’ varieties. Elevated concentrations of vitamin C and polyphenolic compounds, which act synergistically as antioxidants, are detected in fruits of the 'Sonata' and 'Sensation' varieties. On this basis, cultivation of the 'Sensation' and 'Symphony' varieties is recommended for achieving high and stable strawberry yields in the Polissya region of Ukraine. However, the relatively low firmness of the fruits of these varieties limits their suitability for long-term storage and transportation, which necessitates rapid marketing after harvest. Further studies are required to define conditions that ensure optimal quality preservation and to determine the suitability of fruits of the analysed varieties for processing.

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REFERENCES

[1] Agehara, S., & Nunes, M.C.D.N. (2021). Season and nitrogen fertilisation effects on yield and physicochemical attributes of strawberry under subtropical climate conditions. *Agronomy*, 11(7), article number 1391. doi: 10.3390/agronomy11071391.

[2] Akšić, M.F., Tosti, T., Sredojević, M., Milivojević, J., Meland, M., & Natić, M. (2019). Comparison of sugar profile between leaves and fruits of blueberry and strawberry cultivars grown in organic and integrated production system. *Plants,* 8(7), article number 205. doi: 10.3390/plants8070205.

[3] Antunes, L.E.C., Ristow, N.C., Krolow, A.C.R., Carpenedo, S., & Júnior, C.R. (2010). Yield and quality of strawberry cultivars. *Horticultura Brasileira,* 28(2), 222-226. doi: 10.1590/S0102-05362010000200015.

[4] Chowhan, S., Hossain, M., Hoque, M., Rasul, G., & Roni, M. (2016). Yield performance of strawberry genotypes. *Bangladesh Journal of Agricultural Research*, 41(3), 481-489. doi: 10.3329/bjar.v41i3.29720.

[5] Convention on Biological Diversity. (1992, June). Retrieved from https://www.cbd.int/doc/legal/cbd-en.pdf.

[6] Convention on the Trade in Endangered Species of Wild Fauna and Flora. (1976, March). Retrieved from https://surli.cc/ikrzgv.

[7] Døving, A., & Måge, F. (2001). Prediction of strawberry fruit yield. *Acta Agriculturae Scandinavica, Section B – Soil & Plant Science*, 51(1), 35-42. doi: 10.1080/090647101317187870.

[8] Fan, Z., Hasing, T., Johnson, T.S., Garner, D.M., Schwieterman, M.L., Barbey, C.R., Colquhoun, T.A., Sims, C.A., Resende, M.F.R., & Whitaker, V.M. (2021). Correction: Strawberry sweetness and consumer preference are enhanced by specific volatile compounds. *Horticulture Research,* 8, article number 224. doi: 10.1038/s41438-021-00664-2.

[9] Food and Agriculture Organization of the United Nations (FAO). (n.d.). Retrieved from https://www.fao.org/faostat/en/#data/QCL/visualize.

[10] Haynes, B.N. (2024). *Characterisation of fruit composition of North Carolina strawberry germplasm*. (Doctoral thesis, North Carolina State University, North Carolina, USA).

[11] Khammayom, N., Maruyama, N., & Chaichana, C. (2022). The effect of climatic parameters on strawberry production in a small walk-in greenhouse. *AgriEngineering*, 4(1), 104-121. doi: 10.3390/agriengineering4010007.

[12] Kilic, N., Burgut, A., Gündesli, M.A., Nogay, G., Ercisli, S., Kafkas, N.E., Ekiert, H., Elansary, H.O., & Szopa, A. (2021). The effect of organic, inorganic fertilisers and their combinations on fruit quality parameters in strawberries. *Horticulturae*, 7(10), article number 354. doi: 10.3390/horticulturae7100354.

[13] Krüger, E., Josuttis, M., Nestby, R., Toldam-Andersen, T.B., Carlen, C., & Mezzetti, B. (2012). Influence of growing conditions at different latitudes of Europe on strawberry growth performance, yield and quality. *Journal of Berry Research*, 2(3), 143-157. doi: 10.3233/JBR-2012-036.

[14] Lee, J.N., *et al.* (2024). Breeding of new ever-bearing strawberry 'Miha' with high hardness. *Korean Journal of Plant Resources*, 37(1), 87-92. doi: 10.7732/kjpr.2024.37.1.087.
[15] Liu, Z., Liang, T., & Kang, C. (2023). Molecular bases of strawberry fruit quality traits: Advances, challenges, and opportunities. *Plant Physiology*, 193(2), 900-914. doi: 10.1093/plphys/kiad376.
[16] Menzel, C.M. (2021). A review of productivity in strawberries: Marketable yield has a linear, but inconsistent relationship with total yield, and cannot be predicted from total yield. *The Journal of Horticultural Science and Biotechnology*, 96(2), 135-144. doi: 10.1080/14620316.2020.1808086.
[17] Menzel, C.M. (2022). Effect of temperature on soluble solids content in strawberry in Queensland, Australia. *Horticulturae*, 8(5), article number 367. doi: 10.3390/horticulturae8050367.
[18] Navarro-Hortal, M.D., *et al.* (2022). Strawberry (*Fragaria× ananassa* cv. *Romina*) methanolic extract attenuates Alzheimer's beta amyloid production and oxidative stress by SKN-1/NRF and DAF-16/FOXO mediated mechanisms in C. elegans. *Food Chemistry*, 372, article number 131272. doi: 10.1016/j.foodchem.2021.131272.
[19] Newerli-Guz, J., Śmiechowska, M., Drzewiecka, A., & Tylingo, R. (2023). Bioactive ingredients with health-promoting properties of strawberry fruit (*Fragaria x ananassa* Duchesne). *Molecules,* 28*(*6), article number 2711. doi: 10.3390/molecules28062711.
[20] Pădureț, S., Oroian, M., Gutt, G., & Amariei, S. (2017). Evaluation of strawberry texture in close relation with their anisotropy. *International Journal of Food Properties*, 20(2), 247-259. doi: 10.1080/10942912.2016.1155054.
[21] Qaderi, R. (2023). *Factors affecting strawberry quality in fresh and stored fruits*. (Doctoral dissertation, Marche Polytechnic University, Ancona, Italy).
[22] Sarıdaş, M.A. (2021). Seasonal variation of strawberry fruit quality in widely grown cultivars under Mediterranean climate condition. *Journal of Food Composition and Analysis*, 97, article number 103733. doi: 10.1016/j.jfca.2020.103733.
[23] Schwieterman, M.L., *et al.* (2014). Strawberry flavour: Diverse chemical compositions, a seasonal influence, and effects on sensory perception. *Plos One,* 9(2), article number e88446. doi: 10.1371/journal.pone.0088446.
[24] Selamovska, A. (2014). Strawberry: Factors of high yield. In *Strawberries* (pp. 121-188). New York: Nova Science Publishers, Inc.
[25] Simkova, K., Veberic, R., Hudina, M., Grohar, M.C., Ivancic, T., Smrke, T., Pelacci, M., & Jakopic, J. (2023). Berry size and weight as factors influencing the chemical composition of strawberry fruit. *Journal of Food Composition and Analysis*, 123, article number 105509. doi: 10.1016/j.jfca.2023.105509.
[26] State Statistic Service of Ukraine. (n.d.). Retrieved from https://www.ukrstat.gov.ua.
[27] Stürtz, M., Cerezo, A.B., Cantos-Villar, E., & Garcia-Parrilla, M.C. (2011). Determination of the melatonin content of different varieties of tomatoes (*Lycopersicon esculentum*) and strawberries (*Fragaria ananassa*). *Food Chemistry*, 127(3), 1329-1334. doi: 10.1016/j.foodchem.2011.01.093.
[28] Sykalo, O., & Shpak, B. (2024). Study and assessment of the of the Taegro WP application on strawberries biological effectiveness in the conditions of the agricultural sector and private farms. *Biological Systems: Theory and Innovation*, 15(2), 76-83. doi: 10.31548/biologiya15(2).2024.007.
[29] Syngenta. (n.d.). Retrieved from https://www.syngenta.com/.
[30] Yan, J.-W., Ban, Z.-J., Lu, H.-Y., Li, D., Poverenov, E., Luo, Z.-S., & Li, L. (2018). The aroma volatile repertoire in strawberry fruit: A review. *Journal of the Science of Food and Agriculture*, 98(12), 4395-4402. doi: 10.1002/jsfa.9039.
[31] Zhong, C.F., Mazzoni, L., Balducci, F., Di Vittori, L., Capocasa, F., Giampieri, F., & Mezzetti, B. (2017). Evaluation of vitamin C content in fruit and leaves of different strawberry genotypes. In Y. Desjardins (Ed.), *VIII international strawberry symposium* (pp. 371-378). Québec City: ISHS Acta Horticulturae 1156. doi: 10.17660/ActaHortic.2017.1156.56.

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Показники якості інтродукованих сортів суниці (*Fragaria* х *ananassa* Duch.) вирощених в зоні Полісся України

Анотація. Плоди суниці є першим у сезоні та цінним дієтичним продуктом харчування, зокрема, завдяки значному вмісту поживних та біологічно цінних речовини. Щороку до асортименту додаються нові сорти полуниці, які потребують вивчення, особливо щодо їх пристосованості до умов вирощування в різних регіонах. Метою роботи було дослідження інтродукованих сортів суниці садової до умов вирощування Полісся України. Методом зважування встановлювали урожайність та масу ягід, спектрофотометричним методом визначали вміст цукрів і поліфенолів, методом титрування досліджували кількість титрованих кислот і вітаміну С. Статистичний аналіз отриманих даних виконували з допомогою програми STATISTICA та дисперсійного аналізу ANOVA. В результаті досліджень встановлено, що найвищу урожайність мали сорти ‘Сенсація’ та ‘Симфонія’. Цей же сорт та ‘Симфонія’ були з найбільшою масою плоду, понад 30,0 г. Найменшою вона була у ‘Клері’. Вміст сухої речовини у суниці становив 11,1 %, а розчинних сухих речовин – 8,5 %. Істотно більше ніж інші сорти цукрів накопичували плоди ‘Клері’ та ‘Джолі’, а менше – ‘Ельсанта’, ‘Азія’ та ‘Мальвіна’. Відмінні смакові якості на рівні 8,4 цукровокислотного індексу сорту ‘Клері’ забезпечив високий вміст цукрів та низький титрованих кислот – 0,91 %. Досліджувана біоактивна складова плодів суниці варіювала від 31,0 до 68,3 мг на 100 г вітаміну С та від 150,0 до 307,3 мг/100 г поліфенольних речовин. Значним комплексом фіторечовин серед сортів суниці відзначилися плоди ‘Сенсації’, де вміст вітаміну С становив 51,2. Отримані результати досліджень стануть у нагоді селекціонерам при доборі батьківських форм для створення нових сортів та виробникам при виборі сортів для створення промислових насаджень в умовах Полісся України

Ключові слова: плоди; урожайність; цукри; вітамін С; поліфенольні речовини

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Analysis of the varietal composition of soft winter wheat in the context of variety renewal and replacement

Abstract. Weather conditions that have been changing towards extreme values determined the need to carry out variety replacement and renewal of soft winter wheat on a systematic level capable of improving the efficiency of agricultural technologies and ensuring a consistently high level of crop yields. Thus, the aim of the work was to analyse the peculiarities of the formation of the assortment and distribution of soft winter wheat, as well as to select the best varieties in terms of productivity and ecological stability. Field studies were conducted at the State Enterprise Research Farm "Salivinkivske" of the Institute of Bioenergy Crops and Sugar Beet of the NAAS of Ukraine (Kyiv region) during 2020-2024. Indicators of stability and plasticity of grain yield for 36 varieties of soft winter wheat were calculated according to the Eberhart-Russell method. It was established that for full variety replacement or renewal and to achieve a high level of soft winter wheat yield, it is necessary to sow at least 15% of

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areas annually with new varieties or seeds of higher generations. In 2021, this figure in Ukraine stood at 16%; however, in 2022 and 2023, it decreased to 5.2% and 5.5% respectively, which potentially had a negative impact on the overall productivity level of the crop. The varieties 'Lehenda Bilotserkivska', 'MIP Valensiia', 'Optyma Odeska', 'Okhtyrchanka Yuvileina', and 'Analoh', similarly to 'RGT Reform', exhibited high plasticity and were suitable for cultivation using intensive technologies, providing a yield increase of over 3.0 t/ha compared to the long-term average for the Kyiv region (2020-2024) of 4.81 t/ha. When cultivating soft winter wheat using resource-saving technologies, it is advisable to consider varieties such as 'Berehynia Myronivska', 'Vozdvyzhenka', and 'MIP Dniprianka'. These were capable of providing a grain yield increase of over 2.0 t/ha while maintaining productivity under the influence of limiting factors. The practical value of this work lies in the fact that its results can be used by agronomists and seed companies to select effective soft winter wheat varieties and increase yieldss

Keywords: assortment; yield; intensive conditions; environmental limiting factor; certified seeds; cultivation areas

INTRODUCTION

Global wheat production volumes are influenced by the area under cultivation, climate change, agricultural technologies and variety selection. The issue of optimising crop cultivation, especially for grain crops, is particularly acute, as climate change factors – such as an increase in arid areas, erosion and loss of soil fertility – are deteriorating the condition of cultivated land and reducing the amount of land suitable for agriculture.

In a global context, climatic factors are believed to account for one-third of the observed fluctuations in wheat yields, although overall global production of this crop is growing by 1.0% annually. At the same time, researchers Y. Li & F. Tao (2022) have proven that climate change is the main limiting factor and even leads to a decrease in winter wheat yields. Winter crops are particularly sensitive to the reduction or absence of the period with temperatures necessary for their vernalisation. In order for winter wheat plants to produce a high yield, air temperatures of 0-1°C must persist for 40-70 days during the autumn-winter period, as noted by J. Bailey-Serres *et al.* (2019) and W. Xiong *et al.* (2021). Researchers also found that from 1979 to 2000, the temperature during the wheat growing season increased by 1°C, which led to a 3-10% decrease in grain yield.

The reduction in sown areas, partly due to the negative impact of climate change, may lead to a further decline in production. To prevent this, environmentally friendly and resource-efficient cultivation technologies should be introduced and new wheat varieties should be actively introduced into production (Elazab *et al.*, 2021). L. Crespo-Herrera *et al.* (2018) argue that the increase in yield due to genetic factors depends on environmental conditions, and even under unfavourable conditions, it is at least 1.4% per year. In the United States, the increase in yield due to timely variety replacement in 1919-1993 was 0.98% annually; in Brazil in 1949-2009 – 0.92%; in Spain in 1930-2000 – 0.88%, and in Chile – 0.49% in 1965-2019 (del Pozo *et al.*, 2022). All researchers agree that timely variety replacement or renewal is a prerequisite for maintaining high wheat cultivation efficiency.

Three approaches are commonly used to assess the impact of variety replacement or renewal on grain yield: process-based modelling, statistical data, and field experiments, each with its own advantages and limitations (Madhukar *et al.,* 2020). C. Rivera-Amado *et al.* (2020) noted that field experiments are often the most reliable and accessible, but it is difficult to assess the genetic increase in wheat yield based on historical varieties in specific environmental conditions due to the limited number of experiments and varieties used. Thus, it is advisable to consider statistical data as the primary method of analysis, as it effectively reflects the dynamics of yield changes in mass production conditions. It should be noted that among most agricultural crops, winter wheat is relatively simple in terms of seed production: it is based on varietal selection, and high-reproduction varieties, provided that seed material is carefully selected, are capable of ensuring high productivity without the need for annual renewal (Najafi *et al*., 2018). However, in a global context, the issue of variety replacement or renewal should be considered at the level of state policy – as a universal indicator of the effectiveness of winter wheat cultivation technologies.

The aim of the study was to analyse the peculiarities of the formation of the assortment and distribution of soft winter wheat, as well as to assess the level of productivity, ecological stability and economic efficiency of its modern varieties when grown in the forest-steppe zone of Ukraine.

MATERIALS AND METHODS

The research was conducted during 2020-2024 under the conditions of the experimental field of the Institute of Bioenergy Crops and Sugar Beet of the National Academy of Agrarian Sciences (State Enterprise Research Farm "Salivinkivske", Bila Tserkva district, Kyiv region). The field component of the study involved the annual cultivation of the following soft winter wheat varieties: 'Analoh', 'Anatoliia', 'Berehynia Myronivska', 'Vezha Myronivska', 'Vodohrai', 'Vozdvyzhenka', 'Hratsiia Bilotserkivska', 'Hratsiia Myronivska', 'Estafeta Myronivska', 'Zdobna', 'Zorepad Bilotserkivskyi', 'Katrusia Odeska', 'Kesariia Poliska', 'Konka', 'Kraievyd', 'Lehenda Bilotserkivska', 'Manera Odeska', 'Mariia', 'MIP Assol', 'MIP Valensiia', 'MIP Vyshyvanka', 'MIP Dniprianka', 'Mudrist Odeska', 'Nasnaha', 'Optyma Odeska', 'Oranta Odeska', 'Okhtyrchanka Yuvileina', 'Poliska 90', 'Pryvitna', 'RGT Reform' (France), 'Romanivna', 'Svitankova', 'Solovushka', 'Spivanka Poliska', 'Spriiatlyva', and 'Futurum' (France).

The cultivation technology for soft winter wheat was conventional for the conditions of the Kyiv region. The area of the primary plots was 35 m^2, and the experiments were established with three replications. The soil of the experimental field is a deep, medium-loamy chernozem on loess-like loam. The humus content in the arable soil layer was 2.58% (according to Tyurin), alkaline-hydrolysable nitrogen was 176 mg/kg (according to Cornfield), and mobile phosphorus and potassium compounds were 160 and 95 mg/kg respectively (according to Chirikov).

Weather conditions during the research years differed significantly from long-term averages. In particular, March and April 2020 were warm with a slight moisture deficit, while May was cool and excessively wet. In summer, periods of extreme heat prevailed, especially in June and July, coupled with a lack of precipitation, which significantly affected wheat yields both in the region overall and within the experiments. In 2021, spring was cool with unstable precipitation; summer saw hot periods with moisture deficits, which generally negatively impacted wheat growth and development but did not cause a yield decrease compared to the previous year. In 2022, weather conditions were predominantly warm, with particularly significant droughts noted in June and July, leading to substantial plant stress during critical developmental phases. Consequently, wheat yields were the lowest across the entire research period. Conversely, in 2023, spring was moderately wet, and summer featured alternating hot and moderate periods in terms of temperature and moisture supply. Similar weather conditions were observed during the spring-summer vegetation of 2024, which favoured the formation of high yields. The Selyaninov hydrothermal coefficient (HTC) values during the growing periods over the research years are presented in Table 1.

Table 1. HTC for the Kyiv region during the growing season (May-August)

Year	HTC	Characteristics of moisture regime
2020	0.65	Insufficient (arid)
2021	1.15	Sufficient moisture
2022	0.56	Severe drought
2023	1.00	Moderate moisture
2024	0.90	Slight drought / normal

Note: HTC < 0.5 – severe drought; 0.5-0.7 – moderate drought; 0.7-1.0 – slight drought; 1.0-1.3 – sufficient moisture; >1.3 – excessive moisture

Source: compiled by the authors

In general, the weather conditions of the spring-summer growing period in 2020-2024 corresponded to a zone of unstable moisture supply. During this time, periods of drought, instability of precipitation, and high air temperatures were observed, which significantly influenced the course of vegetation. However, it was precisely this variability of conditions that allowed for a more thorough identification of the reactions of soft winter wheat varieties to changes in their cultivation environment. The assessment of the distribution of soft winter wheat varieties was carried out based on data from The Unified State Web Portal of Open Data (n.d.), as well as the results of own research and information from the State Register of Plant Varieties Suitable for Distribution in Ukraine (n.d.).

Yield stability and plasticity were determined using the Eberhart-Russell method, which involves evaluating the crop productivity level through plasticity (b), reflecting the regression to changes in cultivation conditions, and the stability (W) of this reaction (Eberhart & Russell, 1966). The baseline data for the economic analysis of winter wheat cultivation under the conditions of the Kyiv region at 2024 prices were as follows: average yield for the Kyiv region: 4.81 t/ha; wheat sale price: ≈ 7,500 UAH/t; cultivation costs excluding seed costs: ≈20,000 UAH/ha; cost of seeds: elite: 12,000-15,000 UAH/t; 1st reproduction: 9,000-11,000 UAH/t; 2nd-3rd reproduction: 7,000-8,500 UAH/t; weight-based sowing rate of winter wheat: 0.22-0.25 t/ha.

Return on Investment (ROI) was calculated according to the formula:

$$\text{ROI} = (\text{Additional Profit} / \text{Investment}) \times 100\%. \quad (1)$$

The research was conducted in accordance with the methods for field experiments and state variety testing of agricultural crops (Ermantraut *et al.*, 2007; Prysiazhniuk *et al.*, 2021). The study was carried out in compliance with the ethical standards of the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1976).

RESULTS AND DISCUSSION

In Ukraine, according to Law of Ukraine No. 411-IV "On Seeds and Planting Material" (2025), there is a Register of Certificates for Seeds and/or Planting Material, which contains information about batches of seeds of a certain variety (The unified state web portal of open data, (n.d.). The presence of a record of the variety and volume of the seed batch in this register at least confirms the intention to officially sell it as seed material. On the other hand, the presence of an entry for a variety in the State Register of Plant Varieties Suitable for Distribution in Ukraine only indicates the intention to distribute it commercially, but does not confirm the fact of its use. Thus, analysis of the Register of Certificates is the most reliable way to determine the prevalence of modern varieties, including winter wheat (Table 2).

Table 2. Winter wheat varieties included in the 20 most common varieties in terms of area sown with certified high-reproduction seeds

Year of sowing									
2023		2022		2021		2020		2019	
Variety	ha	Variety	ha	Variety	ha	Variety	ha	Variety	ha
'Bohdana'	22,359	'RGT Reform'	19,068	'Bohdana'	51,380	'Bohdana'	39,511	'Podolianka'	5,654
'RGT Reform'	14,167	'KWS Emil'	7,893	'RGT Reform'	31,354	'Podolianka'	29,017	'Zymoiarka'	4,222
'Mudrist Odeska'	9,776	'Mudrist Odeska'	7,642	'Podolianka'	31,315	'RGT Reform'	23,439	'Balaton'	3,313
'Podolianka'	8,083	'Podolianka'	7,093	'Mudrist Odeska'	26,741	'Mudrist Odeska'	22,841	'Bohdana'	2,793
'KWS Emil'	5,940	'Etana'	6,887	'Katrusia Odeska'	15,589	'Kubus'	21,445	'Matrix'	2,287
'Katrusia Odeska'	5,585	'KWS Jersey'	6,313	'Astarta'	13,759	'Skagen'	17,447	'Mudrist Odeska'	2,088
'Julia'	5,030	'Bohdana'	6,303	'Julia'	13,461	'Colonia'	15,992	'Lyst 25'	1,733
'Shestopalivka'	4,986	'Skagen'	5,233	'Skagen'	13,327	'Tobak'	14,914	'Kubus'	1,704

Table 2, Continued

Year of sowing									
2023		2022		2021		2020		2019	
Variety	ha	Variety	ha	Variety	ha	Variety	ha	Variety	ha
'KWS Jersey'	4,923	'Katrusia Odeska'	4,897	'Tobak'	12,765	'Mescal'	13,780	'Lira Odeska'	1,667
'Lemmy'	4,551	'Matchball'	4,761	'Sofiia Kyivska'	12,450	'Julia'	13,767	'Zhytnytsia Odeska'	1,567
'Nordika'	4,547	'Julia'	4,687	'Liha Odeska'	11,050	'Praktik'	12,858	'Nyva Odeska'	1,518
'Matchball'	4,490	'Astarta'	4,408	'Oranta Odeska'	11,045	'Novosmuhlianka'	12,572	'Vanessa'	1,387
'Patras'	4,261	'Lemmy'	4,083	'Shestopalivka'	10,919	'Astarta'	11,648	'Smuhlianka'	1,280
'Asory'	4,187	'Felix'	4,080	'Kubus'	10,692	'Shestopalivka'	11,506	'Julia'	1,260
'Oranta Odeska'	4,065	'KWS Talant'	4,053	'Oktava Odeska'	10,636	'Patras'	11,300	'Nordika'	1,220
'Balitus'	3,760	'Artist'	4,040	'Patras'	10,418	'Lira Odeska'	10,571	'Skagen'	1,193
'Felix'	3,633	'Frisky'	3,573	'Artist'	10,260	'Fermerka'	10,343	'Mulan'	1,153
'Sofiia Kyivska'	3,613	'Aspekt'	3,280	'Aspekt'	10,085	'Katrusia Odeska'	10,274	'Slavna'	1,149
'Futurum'	3,467	'LG Keramik'	3,220	'KWS Jersey'	8,899	'Nordika'	10,147	'Novosmuhlianka'	1,093
'Etana'	3,447	'Emblem'	2,967	'Kraievyd'	8,612	'Pylypivka'	10,065	'Mescal'	1,050

Source: compiled by the authors

In general, there has been a certain renewal of the assortment from year to year, but it cannot be said that Ukrainian varieties are inferior to foreign ones in terms of area. On the contrary, in 2019-2021 and 2023, it was domestic varieties that occupied the leading positions in terms of sown areas. At the same time, 2022 was quite atypical for the agricultural sector of Ukraine, not only because of the war, but also due to the inability to sow part of the areas in the east of the country, where there was traditionally high demand for Ukrainian varieties, as they have the ability to withstand unfavourable growing conditions without a significant reduction in yield.

Analysing the availability of certified winter wheat seeds in general, it should be noted that in 2019, with Ukrainian varieties prevailing by 1.6 times, the areas sown with them were 50% larger than the areas sown with foreign varieties (Fig. 1). Despite the fact that in 2020-2021 the total number of wheat varieties increased, the ratio between domestic and foreign varieties remained 1.0:1.6 in 2020 and 1:2 in 2021. Although the area sown with certified seeds of foreign varieties is growing every year, they only managed to exceed the area of Ukrainian varieties in 2022.

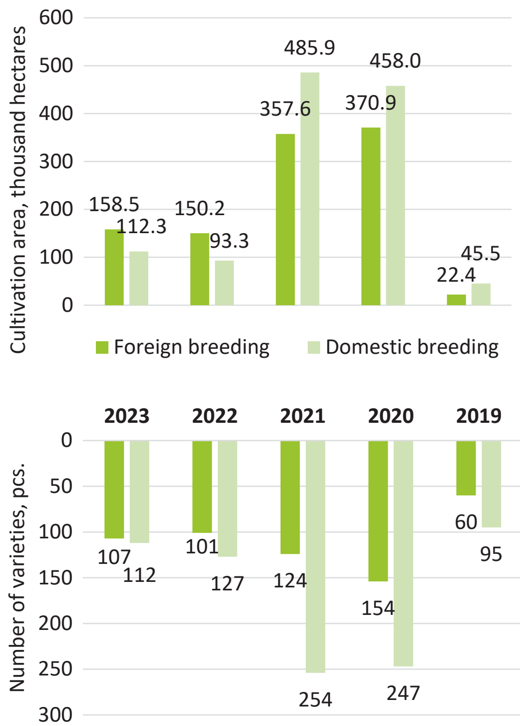

Figure 1. Structure of areas and varieties of high-yielding winter wheat, common in Ukraine
Source: compiled by the authors

At the same time, there is a certain parity in the number of registered varieties, but the area under Ukrainian varieties has decreased. As of 2023, foreign varieties occupied 1.4 times more area. As of 20 September 2025, the State Register of Plant Varieties Suitable for Distribution in Ukraine (n.d.) contains records of 783 varieties of soft winter wheat, but only 219 are available for purchase. It is advisable to carry out a complete replacement or renewal of winter wheat varieties on the farm every 5-7 years. Since this process is gradual, farms should sow 15-25% of their areas with new varieties each year. In this regard, the demand for certified winter wheat seeds in Ukraine has been determined (Table 3).

Table 3. Areas sown with certified winter wheat seeds in Ukraine

Indicator	Year of sowing				
	2023	2022	2021	2020	2019
Certified seeds available per area, ha	270,748	243,484	843,467	828,885	67,834
Sown area, ha	4,950,42 2	4,658,400	5,281,500	7,090,200	6,554,500
Seed requirement, ha	4,679,674	4,414,916	4,438,033	6,261,315	6,486,666
Percentage of area sown with high-reproduction seeds	5.5	5.2	16.0	11.7	1.0

Source: compiled by the authors based on The unified state web portal of open data (n.d.)

Consequently, only in 2021 did producers ensure a sufficient level of variety replacement and renewal for winter wheat, whereas in 2022-2023, this indicator decreased significantly to 5.2-5.5%. According to M. Korkhova & O. Kovalenko (2019), 141 wheat varieties are distributed in Southern Ukraine, of which 32.4% are outdated. This confirms the results obtained regarding the insufficient level of variety replacement and renewal of winter wheat. Global food security challenges require constant improvement of the varietal composition of winter wheat. Research over recent decades convincingly demonstrates that degradation processes on arable lands in various regions of the world, climate change, and the spatial variability of the suitability of soil and climatic conditions for wheat cultivation create additional challenges for stable grain production (Prăvălie *et al.*, 2021; Li & Zheng, 2022). At the same time, an analysis of the dynamics of sown areas and production volumes of major cereal crops, particularly wheat, in leading producing countries shows that productivity growth largely depends on the introduction of new varieties, as noted by Y. Wang *et al.* (2019) and A. Zvonar (2020). This emphasises the critical importance of systematic variety replacement and renewal as a strategic tool for adaptation to changing environmental conditions. Thus, special attention should be paid to the field trials of wheat varieties of Ukrainian and foreign breeding conducted under the conditions of the State Enterprise Research Farm "Salivinkivske" of the Institute of Bioenergy Crops and Sugar Beet of the NAAS (Kyiv region) during 2020-2024 (Table 4).

Table 4. Ecological characteristics of wheat varieties grown under the conditions of the State Enterprise Research Farm "Salivinkivske" (average for 2020-2024)

Variety	Ecological characteristics	Yield increase, t/ha
'Analoh'	low plasticity	1.05
'Anatoliia'	low plasticity	1.99
'Berehynia Myronivska'	low plasticity, withstands limiting factors	2.22
'Vezha Myronivska'	high plasticity, intensive	2.21
'Vodohrai'	low plasticity	1.86
'Vozdvyzhenka'	low plasticity, withstands limiting factors	2.25
'Hratsiia Bilotserkivska'	high plasticity, intensive	2.63
'Hratsiia Myronivska'	low plasticity, limiting factors	2.18
'Estafeta Myronivska'	low plasticity	1.25

Table 4, Continued

Variety	Ecological characteristics	Yield increase, t/ha
‘Zdobna’	low plasticity	1.54
‘Zorepad Bilotserkivskyi’	high plasticity, intensive	2.88
‘Katrusia Odeska’	low plasticity	1.82
‘Kesariia Poliska’	high plasticity, intensive	2.29
‘Konka’	low plasticity	1.78
‘Kraievyd’	high plasticity, intensive	2.66
‘Lehenda Bilotserkivska’	high plasticity, intensive	3.39
‘Manera Odeska’	high plasticity	1.95
‘Mariia’	high plasticity, intensive	2.7
‘MIP Assol’	low plasticity	2.11
‘MIP Valensiia’	high plasticity, intensive	3.02
‘MIP Vyshyvanka’	low plasticity	1.76
‘MIP Dniprianka’	low plasticity, withstands limiting factors	2.55
‘Mudrist Odeska’	high plasticity, intensive	2.83
‘Nasnaha’	high plasticity	2.09
‘Optyma Odeska’	high plasticity, intensive	3.13
‘Oranta Odeska’	low plasticity	1.59
‘Okhtyrchanka Yuvileina’	high plasticity, intensive	3.34
‘Poliska 90’	low plasticity	0.98
‘Pryvitna’	high plasticity, intensive	3.14
‘RGT Reform’	high plasticity, intensive	3.37
‘Romanivna’	low plasticity	1.67
‘Svitankova’	low plasticity	1.61
‘Solovushka’	low plasticity	1.47
‘Spivanka Poliska’	high plasticity, intensive	2.45
‘Spriiatlyva’	low plasticity	1.27
‘Futurum’	low plasticity	2.09
$HIP_{0.05}$		0.11

Source: compiled by the authors

The obtained wheat yield data served as the basis for analysing their stability and plasticity, as well as assessing their suitability for intensive cultivation. Furthermore, the average yield of each variety was compared with the long-term average for the Kyiv region, which is 4.81 t/ha. Research conducted by M. Korkhova & O. Kovalenko (2019) in the Kherson, Mykolaiv, and Odesa regions showed that outdated wheat varieties – such as ‘Anatoliia’, ‘Hurt’, ‘Lira Odeska Blaho’, ‘Konka’, ‘Mariia’, ‘Shestopalivka’, and ‘Zysk’ – remain widespread. This not only underscores the importance of research into new varieties but also indicates an insufficient rate of variety renewal by farmers, which can, among other things, affect average yield levels.

Weather conditions during the years of study were extremely challenging, primarily due to a lack of precipitation and high air temperatures in 2020 and 2022. Under such conditions, the average winter wheat yield in the Kyiv region was 4.28 and 3.84 t/ha, respectively. In contrast, the average yield of the varieties in the trial was 1.34 and 3.54 t/ha higher than the regional average. The studied winter wheat varieties demonstrated high productivity potential over the multi-year period. Specifically, in 21 out of 36 varieties, the yield exceeded the regional average by more than 2 t/ha, and in some cases, by more than 3 t/ha. These include: ‘Lehenda Bilotserkivska’, ‘MIP Valensiia’, ‘Optyma Odeska’, ‘Okhtyrchanka Yuvileina’, and ‘RGT Reform’ (France). These varieties were distinguished by a high level of plasticity and an intensive type of plant development, indicating their ability to respond positively to improved cultivation technologies with a significant yield increase.

Special attention should be paid to varieties with low plasticity that are capable of withstanding limiting factors and ensuring an excess over the regional average yield of more than 2.0 t/ha. Such varieties include: 'Berehynia Myronivska', 'Vozdvyzhenka', and 'MIP Dniprianka'. They form a consistently high yield even under conditions of limited technological resources, which is particularly relevant in wartime. Unlike intensive varieties, they are less sensitive to increased fertilisation or additional crop care. However, a yield difference of approximately 1.0 t/ha does not always compensate for the costs of additional agricultural measures.

According to Ukrainian scientists V. Vlasenko *et al*. (2008), periodic variety replacement or renewal provides an additional yield increase of 0.5 t/ha or more, provided it is carried out every 5-7 years. Yield stability across different environments is ensured by the ability to compensate for its main components – thousand-kernel weight, number of grains per spike, and the number of spikes per square metre (Tadesse *et al*., 2019). Yield formation occurs differently depending on environmental conditions, and modern varieties demonstrate different combinations of yield components compared to varieties from the 1950s-2000s (Valvo *et al*., 2018; Cao *et al*., 2019). An important issue is also the calculation of the economic efficiency of variety replacement or renewal within an average farm in the Kyiv region with a winter wheat cultivation area of 1,000 ha.

Thus, high-intensity soft winter wheat varieties, such as 'Lehenda Bilotserkivska', 'MIP Valensiia', 'Optyma Odeska', 'Okhtyrchanka Yuvileina', and others, provide an increase of over 3.0 t/ha and a total yield under 2024 conditions at a level of 7.81 t/ha. Conversely, for resource-saving varieties – 'Berehynia Myronivska', 'Vozdvyzhenka', 'MIP Dniprianka' – the yield increase was 2.0 t/ha with a total figure of 6.81 t/ha. This allows for a comparison of soft winter wheat replacement strategies when using varieties with different levels of yield formation intensity (Table 5).

Table 5. Comparative effectiveness of soft winter wheat variety replacement strategies

Indicator	Intensive varieties	Resource-saving varieties	No variety replacement
Additional costs, UAH/ha	7,000	2,400	0
Yield increase, t/ha	3	2	-0.96
Cultivation technology costs, UAH/ha	25,000	22,400	20,000
Sales revenue, UAH/ha	62,480	54,480	30,800
Gross profit, UAH/ha	37,480	32,080	10,800
Additional profit, UAH/ha	24,000	16,000	-7,680
Return on investment (ROI), %	343	667	–

Source: compiled by the authors

When using intensive varieties, costs increase not only due to seeds, but also due to the need for additional fertilisers and the use of more protective and stimulating substances. Such varieties respond very well to optimised growing conditions, which increases their productivity. Resource-saving varieties are capable of producing sufficiently high yields under basic cultivation technology conditions. This makes them more attractive for investment in cases of resource shortages or in small farms where intensive technology cannot always be implemented.

The issue of variety renewal in difficult economic conditions, when farms are often forced to grow only existing varieties, deserves special attention. In this case, the decline in yield will be cumulative: in the first year or two, it may be almost imperceptible, and the existing "decline" in productivity can be explained by the influence of weather conditions or shortcomings in agricultural technology. At the same time, it is crucial to be aware of the cumulative effect of losses, which manifests itself over a longer period, for example, over a five-year period on an area of 1,000 hectares. For a more informed analysis, it is also advisable to take into account the annual impact of weather factors, based on retrospective data on the yield of soft winter wheat in the Kyiv region. Thus, in 2020, the harvest on the farm's fields was obtained from third-generation seeds. In subsequent years, there is a gradual increase in the degree of reproduction, which is due to the reuse of the same seed material (Table 6).

Table 6. Potential losses of yield and gross profit in the absence of soft winter wheat variety renewal

Year (reproduction)	Average annual yield, t/ha*	Losses, %	Purchase price, UAH/t	Losses from crop failure, UAH/ha
2020 (III)	4.28	5	5,500	1,177
2021 (IV)	5.06	8	6,850	2,773
2022 (V)	3.84	12	5,250	2,419
2023 (VI)	5.37	15	7,150	5,759
2024 (VII)	5.50	20	8,000	8,800
Total per 1,000 ha				20,928,405

Note: * – according to State Statistics Committee data for Kyiv region
Source: compiled by the authors

The projected decrease in yield when using soft winter wheat seeds of III-IV reproduction in farming is 5 and 8% (0.21 and 0.40 t/ha), respectively, which at first glance does not seem critical. However, over two years, the total losses amount to 3,950 UAH/ha, which is 1,550 UAH/ha more than the cost of timely seed renewal. In the case of variety replacement (using elite or first reproduction seeds), the yield potential is maintained at the average level of the farm in years with similar climatic conditions. In a five-year perspective, failure to renew varieties leads to total losses of UAH 20,928,405, which is a significant economic indicator. In the conditions of the Kyiv region, one of the key criteria for the correct selection of soft winter wheat varieties is their ability to grow and develop effectively in conditions of low rainfall and high air temperatures. It has been established that the relationship between the hydrothermal coefficient (HTC) and wheat yield in the years of research has a strong positive correlation ($r = 0.825$). This indicates that the level of moisture supply during critical periods of crop vegetation is the main limiting factor in the formation of its productivity (Fig. 2).

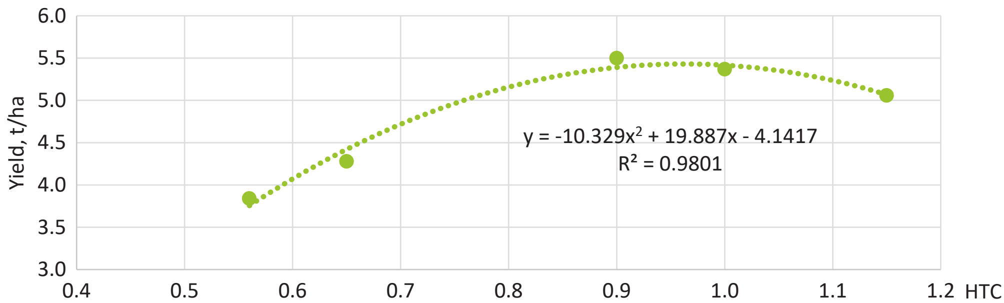

Figure 2. Dependence of soft winter wheat yield on HTC during the growing season
Source: compiled by the authors

Improvements in wheat through breeding and the timely introduction of new varieties ensure stable yield increases, as confirmed by a large-scale study of international breeding programmes by W. Tadesse *et al.* (2019). Modern approaches to variety evaluation based on a comprehensive analysis of soil, climatic and physiological parameters and their contribution to yield formation (Elazab *et al.*, 2021), as well as on the application of technologies (Araus *et al.*, 2018). These scientific achievements justify the need to model the processes of updating the varietal composition as an effective mechanism for increasing wheat productivity and ensuring food security in the context of global climate change and growing anthropogenic pressure on agroecosystems. Based on the modelling results, the forecast indicators for soft winter wheat yield have been determined and requirements for varieties have been formulated (Table 7).

Table 7. Forecast yield indicators for soft winter wheat and requirements for varieties depending on HTC

Level of HTC	Estimated yield, t/ha	Recommended types of varieties
0.5-0.6 (drought)	3.2-4.1	Drought-resistant, resource-efficient
0.7-0.9 (mild drought)	4.7-5.4	Versatile, adaptable
0.9-1.1 (optimum)	5.4-5.2	Intensive, high-yielding
>1.2 (excessive moisture)	<4.8	Resistant to lodging

Source: compiled by the authors

As shown in Table 7, intensive varieties can achieve maximum productivity only under optimal HTC values (0.9-1.1). At the same time, due to current climate change in the Kyiv region, such moisture conditions are relatively rare. An additional complication in the selection of winter wheat varieties is the need to predict the conditions of the growing season for the following year in the autumn. Taking into account climate change and the increasing frequency of extreme weather events, it is advisable to recommend the following variety structure within the farm: 30% of the area should be sown with varieties that can withstand limiting factors, primarily drought-resistant ones (ensuring yield formation at HTC <0.7); 40% of the area should be sown with universal, highly plastic varieties (characterised by stable yields at a HTC of 0.7-1.0); 30% of the area should be sown with intensive varieties (achieving maximum productivity at a HTC >1.0).

Research by S. Lavrenko & N. Lavrenko (2022) has proven that in order to ensure sustainable production of high-quality grain in farms, it is necessary to carry out variety changes and renewal. The introduction of new and promising varieties with increased productivity, quality, and adaptability to external environmental conditions is an important element of agricultural technology. The researchers also claim that in most cases, 2-4 different varieties are sown in production, which is in line with the results on the need to diversify the risks of wheat cultivation not only in terms of the number of varieties but also their response to growing conditions and elements of agricultural technology.

CONCLUSIONS

It has been researched that the State Register of Plant Varieties Suitable for Distribution in Ukraine contains 783 varieties of soft winter wheat, of which only 28% are available on the market. For full variety replacement or renewal and to achieve a high level of soft winter wheat yield, it is necessary to sow at least 15% of areas annually with new varieties or seeds of higher generations. In 2021, this figure in Ukraine stood at 16%; however, in 2022 and 2023, it decreased to 5.2% and 5.5% respectively, which could potentially have a negative impact on the overall productivity level of the crop. The varieties 'Lehenda Bilotserkivska', 'MIP Valensiia', 'Optyma Odeska', 'Okhtyrchanka Yuvileina', and 'Analoh', similarly to 'RGT Reform', exhibit high plasticity and are suitable for cultivation using intensive technologies, providing a yield increase of over 3.0 t/ha compared to the long-term average for the Kyiv region (2020-2024) of 4.81 t/ha.

When cultivating soft winter wheat using resource-saving technologies, it is advisable to consider varieties such as 'Berehynia Myronivska', 'Vozdvyzhenka', and 'MIP Dniprianka'. These are capable of providing a grain yield increase of over 2.0 t/ha while maintaining productivity under the influence of limiting factors. The highest economic efficiency was noted in resource-saving varieties (ROI – 667%). At the same time, the absence of variety replacement or renewal leads to annual losses at a level of 7,680 UAH/ha. The optimal strategy for winter wheat cultivation under the conditions of farms in the Kyiv region is a combination of different variety groups, namely: 30% of areas for varieties capable of withstanding the impact of limiting factors, 40% of areas for universal highly plastic varieties, and 30% of areas for intensive varieties. Such an approach ensures both production resilience to stress conditions and the maximum realisation of productivity potential. Further research should evaluate the possibilities of growing new varieties of soft winter wheat in different soil and climatic zones of Ukraine to improve the variety replacement system and increase the adaptive potential of the crop.

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REFERENCES

[1] Araus, J.L., Kefauver, S.C., Zaman-Allah, M., Olsen, M.S., & Cairns, J.E. (2018). Translating high-throughput phenotyping into genetic gain. *Trends in Plant Science*, 23(5), 451-466. doi: 10.1016/j.tplants.2018.02.001.

[2] Bailey-Serres, J., Parker, J.E., Ainsworth, E.A., Oldroyd, G.E.D., & Schroeder, J.I. (2019). Genetic strategies for improving crop yields. *Nature*, 575, 109-118. doi: 10.1038/s41586-019-1679-0.

[3] Cao, H.-Z., Li, Y.-N., Chen, G.-F., Chen, D.-D., Qu, H.-R., & Ma, W.-Q. (2019). Identifying the limiting factors driving the winter wheat yield gap on smallholder farms by agronomic diagnosis in North China Plain. *Journal of Integrative Agriculture*, 18(8), 1701-1713. doi: 10.1016/s2095-3119(19)62574-8.

[4] Convention on Biological Diversity. (1992, June). Retrieved from https://www.cbd.int/doc/legal/cbd-en.pdf.

[5] Convention on the Trade in Endangered Species of Wild Fauna and Flora. (1976, March). Retrieved from https://surl.lu/rgknzu.

[6] Crespo-Herrera, L.A., Crossa, J., Huerta-Espino, J., Vargas, M., Mondal, S., Velu, G., Payne, T.S., Braun, H., & Singh, R.P. (2018). Genetic gains for grain yield in CIMMYT's semi-arid wheat yield trials grown in suboptimal environments. *Crop Science*, 58(5), 1890-1898. doi: 10.2135/cropsci2018.01.0017.

[7] del Pozo, A., Jobet, C., Matus, I., Méndez-Espinoza, A.M., Garriga, M., Castillo, D., & Elazab, A. (2022). Genetic yield gains and changes in morphophysiological-related traits of winter wheat in Southern Chilean high-yielding environments. *Frontiers in Plant Science*, 12, article number 732988. doi: 10.3389/fpls.2021.732988.

[8] Eberhart, S.A., & Russell, W.A. (1966). Stability parameters for comparing varieties. *Crop Science*, 6(1), 36-40. doi: 10.2135/cropsci1966.0011183x000600010011x.

[9] Elazab, A., Moraga, F., & del Pozo, A. (2021). Photosynthetic organs contributions to grain yield genetic gains in Chilean winter wheat. *Agronomy Journal*, 113(6), 5006-5026. doi: 10.1002/agj2.20718.

[10] Ermantraut, E.R., Prysiazhniuk, O.I., & Shevchenko, I.L. (2007). *Statistical analysis of agronomic experimental data in the Statistica 6.0 software package: Methodological guidelines*. Kyiv: PolihrafKonsaltynh.

[11] Korkhova, M.M., & Kovalenko, O.A. (2019). Analysis of seed production of winter wheat (*Triticum aestivum* L.) in the South of Ukraine. *Taurida Scientific Herald*, 107, 61-68. doi: 10.32851/2226-0099.2019.107.8.

[12] Lavrenko, S.O., & Lavrenko, N.M. (2022). Monitoring of sunflower and winter wheat varieties and hybrids for cultivation in the Steppe zone of Ukraine. *Taurida Scientific Herald*, 124, 70-78. doi: 10.32851/2226-0099.2022.124.10.

[13] Law of Ukraine No. 411-IV "On Seeds and Planting Material". (2025, January). Retrieved from https://zakon.rada.gov.ua/laws/show/411-15#Text.

[14] Li, K.-H., & Zheng, F. (2022). Spatial and interdecadal differences in climatic suitability for winter wheat in China from 1985 to 2014. *International Journal of Biometeorology*, 66, 2091-2104. doi: 10.1007/s00484-022-02343-w.
[15] Li, Y., & Tao, F. (2022). Interactions of genotype, environment and management on wheat traits and grain yield variations in different climate zones across China. *Agricultural Systems*, 203, article number 103521. doi: 10.1016/j.agsy.2022.103521.
[16] Madhukar, A., Dashora, K., & Kumar, V. (2020). Investigating historical climatic impacts on wheat yield in India using a statistical modeling approach. *Modeling Earth Systems and Environment*, 7, 1019-1027. doi: 10.1007/s40808-020-00932-5.
[17] Najafi, E., Devineni, N., Khanbilvardi, R.M., & Kogan, F. (2018). Understanding the changes in global crop yields through changes in climate and technology. *Earth's Future*, 6(3), 410-427. doi: 10.1002/2017ef000690.
[18] Prăvălie, R., Patriche, C., Borrelli, P., Panagos, P., Roșca, B., Dumitraşcu, M., Nita, I.-A., Săvulescu, I., Birsan, M.-V., & Bandoc, G. (2021). Arable lands under the pressure of multiple land degradation processes. A global perspective. *Environmental Research*, 194, article number 110697. doi: 10.1016/j.envres.2020.110697.
[19] Prysiazhniuk, O.I., Klymovych, N.M., Polunina, O.V., Yevchuk, Y.V., Tretiakova, S.O., Kononenko, L.M., Voitovska, V.I., & Mykhailovyn, Yu.M. (2021). *Methodology and organization of scientific research in agriculture and food technologies*. Vinnytsia: Nilan-LTD. doi: 10.47414/978-966-924-927-2.
[20] Rivera-Amado, C., Molero, G., Trujillo-Negrellos, E., Reynolds, M., & Foulkes, J. (2020). Estimating organ contribution to grain filling and potential for source upregulation in wheat cultivars with a contrasting source-sink balance. *Agronomy*, 10(10), article number 1527. doi: 10.3390/agronomy10101527.
[21] State register of plant varieties suitable for distribution in Ukraine. (n.d.). Retrieved from https://minagro.gov.ua/.
[22] Tadesse, W., Sanchez-Garcia, M., Assefa, S.G., Amri, A., Bishaw, Z., Ogbonnaya, F.C., & Baum, M. (2019). Genetic gains in wheat breeding and its role in feeding the world. *Crop Breeding, Genetics and Genomics*, 1, article number e190005. doi: 10.20900/cbgg20190005.
[23] The unified state web portal of open data. (n.d.). Retrieved from https://data.gov.ua/dataset.
[24] Valvo, P.J.L., Miralles, D.J., & Serrago, R.A. (2018). Genetic progress in Argentine bread wheat varieties released between 1918 and 2011: Changes in physiological and numerical yield components. *Field Crops Research*, 221, 314-321. doi: 10.1016/j.fcr.2017.08.014.
[25] Vlasenko, V.A., Kochmarskyi, V.S., Kolomiiets, L.A., & Marynka, S.M. (2008). Improving the productive and adaptive potential of winter soft wheat. *Factors of Experimental Evolution of Organisms*, 5, 21-25.
[26] Wang, Y., Gao, F., Gao, G., Zhao, J., Wang, X., & Zhang, R. (2019). Production and cultivated area variation in cereal, rice, wheat and maize in China (1998-2016). *Agronomy*, 9(5), article number 222. doi: 10.3390/agronomy9050222.
[27] Xiong, W., *et al.* (2021). Increased ranking change in wheat breeding under climate change. *Nature Plants*, 7, 1207-1212. doi: 10.1038/s41477-021-00988-w.
[28] Zvonar, A. (2020). Influence of weather conditions of the year and variety features on nitrogen consumption and formation of winter wheat grain quality. *Ukrainian Black Sea Region Agrarian Science*, 24(3), 87-95. doi: 10.31521/2313-092X/2020-3(107)-11.

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Аналіз сортового складу пшениці м'якої озимої в контексті сортооновлення та сортозаміни

Анотація. Погодні умови, що змінюються в бік екстремальних значень, визначають потребу здійснювати сортозаміну і сортооновлення пшениці м'якої озимої на систематичному рівні, здатному поліпшити ефективність агротехнологій вирощування та забезпечити стабільно високий рівень урожайності культури. Тому метою роботи було проаналізувати особливості формування сортименту та поширення пшениці м'якої озимої, а також підібрати кращі сорти за продуктивністю та екологічною стабільністю. Польові дослідження проводили в умовах ДП ДГ «Саливінківське» Інституту біоенергетичних культур і цукрових буряків НААН України (Київська обл.) упродовж 2020-2024 рр. Показники стабільності та пластичності врожайності зерна 36 сортів пшениці м'якої озимої розраховували за методикою Ебергарда-Рассела. Встановлено, що для повноцінної сортозаміни чи сортооновлення та досягнення високого рівня врожайності пшениці м'якої озимої необхідно щорічно засівати щонайменше на 15 % площ новими сортами або насінням вищих репродукцій. У 2021 році цей показник в Україні становив 16 %, однак у 2022 та 2023 роках знизився до 5,2 і 5,5 % відповідно, що потенційно негативно вплинуло на загальний рівень продуктивності культури. Сорти 'Легенда білоцерківська', 'МІП Валенсія', 'Оптима одеська', 'Охтирчанка ювілейна', 'Аналог', аналогічно 'РЖТ Реформ' мали високу пластичність і були придатні до вирощування за інтенсивних технологій, забезпечуючи приріст урожайності понад 3,0 т/га порівняно із середнім багаторічним показником по Київській області (2020-2024 рр.) – 4,81 т/га. За вирощування пшениці м'якої озимої з використанням ресурсоощадних технологій доцільно звернути увагу на такі сорти, як 'Берегиня миронівська', 'Воздвиженка' та 'МІП Дніпрянка'. Вони були здатні забезпечити приріст урожайності зерна понад 2,0 т/га, зберігаючи продуктивність за умов впливу обмежувальних чинників. Практична цінність роботи полягає в тому, що її результати можуть використовувати агрономи та насіннєві компанії для підбору ефективних сортів пшениці м'якої озимої та підвищення врожайності

Ключові слова: сортимент; урожайність; інтенсивні умови; ліміт факторів середовища; сертифіковане насіння; площі вирощування

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Diversity and correlation analysis of national bell pepper (*Capsicum annuum* L.) accessions in Niger

Abstract. The study on the diversity and correlation analysis of national bell pepper accessions is of paramount importance because it documented and conserved valuable local genetic resources while providing essential information for breeding and varietal improvement. By assessing agro-morphological variability and identifying relationships among key traits, the study helped breeders select superior parent lines and guided farmers in choosing well-adapted accessions for different production contexts. This knowledge supports higher productivity, resilience to climate stress, and improves fruit quality, ultimately contributing to food security, income generation, and better management of national germplasm resources. The purpose was to assess the genetic diversity and identify key trait correlations among national bell pepper accessions in Niger to inform effective selection, conservation, and breeding programmes. Hence, national local germplasm was collected and evaluated in an alpha lattice design with three replicates. Data were collected and analysed

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through correlation, diversity, cluster, and principal component (PCA) analyses. The results uncovered substantial genetic diversity among national bell pepper accessions, highlighting the existence of distinct genetic clusters. Significant relationships were revealed between traits, such as a positive correlation between fruit pericarp thickness and corolla length, fruit pericarp thickness and fruit length, plant circumference and fruit pericarp thickness, total flowers and aborted flowers, plant height and the number of aborted flowers, plant height and the total number of flowers, the height of the first bifurcation and plant height, the height of the first bifurcation and total flowers, and the height of the first bifurcation and aborted flowers. The identified genetic diversity and trait correlations offered crucial information for bell pepper conservation and improvement. The results of this study can be used by breeders and farmers for the selection and cultivation of high-yielding and resilient bell pepper varieties

Keywords: variability assessment; germplasm characterisation; genetic diversity; principal component analysis; cluster analysis; agro-morphological traits

INTRODUCTION

Research on the diversity and correlation analysis of national bell pepper (*Capsicum annuum L.*) accessions in Niger is highly relevant because it provides essential information for strengthening the country's agricultural resilience and productivity. By characterising the genetic variability within local accessions, the study helps identify traits linked to yield, adaptability, and resistance to pests or environmental stresses, which are key factors for improving pepper cultivation in the face of climate change and evolving farmer needs. Understanding correlations among agronomic traits also guides breeders and policy-makers in selecting superior varieties and designing efficient breeding programmes. Ultimately, this research supports food security, enhances the value of local genetic resources, and contributes to sustainable agricultural development in Niger.

No known study has been conducted in the country to date. However, some authors, such as Y. Nas & H. İlbi (2022), have investigated genetic diversity in crops. They reported significant variability among genotypes, which is crucial for breeding programmes and conservation efforts. These studies revealed substantial diversity in morpho-agronomic traits and pungency genes across bell pepper varieties. Additionally, M. Silva & R. Silva (2021) demonstrated considerable genetic variation among the bell pepper genotypes analysed. Bell pepper, also referred to as sweet pepper or capsicum (*Capsicum annuum* L. *var. grossum*), is a member of the Solanaceae family. As a species belonging to *Capsicum annuum*, it is native to Central and South America. Scientists such as L. Muñoz-Ramírez *et al.* (2020) and O. Agapie *et al.* (2023) have shown that domestication occurred more than 6,000 years ago and that the genus represents a highly diverse taxonomic group comprising 44 identified species. Among these, five species have been domesticated: *C. annuum* L., *C. frutescens* L., *C. chinense* Jacq., *C. baccatum* L. (var. *pendulum*), and *C. pubescens* Ruiz & Pav (Hernández-Pérez *et al.*, 2020). Capsicum species are diploid, and most possess 24 chromosomes ($n = x = 12$); however, several wild species have 26 chromosomes ($n = x = 13$). According to G. Barboza *et al.* (2020), *Capsicum annuum* has 24 chromosomes and is one of the most globally important vegetable crops because of its widespread consumption and high nutritional value. Bell peppers (*Capsicum annuum* L.) are versatile and nutritious vegetables available in a wide range of colours. They are valued for their high vitamin C content and other bioactive compounds, such as carotenoids, tocopherols, flavonoids, and capsaicinoids, which contribute to their antioxidant, anti-inflammatory, and anticarcinogenic properties, as noted by L. Anaya-Esparza *et al.* (2021) and A. Onzo *et al.* (2021). They are also appreciated for their adaptability and diverse culinary applications. They can be consumed fresh, cooked, pickled, or used as ingredients in pasta, spices, or natural food colourants (Gamela *et al.*, 2020). In 2020, the global production of pepper was approximately 36 million tonnes. Numerous studies on the genetic diversity of bell peppers have revealed significant variability in morpho-agronomic traits. Understanding genetic diversity, trait correlations among bell pepper accessions, and phylogenetic relationships between accessions is essential for effective conservation, the development of breeding strategies, and varietal improvement programmes.

This study aimed to assess the diversity and correlation patterns of national bell pepper (*Capsicum annuum*) accessions collected from Niger.

MATERIALS AND METHODS

The study adhered to ethical standards by ensuring that all plant materials were collected, used, and conserved in accordance with national regulations governing genetic resources and biodiversity. Permissions were obtained from relevant agricultural and research authorities before accessing germplasm from farmers' fields or national collections. Farmers and local communities involved in providing plant material or agronomic information were informed of the study's objectives, and their contributions were acknowledged in accordance with the principles of fairness and transparency. The research complied with guidelines on the responsible use of plant genetic resources, avoiding any form of biopiracy, and ensuring that data were handled with scientific integrity, accuracy, and confidentiality. No human or animal subjects were involved, and all procedures followed institutional and international standards for ethical research in plant sciences. The study was conducted in accordance with the ethical standards of the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1976).

A collection of national bell pepper accessions was used for this study, which was carried out from April to July 2024 and comprised diverse genotypes representing different geographical regions. Germplasm was collected across the Republic of Niger from December 2022 to February 2023. All regions were included in the collection, except Agadez, where there is no known cultivation of traditional bell pepper cultivars. The targeted regions included Diffa, Zinder, Maradi, Tahoua, Dosso, and Tillabéri (Fig. 1). Agroecological zoning was used to identify areas within each region with potential bell pepper diversity. A participatory approach was employed to document and integrate knowledge of local varieties.

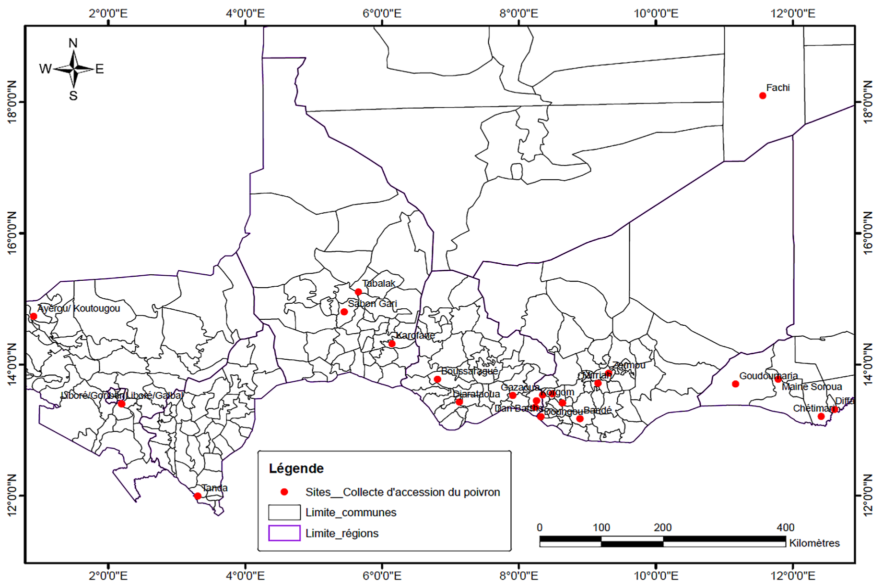

Figure 1. Germplasm collection sites

Source: created by the authors using the geographical coordinates of collection sites recorded during the survey

For the field collection, ethnobotanical surveys were conducted to document traditional knowledge about bell pepper varieties. Details such as local names, uses, and cultivation practices were recorded. Seed samples were collected from multiple sources, including farmers' fields, home gardens, and local markets. Fifty-six collected cultivars (Table 1) were evaluated at Dogondoutchi (13°64′60″ N, 4°05′53″ E, altitude 256.3 m). The following table presents the accession numbers, their local names, sites, communes, departments, and regions of collection.

Table 1. Description of the collected cultivars

Accession number	Local name	Site/village	Commune	Department	Region
1	'Kangadi Nglaro'	Gangura	Bosso	Bosso	Diffa
2	'Mangala'	Diffa Market	Diffa	Diffa	Diffa
3	'Bongo'	Diffa Market	Diffa	Diffa	Diffa
4	'Bounami petit'	Diffa Market	Diffa	Diffa	Diffa
5	'Kangadi Nglaro'	Morey	Chétimari	Diffa	Diffa
6	'Mowor'	Chétimari	Chétimari	Diffa	Diffa
7	'Kangadi Nglaro'	Dabagoune	Chétimari	Diffa	Diffa
8	'Kangadi Nglaro'	Walada	Chétimari	Diffa	Diffa
9	'Mangala long'	Toumoure	Bosso	Bosso	Diffa
10	'Mangala petit'	Toumoure	Bosso	Bosso	Diffa
11	'Tattassé koua'	Annassaboul	Goudoumaria	Goudoumaria	Diffa
12	'Kangadi Nglaro'	Annassaboul	Goudoumaria	Goudoumaria	Diffa
13	'Champo'	Annassaboul	Goudoumaria	Goudoumaria	Diffa
14	'Champo'	NGaori	Goudoumaria	Goudoumaria	Diffa
15	'Borkono'	NGaori	Goudoumaria	Goudoumaria	Diffa
16	'Tattassé koura'	NGaori	Goudoumaria	Goudoumaria	Diffa
17	'Tattassé koura'	Kadélaboua	Goudoumaria	Goudoumaria	Diffa
18	'Tattassé'	Falki Babba	Mirriah	Mirriah	Zinder
19	'Koriyaram'	Bosso	Bosso	Bosso	Diffa
20	'Lardou'	Zermou	Mirriah	Mirriah	Zinder
21	'Dan Damso'	Tsamia	Bandé	Bandé	Zinder
22	'Dan Izala'	Tsamia	Bandé	Bandé	Zinder
23	'Maybiro'	Sabon Gari	Karofane	Bouza	Tahoua
24	'Hanchin Sania'	Dan Bartho	Dan Bartho	Kantché	Zinder
25	'Tchilam Glaro'	Diffa	Diffa	Diffa	Diffa
26	'Dan Tcharantchi'	Ichirnaoua	Ichirnaoua	Kantché	Zinder
27	'Dan Damastché'	Ichirnaoua	Ichirnaoua	Kantché	Zinder
28	'Dan Tcharantchi'	Koré Haoussa	Doungou	Kantché	Zinder
29	'Hantchi Sania'	Tassaou	Kantché	Kantché	Zinder
30	'Tattassé'	Djirataoua	Djirataoua	Madarounfa	Maradi
31	'Dourgou'	Kolma	Hawandawaki	Tessaoua	Maradi
32	'Kahon Baréwa'	Kolma	Hawandawaki	Tessaoua	Maradi
33	'Kahon Baréwa'	Romaza	Korgom	Tessaoua	Maradi
34	'Dourgou'	Romaza	Korgom	Tessaoua	Maradi
35	'Hantchi Sa'	Romaza	Korgom	Tessaoua	Maradi
36	'Kahon Baréwa'	Lawni	Gazaoua	Gazaoua	Maradi
37	'Dan Dourgou'	Lawni	Gazaoua	Gazaoua	Maradi
38	'Bakin Iri'	Lawni	Gazaoua	Gazaoua	Maradi
39	'Kahon Baréwa'	Sadjamandja	Gangara	Gazaoua	Maradi
40	'Koriyaram'	Diffa	Diffa	Diffa	Diffa

Table 1, Continued

Accession number	Local name	Site/village	Commune	Department	Region
41	'Bongo/Kouri Moro'	Tam	Mainé Soroua	Maine Soroa	Diffa
42	'Kangadi Nglaro'	Tam	Mainé Soroua	Maine Soroua	Diffa
43	'Bongo/Kouri Moro'	Blakouna	Mainé Soroua	Maine Soroa	Diffa
44	'Kangadi Nglaro'	Blakouna	Mainé Soroua	Maine Soroa	Diffa
45	'Tougandé'	Boussaradjé	Keita	Keita	Tahoua
46	'Tougandé'	Fachi	Tabalak	Abala	Tahoua
47	'Dan Talabé'	Talabé	Tahoua commune2	Tahoua	Tahoua
48	'Maybiro'	Sabon Gari	Karofane	Bouza	Tahoua
49	'Soumba'	Tounfafi	Madaoua	Madaoua	Tahoua
50	'Tattassé'	Soutoura	Doguéraoua	Malbaza	Tahoua
51	'Na Damana'	Konni	Konni	Konni	Tahoua
52	'Tonko Béro'	Tanda	Tanda	Gaya	Dosso
53	'Saye Hillo'	Koutougou	Ayérou	Ayérou	Tillabéri
54	'Simbad'	Gorou Béri	Liboré	Kollo	Tillabéri
55	'Chinoi'	Gorou Béri	Liboré	Kollo	Tillabéri
56	'Simbad'	Galbal	Liboré	Kollo	Tillabéri

Source: created by the authors using germplasm collection data obtained during the survey

The soil had a sandy-clay texture. The trial was conducted in an incomplete block design, specifically an alpha lattice design (9×3) with three replicates. Each replication consisted of three sub-blocks, each containing nine experimental units. Each accession was represented once per replication and transplanted into ten planting hills per elementary plot, with a spacing of 40 cm between plants within rows and 50 cm between rows. Each elementary plot measured 1 m in width and 2 m in length, covering an area of 2 m². The experimental units, or elementary plots, were spaced 0.5 m apart, while sub-blocks were spaced 1 m apart. A distance of 2 m was maintained between replications. The nursery was established in January 2024. Transplanting was carried out 50 days after sowing, when the seedlings had reached the stage of six to nine leaves. This operation was followed by the incorporation of carbofuran for the control of insects and nematodes. Prior to transplanting, the elementary plots were thoroughly tilled, levelled, and watered. Irrigation was carried out at regular intervals, either early in the morning or in the evening, and with different quantities of water depending on the phenological stage. From transplanting to early flowering, 20 L of water was applied per plot. From early flowering to harvest, 30 L per plot was applied. The weeding was carried out as required. Fertilisation was performed using NPK (15-15-15) fertiliser applied on the 15th, 30th, 50th, and 80th days after transplanting at a rate of 30 g per plot.

Phenotypic data on various morphological and agronomic traits were recorded. Leaf shape, leaf colour, and stem pubescence (presence or absence of small hairs) were recorded at the vegetative stage. Plant height was measured on the central rows (cm) when the first fruits on 50% of the plants had begun to ripen. Canopy width was measured on the central rows (cm) and recorded after the first harvest at the widest point. Stem length (height of the first bifurcation) was measured on the central rows (cm) after the first harvest. Stem diameter was measured on the central row at the middle of the first bifurcation after the first harvest. The duration to 50% flowering, defined as the number of days from sowing to the stage when 50% of the plants in an experimental unit had flowered, was recorded. Corolla spot (presence or absence of a spot on the corolla) and corolla shape were recorded on the outer rows. Corolla length was determined as the mean length of ten petals measured on plants from the outer rows. Anther colour and anther length (the mean length of ten flowers selected from different plants) were recorded at the anthesis stage on the outer rows. Fruiting date, defined as the number of days from sowing to 50%

fruiting within an experimental unit, and fruit colour were recorded at maturity. Fruit shape, fruit length (mean length of ten fruits), fruit width (mean width of ten fruits measured at the widest point), fruit weight (mean weight of ten fruits), pedicel length (mean length of ten pedicels), fruit pericarp thickness (mean thickness of ten ripe fruits), number of locules (mean number determined from fruit cross-sections), and the number of seeds per fruit (mean value based on ten fruits from ten randomly selected plants) were recorded at the second harvest. Number of fruits (total number of fruits), fresh fruit yield (mean yield of plants in the middle row), dry fruit yield (mean yield of plants in the middle row), and seed yield were recorded at each harvest. Statistical analyses, including principal component analysis (PCA) and correlation analysis, were performed using R software to explore the relationships among traits.

To summarise the multidimensional morpho-agronomic traits and to identify the main factors underlying the variability among the studied pepper accessions, PCA was applied. This method enabled the reduction of data dimensionality and provided a clear assessment of the contribution of individual traits to the genetic and phenotypic diversity of the ecotypes.

RESULTS AND DISCUSSION

The PCA revealed key traits that contribute to the diversity among accessions (Fig. 2). It illustrates the relationships between the principal components (PCs) and the original variables. Hence, the first principal component is essentially orthogonal to plant height, plant width, height of the first bifurcation, and the number of aborted flowers. Likewise, this component is also orthogonal to plant circumference, grain number, and corolla length. The second PC is oriented in the opposite direction to plant height, plant width, height of the first bifurcation, and the number of aborted flowers. Furthermore, the graph indicates that the second component is primarily aligned with grain number, corolla length, pericarp thickness, anther length, and fruit width.

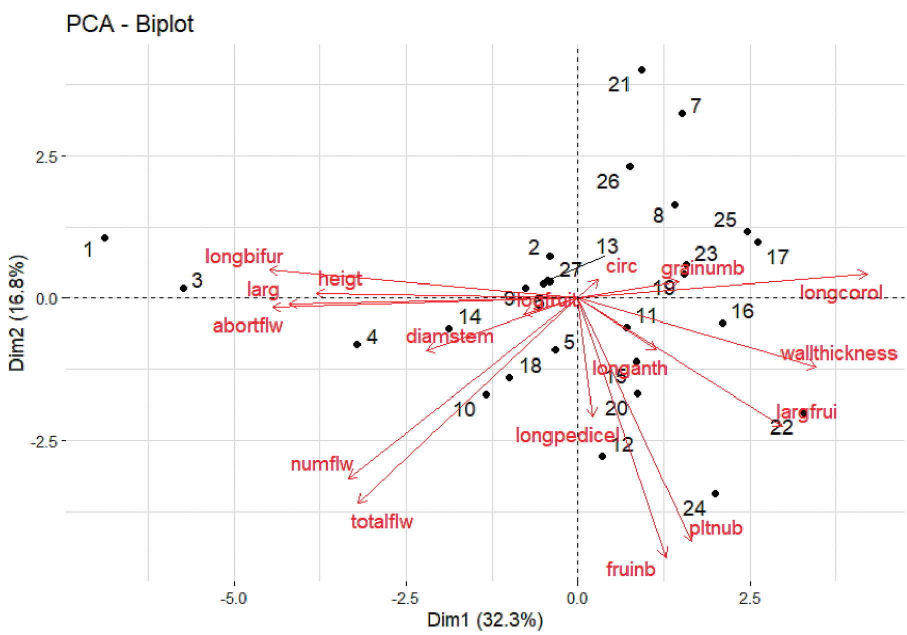

Figure 2. Principal components of pepper ecotypes

Note: V = accession; 1 = V4, 2 = V9, 3 = V10, 4 = V12, 5 = V21, 6 = V22, 7 = V23, 8 = V25, 9 = V29, 10 = V30, 11 = V31, 12 = V32, 13 = V33, 14 = V34, 15 = V35, 16 = V37, 17 = V38, 18 = V39, 19 = V40, 20 = V46, 21 = V49, 22 = V53, 23 = V54, 24 = V56, 25 = V57, 26 = V58, 27 = V59

Source: created by the authors using germplasm evaluation data

The first principal component is negatively correlated with four original variables, including plant height, plant width, height of the first bifurcation, and the number of aborted flowers. Hence, the first component increases as these variables decrease. The first component is positively correlated with corolla length. Thus, this component increases with increasing corolla length. The second component is strongly and negatively correlated with plant number, fruit number, and flower number. Therefore, the second component decreases as plant number, fruit number, and flower number increase. The third principal component is strongly and negatively correlated with fruit length and anther length (Table 2).

Table 2. Principal components

	PC1	PC2	PC3	PC4	PC5
Pltnub	0.14	-0.50	0.12	0.20	0.16
Fruinb	0.11	-0.52	0.16	0.14	0.13
Heigt	-0.32	0.01	-0.24	-0.07	0.01
Circ	0.02	0.04	0.21	0.05	-0.78
Larg	-0.35	-0.01	0.09	-0.24	0.03
Longbirtur	-0.37	0.06	-0.001	-0.18	0.09
Diamstem	-0.18	-0.11	-0.10	0.56	-0.16
Longcorol	0.35	0.05	-0.16	-0.20	0.09
Longanth	0.09	-0.11	-0.55	0.05	0.04
longpedicel	0.02	-0.24	-0.30	-0.48	0.04
Logfruit	-0.07	-0.03	-0.59	0.24	-0.21
Largfrui	0.25	-0.26	-0.14	-0.16	-0.14
Pericarpthickness	0.29	-0.14	-0.02	-0.27	-0.43
Grainumb	0.12	0.03	0.15	-0.21	-0.03
Totalflw	-0.27	-0.42	0.04	-0.06	-0.091
Numflw	-0.28	-0.32	0.11	-0.12	-0.05
Abortflw	-0.37	-0.02	-0.09	-0.18	-0.20

Note: PC = principal component, Pltnub = plants number, Fruinb = number of fruits, Heigt = plant height, Circ = plant circumference, Larg = plant width, Longbirtur = height of the first bifurcation, Diamstem = stem diameter, Longcorol = corolla length, Longanth = anther length, Longpedicel = pedicel length, Logfruit = fruit length, Largfrui = fruit width, Pericarpthickness = pericarp thickness, Grainumb = mean number of grains per fruit, Totalflw = total number of flowers, Abortflw = number of aborted flower
Source: created by the authors using germplasm evaluation data

Significant diversity was revealed among national bell pepper accessions, as indicated by the presence of distinct genetic clusters. Hence, at a linkage distance of 8, the hierarchical clustering dendrogram shows four major groups (Fig. 3).

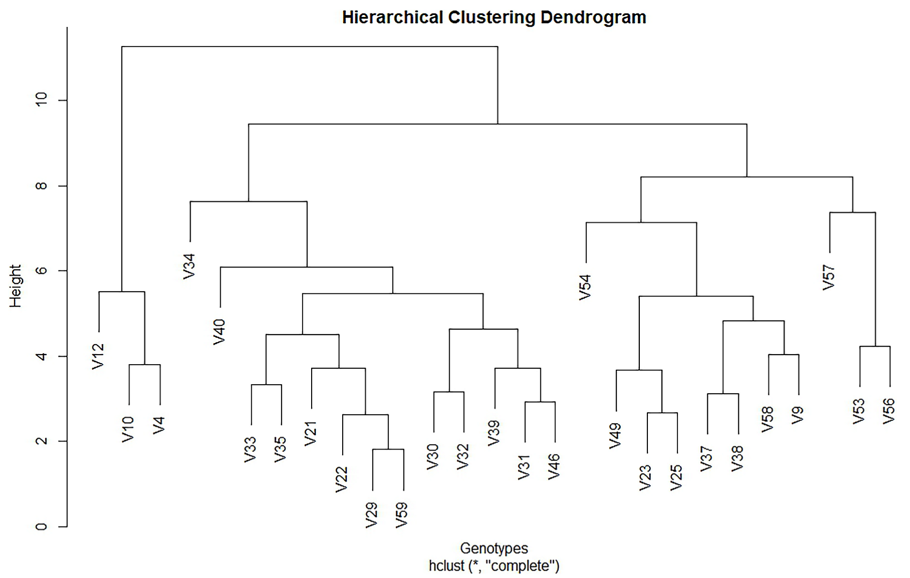

Figure 3. Classification of different ecotypes

Note: V = accession, 1 = V4, 2 = V9, 3 = V10, 4 = V12, 5 = V21, 6 = V22, 7 = V23, 8 = V25, 9 = V29, 10 = V30, 11 = V31, 12 = V32, 13 = V33, 14 = V34, 15 = V35, 16 = V37, 17 = V38, 18 = V39, 19 = V40, 20 = V46, 21 = V49, 22 = V53, 23 = V54, 24 = V56, 25 = V57, 26 = V58, 27 = V59

Source: created by the authors using germplasm evaluation data

The first cluster is composed of V4, V10, and V12. The second cluster, which is the largest, comprises 13 varieties, including V34, V40, V33, V35, V21, V22, V29, V59, V30, V32, V39, V31, and V46. The third cluster is made up of eight ecotypes, namely V54, V49, V23, V25, V37, V38, V58, and V9. The fourth cluster comprises three cultivars: V57, V53, and V56. The first group, including V4, V10, and V12, shows similarities in terms of plant width, plant height, number of aborted flowers, and height of the first bifurcation. This group is markedly dissimilar to the fourth group (V57, V53, and V56). The similarities observed within this cluster are related to fruit number, fruit width, anther length, and pedicel length. At a linkage distance of 4, Group 1 is subdivided into two clusters. On the one hand, V10 and V4 formed one subgroup, while on the other hand, V12 formed a separate subgroup. At this level, Group 2 is divided into six subclusters: subgroup 1 (V46, V31, V39), subgroup 2 (V32, V30), subgroup 3 (V59, V29, V22, V21), subgroup 4 (V33, V35), subgroup 5 (V40), and subgroup 6 (V34). V40 differs from the other accessions in terms of grain number, whereas V34 is distinct in terms of stem diameter. V33 and V35 are similar in terms of plant height and fruit length. Figure 4 illustrates the correlation matrix among the studied traits, highlighting the strength and direction of significant relationships between morphological and agronomic characteristics of the pepper accessions.

Correlation analysis shows several highly significant ($p < 0.001$) positive associations among traits, including fruit pericarp thickness and corolla length, fruit pericarp thickness and fruit length, plant circumference and fruit pericarp thickness, total number of flowers and number of aborted flowers, plant height and number of aborted flowers, plant height and total number of flowers, height of the first bifurcation and plant height, height of the first bifurcation and total number of flowers, and height of the first bifurcation and number of aborted flowers. Highly significant ($p < 0.01$) positive associations were observed among traits such as fruit length and corolla length, height of the first bifurcation and mean number of fruits, plant height and mean number of fruits, and number of fruits and fruit length. Significant ($p < 0.05$)

positive associations were also detected among traits, corolla length and number of grains (seeds), total fruit number and fruit length, total fruit number and fruit pericarp thickness, and pedicel length and fruit length.

Very highly significant ($p < 0.001$) negative associations were found among traits, including plant canopy width and corolla length, and height of the first bifurcation and corolla length. In addition, highly significant ($p < 0.01$) negative correlations were observed between the number of aborted flowers and corolla length, and between the number of aborted flowers and fruit length. Furthermore, significant negative correlations ($p < 0.05$) were recorded between the number of flowers and corolla length, plant height and number of grains (seeds), plant height and corolla length, plant height and fruit length, and plant height and fruit pericarp thickness. Qualitative traits, such as leaf shape, leaf colour, and stem pubescence, classified the accessions into five groups. The largest group was composed of accessions with deltoid-shaped leaves, dark green colour, and without stem pubescence. The second group included accessions with deltoid-shaped leaves, dark green colour, and with stem pubescence (Fig. 5).

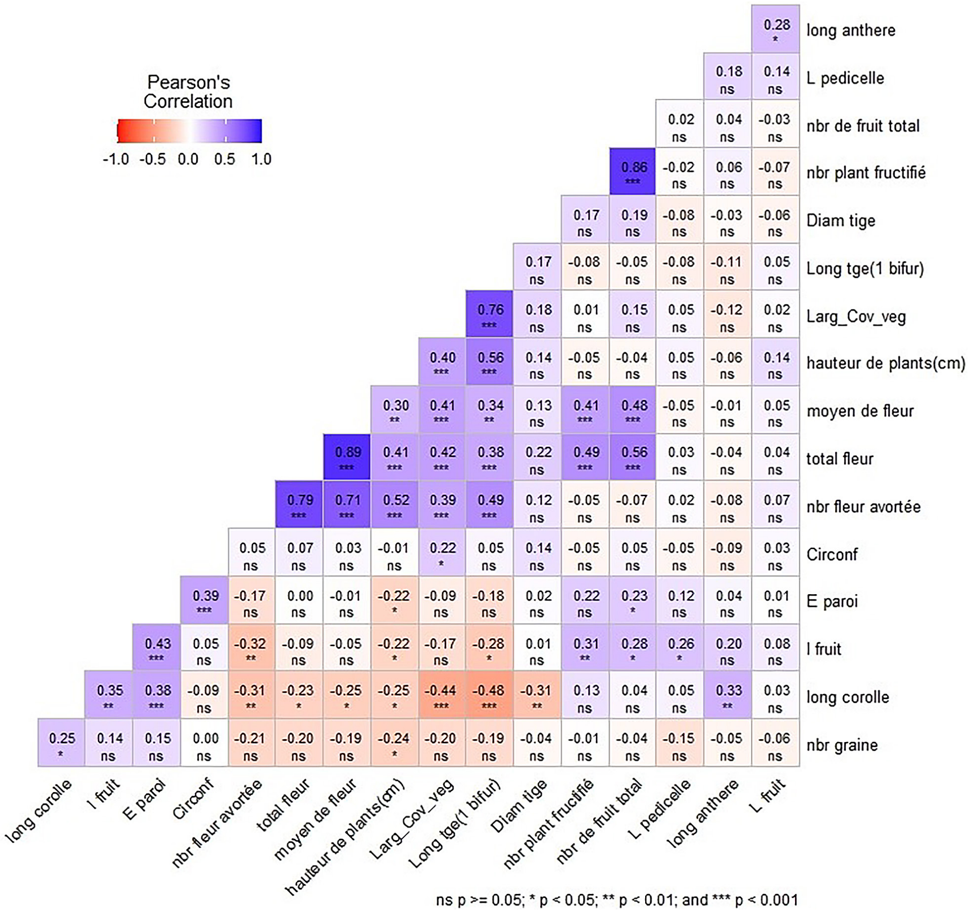

Figure 4. Cluster showing the diversity of pepper accessions

Note: V = accession, 1 = V4, 2 = V9, 3 = V10, 4 = V12, 5 = V21, 6 = V22, 7 = V23, 8 = V25, 9 = V29, 10 = V30, 11 = V31, 12 = V32, 13 = V33, 14 = V34, 15 = V35, 16 = V37, 17 = V38, 18 = V39, 19 = V40, 20 = V46, 21 = V49, 22 = V53, 23 = V54, 24 = V56, 25 = V57, 26 = V58, 27 = V59

Source: created by the authors using germplasm evaluation data

Figure 5. Distribution of accessions according to leaf shape, colour, and stem pubescence

Source: created by the authors using germplasm evaluation data

Additionally, fruit shape and surface texture classified the accessions into eight groups (Fig. 6). The two largest groups consisted of accessions with elongated fruits and smooth texture, on the one hand, and accessions with elongated fruits and rough (scrubbed) texture, on the other. Furthermore, fruit lobule number and seed colour classified the accessions into nine groups (Fig. 7).

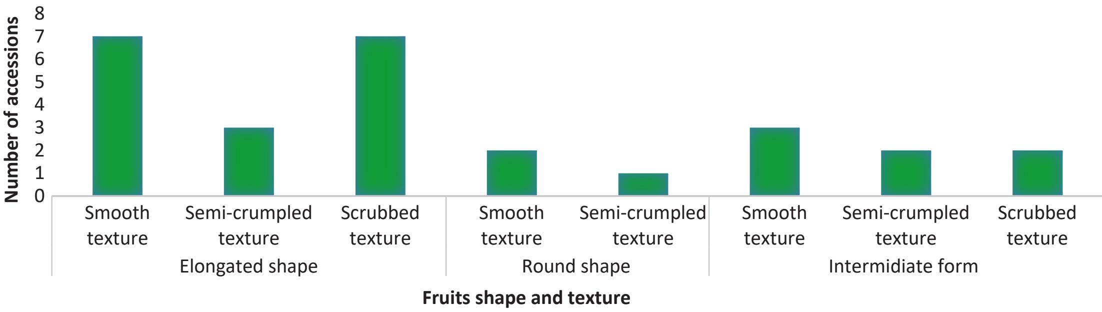

Figure 6. Distribution of accessions according to fruit characteristics

Source: created by the authors using germplasm evaluation data

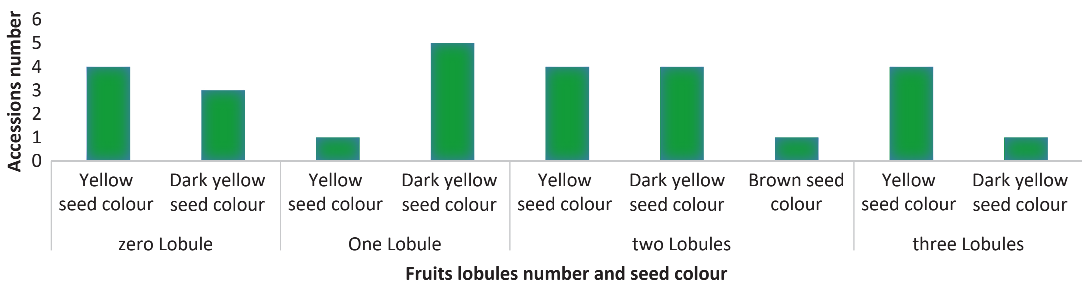

Figure 7. Grouping of accessions according to fruit lobule number and seed colour

Source: created by the authors using germplasm evaluation data

The frequency of yellow seed colour was the highest, followed by dark yellow, whereas brown occurred only once. The figure illustrates the association pattern and correlation between the number of lobules per fruit and seed colour. Hence, fruits with two lobules exhibited three seed colour types: yellow, dark yellow, and brown. In this study, bell pepper accessions from five regions in Niger were evaluated using thirty-eight morphological characters. Results showed substantial genetic diversity among accessions. The qualitative traits effectively discriminated the accessions into several distinct groups. The quantitative traits were also highly discriminative, with the first two principal component axes accounting for most of the observed variation. Cluster analysis further classified the accessions into four major groups, indicating a high level of genetic diversity. According to A. Simonne *et al.* (1997), C. Frank *et al.* (2001), and R. Frankham (2005), genetic diversity plays an important role in the survival and adaptability of a species and is indispensable for its conservation and management. This is because, when genetic diversity is low, a species becomes more susceptible to diseases and natural hazards, and entire crop populations may be severely affected or even lost (Edak *et al.*, 2014). Within a population, variability is essential for maintaining biodiversity, as limited variability reduces the capacity of populations to adapt to environmental change. Consequently, populations with low variability are more prone to decline or extinction (Terfa & Gurmu, 2020; Karim *et al.*, 2022; Menisha *et al.*, 2023). Similar findings have been reported for okra by H. Chheda & C. Christian (1982) and for Bambara groundnut by H. Aktaş *et al.* (2013) and C. Uba *et al.* (2021), emphasising the importance of understanding genetic diversity within landrace collections. Accessions were grouped into eleven clusters based on their morphological similarities. The largest cluster contained six accessions, whereas the smallest contained one. This indicated that individuals within the same cluster are genetically similar, while accessions in different clusters are genetically divergent (Pickersgill, 1991; Tong & Bosland, 2003; Sanwal *et al.*, 2012). These findings provide valuable insights into the genetic diversity of bell pepper accessions in Niger and can inform future conservation and breeding strategies.

Very highly significant positive associations were observed between height of the first bifurcation and plant height, height of the first bifurcation and total number of flowers, and height of the first bifurcation and number of aborted flowers. This implies that a higher position of the first bifurcation is associated with taller plants and increased numbers of both total and aborted flowers. Hence, the height of the first bifurcation may be used as an indirect selection criterion to improve these traits. In addition, very highly significant positive associations were found between plant circumference and fruit pericarp thickness, and between plant height and number of aborted flowers. This indicates that accessions with larger plant circumference tend to have thicker fruit pericarps, and that taller genotypes are more prone to flower abortion.

The results also showed significant negative correlations between the number of aborted flowers and corolla length, and between the number of aborted flowers and fruit length. This implies that flowers with shorter corollas are less susceptible to abortion than those with longer corollas. This interpretation is further supported by the significant negative correlation between the number of flowers and corolla length, indicating that genotypes with shorter corollas tend to produce more fertile flowers. Hence, considering that the experiment was conducted during the hot season, it can be assumed that accessions with shorter corollas lose fewer flowers under high-temperature conditions. Thus, this trait (short corolla) can be used to indirectly select genotypes with improved heat tolerance. Furthermore, genotypes that lost more flowers also produced shorter fruits. This may be explained by the fact that these accessions are more sensitive to heat stress.

CONCLUSIONS

This research provides a comprehensive assessment of the diversity in Niger's bell pepper germplasm, revealing significant correlations among key agronomic traits. The positive correlations between specific traits point to potential targets for simultaneous improvement through strategic breeding. Understanding the genetic basis of these trait associations can facilitate the development of superior bell pepper varieties with enhanced agronomic performance. This study offers an in-depth examination of the diversity and correlations among national bell pepper accessions, enriching current knowledge of genetic variability and trait relationships in bell pepper. The findings emphasise the critical role of genetic diversity analysis in crop improvement programmes aimed at increasing productivity and fruit quality. This diversity reflects the processes of adaptation and selection by local farmers and represents a vital buffer against climate change and pest pressure.

Future research should focus on a more detailed exploration of the genetic potential of Niger's national bell pepper collection to enable its more effective use in breeding programmes. First, emphasis should be placed on the genetic analysis of accessions exhibiting rare and unique trait combinations, such as brown seeds with two lobules, in order to identify uncommon alleles that could serve as valuable resources for the development of new varieties. Second, correlated traits should be evaluated for their impact on yield, fruit quality, and nutritional value, thereby allowing the identification of trait complexes suitable for simultaneous improvement through targeted breeding strategies. Third, it is essential to integrate the morphological data obtained with molecular marker analyses, which would help to establish relationships between phenotypic variability and the genetic structure of the collection. This comprehensive approach will promote the rational utilisation of genetic resources, facilitate the effective selection of promising genotypes, and enhance the productivity and resilience of new varieties, ultimately supporting sustainable agricultural development in Niger.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest associated with this study. The research was conducted independently, without any financial, commercial, or personal relationships that could have influenced the study design, data collection, analysis, or interpretation of the results. All funding sources were transparently acknowledged, and the study reflects independent scientific judgement and a commitment to advancing knowledge of Niger's genetic resources.

REFERENCES

[1] Agapie, O.L., Barcanu, E., Kivu, B.E., Gherase, I., & Dobre, G. (2023). Assessment of romanian peppers cultivars for fruit quality traits. *Journal of International Scientific Publications: Agriculture & Food*, 11, 356-365. doi: 10.62991/AF1996333889.

[2] Aktaş, H., Abak, K., & Şensoy, S. (2013). Genetic diversity in some Turkish pepper (*Capsicum annuum* L.) genotypes revealed by AFLP analyses. *African Journal of Biotechnology*, 8, 4378-4386. doi: 10.4314/ajb.v8i18.62388.

[3] Anaya-Esparza, L.M., Mora, Z.V.-D.L., Vázquez-Paulino, O., Ascencio, F., & Villarruel-López, A. (2021). Bell peppers (*Capsicum annum* L.) losses and wastes: Source for food and pharmaceutical applications. *Molecules*, 26(17), article number 5341. doi: 10.3390/molecules26175341.

[4] Barboza, G.E., García, C.C., Scaldaferro, M., & Bohs, L. (2020). An amazing new *Capsicum* (Solanaceae) species from the Andean-Amazonian Piedmont. *PhytoKeys*, 167, 13-29. doi: 10.3897/phytokeys.167.57751.

[5] Chheda, H.R., & Fatokun, C.A. (1982). Numerical analysis of variation patterns in okra (*Abelmoschus esculentus* [L.] Moench). *Botanical Gazette*, 143(2), 253-261.

[6] Convention on Biological Diversity. (1992, June). Retrieved from https://surli.cc/kyhror.

[7] Convention on the Trade in Endangered Species of Wild Fauna and Flora. (1976, March). Retrieved from https://surl.lu/brffmq.

[8] Edak, U., Chukwudi, U.T., & Peter, O.A. (2014). Genetic diversity in African nutmeg (*Monodora myristica*) accessions from South Eastern Nigeria. *African Journal of Biotechnology*, 13(42), 4105-4111. doi: 10.5897/AJB2014.14075.

[9] Frank, C.A., Nelson, R.G., Simonne, E.H., Behe, B.K., & Simonne, A.H. (2001). Consumer preferences for color, price, and vitamin C content of bell peppers. *HortScience*, 36(4), 795-800. doi: 10.21273/hortsci.36.4.795.

[10] Frankham, R. (2005). Genetics and extinction. *Biological Conservation*, 126, 131-140.

[11] Gamela, R.R., Costa, V.C., & Pereira-Filho, E.R. (2020). Multivariate optimization of ultrasound-assisted extraction procedure for the determination of Ca, Fe, K, Mg, Mn, P, and Zn in pepper samples by ICP OES. *Food Analytical Methods*, 13, 69-77. doi: 10.1007/s12161-019-01524-5.

[12] Hernández-Pérez, T., Gómez-García, M.D.R., Valverde, M.E., & Paredes-López, O. (2020). *Capsicum annuum* (hot pepper): An ancient Latin-American crop with outstanding bioactive compounds and nutraceutical potential. A review. *Comprehensive Reviews in Food Science and Food Safety*, 19(6), 2972-2993. doi: 10.1111/1541-4337.12634.

[13] Karim, K.M.R., Rafii, M.Y., Misran, A., Ismail, M.F., Harun, A.R., Ridzuan, R., Chowdhury, F.N., Hosen, M., Yusuff, O., & Haque, A. (2022) Genetic diversity analysis among *Capsicum annuum* mutants based on morpho-physiological and yield traits. *Agronomy*, 12(10), article number 2436. doi: 10.3390/agronomy12102436.

[14] Menisha, R., Kumar, J.S., & Prakash, M.O. (2023). Genetic variability for plant growth, fruit, seed and biochemical traits in bell pepper breeding populations under North Indian plains. *Genetika*, 55(1), 111-124. doi: 10.2298/GENSR2301111R.

[15] Muñoz-Ramírez, L.S., Peña-Yam, L.P., Álvarez-Gil, M.A., Iglesias-Andreu, L.G., Avilés-Viñas, S.A., Canto-Flick, A., Guzmán-Antonio, A., & Santana-Buzzy, N. (2020). Selection of habanero pepper F1 hybrids (*Capsicum chinense* Jacq.) at the Yucatan Peninsula, Mexico with a high potential for different markets. *Agriculture*, 10(10), article number 478. doi: 10.3390/agriculture10100478.

[16] Nas, Y., & İlbi, H. (2022). Determination of genetic diversity in banana and bell pepper lines using molecular markers. *International Journal of Agriculture and Wildlife Sciences*, 8(2), 234-244. doi: 10.24180/ijaws.1098482.

[17] Onzo, A., Acquavia, M.A., Pascale, R., Iannece, P., Gaeta, C., Nagornov, K.O., Tsybin, Y.O., & Bianco, G. (2021). Metabolic profiling of Peperoni di Senise PGI bell peppers with ultra-high resolution absorption mode Fourier transform ion cyclotron resonance mass spectrometry. *International Journal of Mass Spectrometry*, 470, article number 116722. doi: 10.1016/j.ijms.2021.116722.

[18] Pickersgill, B. (1991). Cytogenetics and evolution of *Capsicum* L. *Developments in Plant Genetics and Breeding*, 2(B), 139-160. doi: 10.1016/B978-0-444-88260-8.50013-6.

[19] Sanwal, S., Singh, B., & Verma, S.S. (2012). Genetic divergence and its implication in breeding of desired plant type in okra (*Abelmoschus esculentus*). *The Indian Journal of Agricultural Sciences*, 82(3), 264-266. doi: 10.56093/ijas.v82i3.15975.

[20] Silva, M.R.E., & Silva, R.N.O. (2021). Morpho-agronomic characterization and genetic diversity in peppers (*Capsicum* spp.). *Revista Caatinga*, 34(3), 505-513. doi: 10.1590/1983-21252021v34n302rc.

[21] Simonne, A.H., Simonne, E.H., Eitenmiller, R.R., Mills, H.A., & Green, N.R. (1997). Ascorbic acid and provitamin A contents in unusually colored bell peppers (*Capsicum annuum* L.). *Journal of Food Composition and Analysis*, 10(4), 299-311. doi: 10.1006/jfca.1997.0544.

[22] Terfa, G.N., & Gurmu, G.N. (2020). Genetic variability, heritability and genetic advance in linseed (*Linum usitatissimum* L) genotypes for seed yield and other agronomic traits. *Oil Crop Science*, 5(3), 156-160. doi: 10.1016/j.ocsci.2020.08.002.

[23] Tong, N., & Bosland, P.W. (2003). Observations on interspecific compatibility and meiotic chromosome behavior of *Capsicum buforum* and *C. lanceolatum*. *Genetic Resources and Crop Evolution*, 50, 193-199. doi: 10.1023/A:1022986615694.

[24] Uba, C.U., Oselebe, H.O., Tesfaye, A.A., & Abtew, W.G. (2021). Genetic diversity and population structure analysis of bambara groundnut (*Vigna subterrenea* L) landraces using DArT SNP markers. *Plos One*, 16, article number 0253600. doi: 10.1371/journal.pone.0253600.

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Різноманітність та кореляційний аналіз національних доступів солодкого перцю (*Capsicum annuum* L.) Нігеру

Анотація. Дослідження різноманітності та кореляційного аналізу національних доступів солодкого перцю має велике значення, оскільки воно задокументувало та зберегло цінні місцеві генетичні ресурси, а також надало важливу інформацію для селекції та вдосконалення сортів. Оцінюючи агроморфологічну мінливість та виявляючи взаємозв'язки між ключовими ознаками, дослідження допомогло селекціонерам у виборі кращих батьківських ліній та направило фермерів у виборі добре адаптованих доступів для різних умов вирощування. Це знання сприяє підвищенню продуктивності, стійкості до кліматичного стресу та покращенню якості плодів, що в кінцевому підсумку посприяє продовольчій безпеці, генерації доходів та кращому управлінню національними ресурсами генетичного матеріалу. Метою дослідження було оцінити генетичну різноманітність та визначити ключові кореляції ознак серед національних доступів солодкого перцю в Нігері для ефективного відбору, збереження та програм селекції. Для цього було зібрано національний місцевий генетичний матеріал і оцінено за схемою Альфа-Латіс із 3 повтореннями. Дані були зібрані та проаналізовані за допомогою кореляційного аналізу, оцінки різноманітності, кластерного аналізу та аналізу головних компонент (PCA). Результати виявили значну генетичну різноманітність серед національних доступів солодкого перцю, підкреслюючи існування окремих генетичних кластерів. Було встановлено значущі взаємозв'язки між ознаками, такі як позитивна кореляція між товщиною перикарпу плода та довжиною віночка, товщиною перикарпу та довжиною плода, обхватом рослини та товщиною перикарпу плода, загальною кількістю квіток та кількістю абортованих квіток, висотою рослини та кількістю абортованих квіток, висотою рослини та загальною кількістю квіток, висотою першого відгалуження та висотою рослини, висотою першого відгалуження та загальною кількістю квіток, висотою першого відгалуження та кількістю абортованих квіток. Виявлена генетична різноманітність та кореляції ознак надали важливу інформацію для збереження та поліпшення сортів солодкого перцю. Результати роботи можуть використовуватися селекціонерами та фермерами для відбору та вирощування високопродуктивних і стійких сортів солодкого перцю

Ключові слова: оцінка мінливості; характеристика генофонду; генетична різноманітність; аналіз головних компонент; кластерний аналіз; агроморфологічні ознаки

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Impact of military activities on the biogenicity of southern chernozem

Abstract. Among a number of significant problems that have arisen as a result of military operations on the territory of Ukraine is the degradation of soils, which requires finding ways to accelerate the processes of their recovery after damage. The purpose of the study was to assess the biogenicity indicators of the state of southern chernozem and low-humus sands under military influence and the use of a recovery complex, which consisted of organic fertiliser Parostok and

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bacterial-metabolic preparation Ultrachist. The research methods included laboratory analysis of samples using microbiological seeding on media suitable for microorganisms of ecological-trophic, functional, and taxonomic groups, and statistical data processing to determine the reliability of discrepancies. The conducted studies indicated a significant negative impact on the density of populations of soil microorganisms of southern chernozem from rocket hits and low-humus sands from fires as a result of military operations. The number of representatives of the native microbiota in soils has tripled after the military impact. The biogenicity indicators of southern chernozem and low-humus sands decreased by 7.7 and 4.9 million CFU/g of dry soil (2.6 and 2.3 times), respectively, compared to the control. The restoration complex contributed to the growth of soil biogenicity in all variants of the experiment. In the damaged samples, the increase in indicators under the action of the recovery complex was higher than in the control samples. The use of the recovery complex in the background southern chernozem conditions increased the biogenicity of the soil by 4.2 times, and after a missile hit – by 6.1 times. In the slightly humus-rich sands of forest lands under the influence of the restoration complex, an increase in its biogenicity was observed by 1.9 times, while in the sample after pyrogenic exposure by 9.9 times. The proposed recovery complex based on organic matter and beneficial microorganisms can be considered as a stabilisation factor that will activate the microbiota of degraded soil for the restoration of soil ecosystems

Keywords: soil microorganisms; low-humus sands; impact of military operations; degradation of the microbiocoenosis; recovery complex

INTRODUCTION

Chernozem soils are unique in their morphological, physical, and chemical characteristics and perform versatile functions, in particular, productive, biospheric, ecological, and social. The military actions of recent years have affected all links of ecosystems on the territory of Ukraine. The negative consequences of military influence on the condition of soils are associated with mechanical damage to their natural structure, the ingress of chemicals, in particular heavy metals and petroleum products, which leads to long-term deterioration of soil quality and loss of its productive properties. First of all, the soil microbiota responds to changes in conditions, which is a key component of ecosystems and an indicator of soil condition. Studies of soil microorganisms are relevant, as they allow assessing the processes occurring in degraded soils, and the search for ways to increase microbiological activity will improve the condition of the soil and, as a result, restore soil ecosystems.

Studies of the soils of Ukraine after a full-scale invasion and intensification of military operations show that more than 5 million hectares of chernozems alone have undergone military degradation, as noted by S. Balyuk *et al.* (2023) and S. Balyuk *et al.* (2025). O. Dmitrenko *et al.* (2023) in their research showed that soil degradation due to the use of mortar weapons was confirmed by the presence of heavy metals after a year of observations. The damage caused by the war to the environment reaches tens of billions of USD (Hryhorczuk *et al.*, 2024). Soils that have been degraded as a result of destruction, fires, chemical and other types of pollution require active actions in finding ways to restore them.

The role of both aerobic and anaerobic microorganisms in bioremediation of heavy metal-contaminated soils is known, which is based on the ability of some representatives of the microbiota to absorb, deposit, or change the valence of heavy metals, which allows reducing their concentration in the soil to a safe level (Abo-Alkasem *et al.*, 2023; Galkin *et al.*, 2024). A. Danial & F. Dardi (2023) proved that there are known bacteria that have the ability to biosorb metals, which reduces their movement and toxicity in the soil. The study by A. Johnsen *et al.* (2021) pointed to the ability of destructive microorganisms to promote the restoration of diesel-contaminated soils even at low temperatures.

The soil microbiota is sensitive to various factors, so it is an indicator of changes that occur under their influence (Goulart *et al.*, 2025). Soil biogenicity is one of the most important indicators of the activity of microbiological processes of metabolism and energy in the trophic chains of the soil biocoenosis. Therefore, increasing the activity of the soil microbiota is an important area of research that has great prospects in solving the problem of restoring degraded soils, research aimed at restoring microbiological balance is particularly relevant, since it is microorganisms that are the initial link in restoring trophic connections in soil ecosystems.

Since the natural processes of reclamation of contaminated soils are long-term and often insufficiently effective, there is a need to use biological means that can accelerate these processes. The paper by V. Vakhnyak *et al.* (2025) emphasised that the restoration of degraded soils is a strategically important factor in ensuring the country's food security, especially in the face of increasing anthropogenic and military loads. The researchers proved that degradation processes negatively affect not only soil fertility, but also the stability of agroecosystems in general, so the introduction of effective biological methods of restoration is key to preserving the productive potential of chernozems. The paper noted the expediency of using organic and biological preparations that can activate microbiological processes, improve the structure of the soil and restore its ecological functions. It is known that the use of organic fertilisers in combination with microbial preparations has a positive effect on the activation of the soil microbiota and accelerates the restoration of biological balance in degraded ecosystems.

Therefore, the purpose of the study was to evaluate the effectiveness of combined application of organic fertiliser Parostok and biological preparation Ultrachist in restoring damaged and contaminated soils, in particular, by stimulating microbiological processes, increasing biogenicity, and improving the physical and chemical properties of chernozems. The objective of the study was to determine the extent to which these preparations can enhance the metabolic activity of soil microbiota, promote the detoxification of pollutants, and restore the natural productivity of soil, which is crucial for the rehabilitation of ecosystems affected by military operations.

MATERIALS AND METHODS

The study was conducted during 2023-2024, which allowed tracing the dynamics of recovery processes in soils after applying organic fertilisers and biologics. Organic fertiliser Parostok was used to restore and increase humus reserves, improve the phytosanitary condition of soils, and reduce the negative anthropogenic impact of chemical pollutants. It accumulated a large number of macro- and microelements, biologically active substances, and a balanced symbiotic consortium of effective microorganisms. In turn, the biologic Ultrachist is a bacterial and metabolic agent containing highly effective natural strains of microorganisms, which in a stable symbiosis with each other can decompose pesticides, toxic and explosive substances, and hydrocarbons of oil and petroleum products. It was designed for detoxification and remediation of environments contaminated with organic and chemical substances. In addition, the biological product acts not only as a direct destructor of pollutants, but also as an activator of biological destruction, since it can stimulate the native microbiota, which accelerates processes several times. The study took into consideration the impact on the environment, as outlined in the Universal Declaration on Bioethics and Human Rights (2005).

The research was conducted at the Ukrainian Laboratory for Quality and Safety of Agricultural Products at the National University of Life and Environmental Sciences of Ukraine. Soil sampling from locations that represented different types of environmental violations was carried out in the Mykolaiv region: southern chernozem from residential territory of Snihurivka Territorial Community and soil contaminated with pesticides as a result of a rocket hit in a warehouse with toxic chemicals; low-humus sands of the Halytsynove forest and forest lands after fires as a result of armed conflict. Organic fertiliser Parostok, supplemented with bacterial-metabolic biological product Ultrachist, was used as a restoring complex (RC). The model experiments were conducted in triplicate in 500 cm^3 vessels with 0.3 kg of soil and the calculation of preparations in accordance with the recommended application rate: organic fertiliser Parostok – 4 t/ha, Ultrachist – 10 cm^3 of working solution per

1 dm^3 of soil. Microbiological seeding was carried out after 7 days of composting at a temperature of 25°C and humidity of 55-70%. The study was conducted according to the following scheme: control 1 – residential areas near the zone affected by rocket strikes; pesticide contamination due to rocket strikes on a pesticide storage facility in a residential area; control 2 – forest land that did not undergo pyrogenic impact; forest land after fires caused by armed conflict. RC was added to each of the options.

The number of microorganisms of various taxonomic (bacteria, including actinobacteria, and microscopic fungi (micromycetes) and ecological and trophic groups (pedotrophic, ammonifying, amylolytic, oligotrophic, oligoazotrophic microorganisms, etc.) was determined by seeding soil cultures on appropriate nutrient media. For the total number of bacterial coenosis (pedotrophs) – soil agar was used, ammonifiers – meat-peptone agar, oligoazotrophs – Ashby medium, amylolytics – starch-ammonia agar, phosphatmobilisers – Menkina medium, oligotrophs – starvation agar, humatrophs – humate agar, actinobacteria – potato-glucose agar, micromycetes – Czapek medium. The composition of media was generally accepted in soil microbiology (Volkogon *et al.*, 2010). The number of microorganisms was expressed in colony-forming units (CFU) per 1 g of absolutely dry soil. The humidity of soil samples was determined by the thermostatic-weight method to recalculate the obtained number of colonies at a certain dilution of soil suspension. Mathematical statistics methods were used to calculate the confidence interval of the number of microorganisms.

Assessment of the course of processes occurring in the soil was determined using microbiological indicators of total biological activity (biogenicity = cultural nitrogen-fixing activity (NFA) + mineralising activity (MPA) + Ashby bacteria (Ashby) + humate-decomposing microorganisms (HA), mln CFU/g of dry soil), nitrogen pool mobilisation coefficient (KMAF = (MPA + NFA) / (Ashby + HA)) (Rieznik, 2021), mineralisation coefficients and indices and nitrogen immobilisation (K min = NFA / MPA), oligotrophy (K olig = HA / MPA), oligoazotrophy (K oligaze = Ashby / MPA).

RESULTS AND DISCUSSION

Soil damage as a result of military operations led to a decrease in the population density of the ecological-trophic and taxonomic groups of microorganisms under study. The native microbiota of southern chernozem decreased by 3.4 times due to a rocket hit on an agrochemical warehouse (Table 1). Pyrogenic effects on the low-humus sands of the Halytsynove forest also affected a decrease in the number of pedotrophs, three times compared to the control.

Table 1. Number of microorganisms of the main ecological, trophic, and taxonomic groups in soil samples

A)

Variant	Number of microorganisms by group, million CFU/g of dry soil				
	ammonifying	amylolytic	pedotrophic	phosphate mobilising	oligoazotrophic
Control 1 – background soil near the area affected by rocket impact	1.9±0.02	1.3±0.08	2.7±0.22	0.4±0.01	3.9±0.22
Control 1 + Recovery Complex (RC)	13.8±0.11	11.5±1.76	15.7±0.15	21.9±0.16	17.5±0.45
Contaminated with pesticides and explosives after a rocket hit	2.1±0.05	0.3±0.03	0.8±0.07	0.5±0.05	0.5±0.05
Contaminated with pesticides and explosives + RC	12.2±0.49	1.4±0.01	6.1±0.33	13.7±0.46	3.1±0.15
Control 2 – forest areas (background – in the absence of fire exposure)	0.2±0.01	2.0±0.09	0.9±0.06	0.2±0.02	2.1±0.06
Control 2 + RC	4.1±0.3	3.3±0.04	6.6±0.2	1.5±0.09	4.6±0.23
Forest lands after fires	0.6±0.02	0.1±0.01	0.3±0.03	0.4±0.03	0.2±0.02
Forest lands after fires + RC	12.6±0.07	6.9±1.62	9.7±0.26	8.0±0.43	8.8±0.21

Table 1, Continued

B)

Variant	Number of microorganisms by group				
	million CFU/g of dry soil		thousand CFU/g of dry soil		
	oligotrophic	humate-decomposing	cellulolytic	actinobacteria	micromycetes
Control 1 – background soil near the area affected by rocket impact	5.5±0.52	4.7±0.30	30.9±3.69	359.4±6.67	32.1±0.58
Control 1 + Recovery Complex (RC)	10.9±0.11	16.0±0.53	34.9±0.75	1.061.5±5.29	80.7±22.28
Contaminated with pesticides and explosives after a rocket hit	2.0± 0.19	3.5±0.59	6.1±0.11	38.4±1.53	24.5±1.0
Contaminated with pesticides and explosives + RC	13.5±0.86	7.0±0.30	15.6±0.75	254.2±13.7	13.8±1.15
Control 2 – forest areas (background – in the absence of fire exposure)	4.4±0.16	2.6±0.06	13.6±1.56	43.2±1.53	90.6±1.53
Control 2 + RC	4.6±0.07	5.6±0.40	27.7±1.33	335.1±2.65	135.0±2.52
Forest lands after fires	2.9±0.46	1.5±0.06	3.1±0.09	97.2±5.57	119.6±0.58
Forest lands after fires + RC	9.2±0.39	10.1±0.33	13.7±1.32	269.6±1.15	100.6±5.51

Source: compiled by the authors

Studies of the effect of the proposed recovery complex on the number of microorganisms revealed significant changes in indicators that depended on the initial sample (Table 1). All groups of microorganisms that showed an increase in their number, especially in damaged soils, were sensitive to the introduction of the recovery complex. Thus, the number of microorganisms that absorb organic nitrogen in soil contaminated with pesticides and explosives under the action of RC increased by 5.8 times and by 21 times in samples of forest land after fires. The same trends of increase of 4.6 and 69 times, respectively, were observed in the number of microorganisms that assimilate mainly mineral forms of nitrogen, and in the pedotrophic microbiota, where the increase in their number was 7.6 and 32.3 times, respectively, when using the recovery complex. Exceptions were groups of ammonifying and phosphatmobilising microorganisms in the organic-depleted soil of forest lands under the influence of fires.

The reaction of microorganisms capable of converting soil phosphates was different with a negative military effect, while the addition of RC also contributed to a 27.4-fold increase in their numbers in relation to contaminated soil and a 20-fold increase in forest land after fires. Diazotrophs play an important role in the nitrogen cycle. Their introduction into agrocoenoses is one of the priorities of agricultural microbiology (Kozar, 2021). The sensitivity of nitrogen-fixing bacteria to contamination affected their number by a decrease of 7.8 times, while the addition of RC brought the indicators closer to the background soil (3.1 million CFU/g of dry soil). Forest fires reduced their number in low-humus sandy soil by 10.5 times, and RC provided an increase of 44 times compared to the control.

The missile hit, which caused contamination of southern chernozem with pesticides, affected a decrease in the number of oligotrophs and humate-decomposing microorganisms by 2.7 and 1.3 times, respectively (Table 1B). The recovery complex contributed to an increase in the number of microorganisms of these groups by 6.7 and 2.0 times, respectively, compared to contaminated soil. Fires of forest lands also negatively affected their number, while under the action of RC, there was an increase in indicators by 3.1 and 6.7 times, respectively, compared to damaged soil.

An important role in enriching soils with organic matter is played by microorganisms that have the ability to decompose cellulose. Highly active cellulolytic microorganisms that have a complex of useful properties, in particular protective action, are potential bioagents of drugs for use in environmentally friendly agricultural technologies. When using the reducing complex, the number of microorganisms that decompose cellulose increased in controls 1 and 2 by 1.1 and 2 times, while in damaged soils this increase was more significant and amounted to 2.6 and 4.4 times, respectively. In the soils of controls 1 and 2, when exposed to VC, there was also an increase in the number of micromycetes by 2.5 and 1.5 times, respectively, while in damaged samples it was observed to decrease.

Actinobacteria are an important component of the soil microbiota, have a wide range of beneficial properties and are widely used in biotechnology, as noted by I. Levchuk *et al.* (2022) and M. Loboda *et al.* (2024). Among this taxonomic group, there are representatives that are able to decompose resistant herbicides that are dangerous to the environment, and thus act as potential bioremediation agents (Rebai *et al.*, 2024). Under conditions of pollution, there was a significant decrease in their number by 9.4 times to the background soil, but the introduction of a recovery complex stimulated their partial recovery by 6.6 times to the contaminated soil.

No less important is the ecological role of actinobacteria in soil recovery after fires. S. Jiang *et al.* (2025) in their studies showed that in soils exposed to pyrogenic effects, actinobacteria can become dominant. In forest soils after fires caused by armed conflict, their numbers were higher than the background level, reaching 97,200. CFU/g of dry soil, which increased 2.8 times under the action of RC. The negative impact of the missile hit affected a decrease in the biogenicity of southern chernozem by 7.7 million CFU/g of dry soil and 2.6 times compared to control 1 (Fig. 1). Fires as a result of military operations at the location of the Halytsynove forest also significantly reduced the biogenicity of low-humus sands by 4.9 million CFU/g of dry soil, which was 2.3 times in relation to control 2.

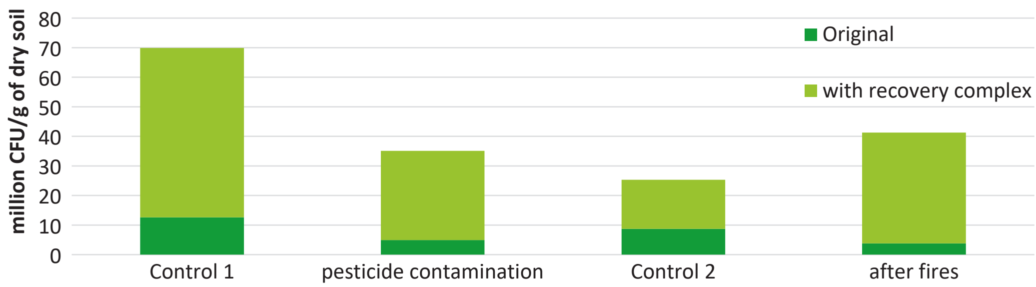

Figure 1. Soil biogenicity under military action and the use of a recovery complex, million CFU/g of dry soil

Note: control 1 – southern chernozem near the zone of impact of a missile hit in a warehouse with agrochemicals; control 2 – low-humus sands of forest land with no impact from fires

Source: compiled by the authors

The restoration complex contributed to the growth of soil biogenicity in all variants of the experiment. In addition, the growth rate was higher in the damaged samples than in the control soil. Thus, RC in the conditions of background southern chernozem (control 1) provided an increase in soil biogenicity by 4.2 times, while after a missile hit – by 6.1 times. The same trends, but with a larger gap, were also observed in low-humus forest fands: 1.9 times in control 2 and 9.9 times in samples after fires as a result of armed exposure. One of the most important indicators of the biological component of soil is microbial biomass, which also responds sensitively to changes occurring in the pedosphere. The military impact affected the reduction of biomass of soil microorganisms, while the recovery complex reduced the negative impact of factors (Melnychuk *et al.*, 2025). Biogenicity is closely related to microbial biomass values, as evidenced by the Pearson correlation coefficient, which was in the range of 0.68 in control 2 with the addition of RC to 1 in samples of low-humus forest sands after fires as a result of armed exposure.

The calculation of indices allows assessing the intensity and course of processes occurring in soils under the influence of certain factors. The military impact caused a violation of the direction of microbiological processes of the studied soils, which affected a decrease in the indicators of most indices and coefficients. The coefficient of mineralisation and immobilisation in southern chernozem was at the level of 0.68, pollution caused its decrease by 4.9 times, which indicates the suppression of mineralisation processes (Table 2).

Table 2. Orientation of microbiological processes in soil samples

Variant	Indexes and coefficients					
	pedotrophicity	oligotrophicity	mineralisation and immobilisation	oligoazototrophicity	mobilisation of nitrogen reserves	microbial transformation of organic matter
Control 1 – background soil near the area affected by rocket impact	1.42	2.89	0.68	2.05	0.34	4.67
Control 1 + recovery complex (RC)	1.14	0.79	0.83	1.27	0.89	30.36
Contaminated with pesticides and explosives after a rocket hit	0.38	0.95	0.14	0.23	0.96	168.8
Contaminated with pesticides and explosives + RC	0.50	1.11	0.11	0.25	0.82	118.51
Control 2 – forest areas (background – in the absence of fire exposure)	4.5	22.0	10.0	10.5	0.34	0.22
Control 2 + RC	1.61	1.12	0.80	1.12	0.8	9.19
Forest lands after fires	0.50	4.83	0.17	0.33	0.23	4.2
Forest lands after fires + RC	0.77	0.73	0.55	0.7	1.08	35.6

Source: compiled by the authors

The introduction of the complex contributed to an increase in the coefficient of mineralisation and immobilisation by 3.2 times in conditions of low-humus sands damaged by fires as a result of military operations, which indicates the activation of the nitrogen cycle. Contamination with pesticides and explosives after a missile hit had a different effect on the coefficients of nitrogen reserves mobilisation and microbial transformation of organic matter, where the increase in indicators was 2.8 and 35.7 times, respectively. The use of the recovery complex has somewhat stabilised the situation, with low indicators increasing and decreasing at high indicators.

The soil microbiota is an important component of healthy ecosystems and can play an essential role in restoring degraded soils, contributing to increasing their biodiversity, functionality, and sustainability (Peddle *et al.*, 2025). T. Krell *et al.* (2023) proved that microorganisms are exposed to various influences in natural niches and are sensitive to changes in living conditions. O. Demydenko (2021), investigating the correlations of ecological and trophic groups of soil microorganisms with soil fertility, showed that the increase in biogenicity due to the increase in the number and activity of ammonifying, amylolytic, pedotrophic, oligotrophic microorganisms and a decrease in the activity of humate-decomposing groups of microorganisms ensures the reproduction of humus in the conditions of podzolized chernozem. The practical use of microorganisms, combining them into suitable complexes for their intended purpose, enhances their functional activity and provides greater stability and efficiency (Tytova *et al.*, 2023). Therefore, the study of the microbiota of degraded soils and the search for ways to regulate its activity is one of the priority areas in present-day conditions.

Thus, the conducted research showed that military exposure in the form of rocket hits, fires, and pollution with pesticides and explosives significantly reduces the number and activity of most ecological-trophic and taxonomic groups of soil microorganisms, disrupts the biogenicity and microbial biomass of soils, and also negatively affects the key indicators of mineralisation and immobilisation of organic matter. However, the use of the reducing complex contributed to a significant restoration of the abundance and functional activity of the microbiota in all groups, especially in degraded soils, increased nitrogen mobilisation coefficients, and stabilised mineralisation processes. The results show that the integrated use of biological and organic components is an effective approach for the rehabilitation of damaged soils, increasing their productivity and environmental sustainability, which is important for the restoration of affected agroecosystems and forest lands.

CONCLUSIONS

The conducted studies indicate a negative military impact on the microbiota of southern chernozem, which is sensitive to various environmental factors, which affected a significant decrease in the population density of the main ecological-trophic, taxonomic, and functional groups of soil microorganisms. The number of representatives of the native microbiota in soils after military exposure decreased by 3-3.4 times. Indicators of biogenicity of southern chernozem decreased by 7.7 million CFU/g of dry soil, or 2.6 times compared to the control. Fires as a result of military operations at the location of the Halytsynove forest also significantly reduced the biogenicity of low-humus sands by 4.9 million CFU/g of dry soil, which was 2.3 times in relation to the control. A decrease in the number of representatives of the microbiota of ecological-trophic, functional, and taxonomic groups indicates a violation of the biological activity of the soil and the nutrient cycle. The restoration complex contributed to the growth of soil biogenicity in all variants of the experiment. In the damaged samples, the increase in indicators under the action of the recovery complex was higher than in the control samples. The use of RC in the conditions of background southern chernozem provided an increase in soil biogenicity by 4.2 times, after a missile hit – by 6.1 times. In the low-humus sands of forest lands under the influence of the recovery complex, an increase in biogenicity was observed by 1.9 times, while in the sample after fires due to armed conflict – by 9.9 times.

Consequently, military operations caused a sharp load on the soil, which affected the decrease in the number of microorganisms, inhibition of biological activity, and degradation of the microbiocoenosis.

The use of the recovery complex can be considered as an environmentally safe means and a stabilising factor that will activate the soil microbiota to play an important role in the restoration of both soils and soil ecosystems. The prospects for further research are to investigate the long-term impact of restorative complexes on the stability of microbiocoenosis, assess their effectiveness in various soil types and climatic conditions, and to develop optimal combinations of microorganisms and organic components to increase soil resistance to anthropogenic and military stresses. Special attention should be paid to determining the mechanisms of detoxification of pollutants and restoration of trophic chains, which will create scientifically based recommendations for the rehabilitation of affected agroecosystems and forest lands.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

[1] Abo-Alkasem, M.I., Hassan, N.H., & Elsoud, M.M.A. (2023). Microbial bioremediation as a tool for the removal of heavy metals. *Bulletin of the National Research Centre*, 47, article number 31. doi: 10.1186/s42269-023-01006-z.

[2] Balyuk, S., Vorotyntseva, L., Solovei, V., & Shymel, V. (2023). Realities of Ukrainian chornozem: Current state, evolution, preservation, and sustainable management. *Bulletin of Agricultural Science*, 101(3), 5-13. doi: 10.31073/agrovisnyk202303-01.

[3] Balyuk, S.A., *et al.* (2025). *Assessment of the impact of armed aggression on the state of black soils and measures for its restoration: Monograph*. Kyiv: Agricultural Science. doi: 10.31073/978-966-540-641-9.
[4] Danial, A.W., & Dardir, F.M. (2023). Copper biosorption by *Bacillus pumilus* OQ931870 and *Bacillus subtilis* OQ931871 isolated from Wadi Nakheil, Red Sea, Egypt. *Microbial Cell Factories*, 22, article number 152. doi: 10.1186/s12934-023-02166-3.
[5] Demydenko, O. (2021). Correlation links of physiological groups of microorganisms with fertility indicators of degraded chernozem for different fertilizer systems. *Bulletin of Agricultural Science*, 99(4), 20-27. doi: 10.31073/agrovisnyk202104-03.
[6] Dmitrenko, O.V., Demianiuk, O.S., Pohorila, L.P., Svidiniuk, N.L., Rozha, V.V., Kyryliuk, P.M., & Romanenko, V.M. (2023). Ecotoxicological assessment of sod-podzolic soil under the influence of military operations. *Agroecological Journal*, 4, 89-96. doi: 10.33730/2077-4893.4.2023.293758.
[7] Galkin, M.B., Strashnova, I.V., & Andryushchenko, A.V. (2024). Use of microorganisms in bioremediation of soils contaminated as a result of military actions. *Microbiology & Biotechnology*, 2(61), 28-55. doi: 10.18524/2307-4663.2024.2(61).310553.
[8] Goulart, P.W., Santini, A.T., Medina, L.R., Cerqueira, A.E.S., Gazolla, A.C., Silva, W.M., de Assis, I.R., Aniceto, D., de Paula, S.O., & da Silva, C.C. (2025). Microbial indicators show the rehabilitation flow of soil microbiota after the Brumadinho dam collapse. *Mining*, 5(1), article number 16. doi: 10.3390/mining5010016.
[9] Hryhorczuk, D., Levy, B.S., Prodanchuk, M., Kravchuk, O., Bubalo, N., Hryhorczuk, A., & Erickson, T.B. (2024). The environmental health impacts of Russia's war on Ukraine. *Journal of Occupational Medicine and Toxicology*, 19, article number 1. doi: 10.1186/s12995-023-00398-y.
[10] Jiang, S., Qu, H., Cheng, Z., Fu, X., Yang, L., & Zhou, J. (2025). Actinobacteria emerge as novel dominant soil bacterial taxa in long-term post-fire recovery of taiga forests. *Microorganisms*, 13(6), article number 1262. doi: 10.3390/microorganisms13061262.
[11] Johnsen, A.R., Boe, U.S., Henriksen, P., Malmquist, L.M.V., & Christensen, J.H. (2021). Full-scale bioremediation of diesel-polluted soil in an Arctic landfarm. *Environmental Pollution*, 280, article number 116946. doi: 10.1016/j.envpol.2021.116946.
[12] Kozar, S.F. (2021). Diazotroph activity regulating strategy under their introduction in agrocenoses. *Agricultural Microbiology*, 33, 33-43.
[13] Krell, T., Gavira, J.A., Roca, A., & Matilla, M.A. (2023). The emerging role of auxins as bacterial signal molecules: Potential biotechnological applications. *Microbial Biotechnology*, 16(8), 1611-1615. doi: 10.1111/1751-7915.14235.
[14] Levchuk, I., Iutynska, G., & Yamborko, N. (2022). *Stenotrophomonas maltophilia* IMV B-7288, *Pseudomonas putida* IMV B-7289 and *Bacillus megaterium* IMV B-7287 – new selected destructors of organochlorine pesticide hexachlorocyclohexane. *Archives of Microbiology*, 204, article number 611. doi: 10.1007/s00203-022-03220-1.
[15] Loboda, M., Biliavska, L., Iutynska, G., Newitt, J., & Mariychuk, R. (2024). Natural products biosynthesis by *Streptomyces netropsis* IMV Ac-5025 under exogenous sterol action. *Antibiotics*, 13(2), article number 146. doi: 10.3390/antibiotics13020146.
[16] Melnychuk, T.M., Vishovan, Yu.Yu., Samkova, O.P., Bogdanovich, R.P., Fedelesh-Gladynets, M.I., & Savchenko, E.A. (2025). Military impact on soil microbial biomass. In S. Shevchuk, O. Havryliuk & O. Tonkha (Eds.), *International scientific and practical conference "Food security in Ukraine. Preservation and restoration of soil and plant resources"* (pp. 154-157). Kyiv: National University of Life and Environmental Sciences of Ukraine. doi: 10.13140/RG.2.2.33546.58561.
[17] Peddle, S.D., *et al.* (2025). Practical applications of soil microbiota to improve ecosystem restoration: Current knowledge and future directions. *Biological Reviews*, 100(1), 1-18. doi: 10.1111/brv.13124.
[18] Rebai, H., Sholkamy, E.N., Abdelhamid, M.A.A., Thanka, P.P., Hassan, A.A., Pack, S.P., Ki, M.-R., & Boudemagh, A. (2024). Soil actinobacteria exhibit metabolic capabilities for degrading the toxic and persistent herbicide metribuzin. *Toxics*, 12(10), article number 709. doi: 10.3390/toxics12100709.

[19] Rieznik, S.V. (2021). Influence of different systems of crop farming on ecological and trophic groupings of microorganisms of typical chornozem in the conditions of the Left-bank Forest-steppe of Ukraine. *Agricultural Microbiology*, 33, 62-71.

[20] Tytova, L., Sergiienko, V., Pylypiuk, Y., & Iutynska, G. (2023). Effectiveness of the complex microbial formulation for disease protection and productivity enhancement of plants. *Agriculture (Poľnohospodárstvo)*, 69(4), 161-170. doi: 10.2478/agri-2023-0014.

[21] Universal Declaration on Bioethics and Human Rights. (2005, October). Retrieved from https://www.unesco.org/en/legal-affairs/universal-declaration-bioethics-and-human-rights?hub=66535.

[22] Vakhnyak, V., Khomovyi, M., Trach, I., Yavorov, V., & Petryshche, O. (2025). The role of restoring degraded soils in ensuring food security in the agro-industrial sector. *Scientific Horizons*, 28(2), 73-88. doi: 10.48077/scihor2.2025.73.

[23] Volkogon, V.V., *et al.* (2010). *Experimental soil microbiology*. Kyiv: Agrarian Science.

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Мілітарний вплив на біогенність чорнозему південного

Анотація. Серед низки значних проблем, що виникли в результаті воєнних дій на території України, є деградація ґрунтів, що потребує пошуку шляхів прискорення процесів їх відновлення після пошкодження. Метою дослідження було оцінити за показниками біогенності стан чорнозему південного і слабогумусованих пісків за мілітарного впливу та використання відновлювального комплексу, який складався з органічнного добрива Паросток і бактеріально-метаболічного препаратому Ультрачист. Методи дослідження включали лабораторний аналіз зразків, застосовуючи мікробіологічний посів на середовища, відповідні для мікроорганізмів еколого-трофічних, функціональних і таксономічних груп, та статистичну обробку даних для визначення достовірності розбіжностей. Проведені дослідження свідчать про значний негативний вплив на щільність популяцій ґрунтових мікроорганізмів чорнозему південного від ракетного влучання та слабогумусованих пісків від пожеж внаслідок воєнних дій. Кількість представників аборигенної мікробіоти у ґрунтах після мілітарного впливу зменшилася утричі. Показники біогенності чорнозему південного і слабогумусованих пісків зазнали зниження на 7,7 та 4,9 млн КУО/г сухого ґрунту (2,6 і 2,3 разів) відповідно, порівняно з контролем. Відновлювальний комплекс сприяв зростанню біогенності ґрунту в усіх варіантах досліду. У пошкоджених зразках зростання показників за дії відновлювального комплексу було вищим, ніж у контрольних. Застосування в умовах фонового чорнозему південного відновлювального комплексу забезпечило збільшення біогенності ґрунту в 4,2 разів, після ракетного влучання – в 6,1 разів. У слабогумусованих пісках лісових угідь під впливом відновлювального комплексу спостерігали зростання його біогенності в 1,9 разів, тоді як у зразку після пірогенного впливу в 9,9 разів. Запропонований відновлювальний комплекс на основі органічної речовини та корисних мікроорганізмів може розглядатись, як стабілізаційний чинник, що дозволить активізувати мікробіоту деградованого ґрунту для відновлення ґрунтових екосистем

Ключові слова: ґрунтові мікроорганізми; слабогумусовані піски; вплив воєнних дій; деградація мікробоценозу; відновлювальний комплекс

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Heterosis analysis for yield and quality in eggplant (*Solanum melongena* L.)

Abstract. The experiment was conducted with 55 eggplant hybrids derived from 11 x 11 half diallel crosses along with standard variety at the field 10 and field 15 of University of Putra Malaysia (Serdang, Selangor, Malaysia) at one season during November 2020 to January 2021. The aim of this research was to develop high yield and quality eggplant hybrids. This research was followed by randomised complete block design with three replications at two locations. 15 morphological and

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biochemical traits were estimated for heterosis. Among these, BM9 × BB26 was chosen as the best hybrid for yield per plant considering standard heterosis, heterobeltosis and relative heterosis. Besides, BB1 × BT15 hybrid was also the best for total soluble solid over check variety and BT6 × BT15 was the best for total phenol content considering all three types of heterosis i.e. relative heterosis, heterobeltosis and standard heterosis. Conversely, the highest value for heterobeltosis and relative heterosis was found in the hybrid BM5 × BT15 and the hybrid BM9 × BB23 was the best over standard heterosis for DPPH of antioxidant activity. Hence, these two hybrids could be considered to get higher antioxidant activity in eggplants. The breeders, agronomists, and horticulturists can use these results to select the best hybrids for further practical research

Keywords: hybrids; half diallel; per se performance; best parent heterosis; antioxidant activity

INTRODUCTION

Eggplant is the most significant crop of solanaceae family, which is popular because of its high nutrition and palatability of fruits. It is widely spread as one of the most important vegetables cultivated in both tropical and subtropical regions throughout the world. The preferences of eggplant vary from area to area for colour, shape, and size. Thus, it is crucial to create hybrids, having high quality along with high yields. Heterosis has become widely used in the breeding method to increase production of solanaceaous vegetable like eggplant. The effect of heterosis in vegetable crops is clearly shown by the significant increases of yield observed over the last 50 years, following the introduction of hybrids into crop production. Both hybrids and enhanced agronomic techniques has resulted to a consistent, linear enhancement in the performance of vegetable crops. Hybrid vigour exploitation has become an effective tool to improve of eggplant. With the increasing popularity of F_1 hybrid, this trend has allowed for its commercial utilisation in the eggplant industry. Moreover, the researchers found that the level of heterosis is directly proportionate to the genetic diversity existed within parents, which provides together a variety of favourable alleles coming from multiple genes.

A lot of studies have been published by supporting the potentiality of heterosis in various traits. of E. Hassan (2021) indicated in the work that the hybrid (P3 x P6) had the highest value of relative heterosis and heterobeltosis i.e. 230.02% and 218.85% respectively for the character total yield. Furthermore, S. Anvesh *et al.* (2025) pointed out in the work that the highest level of heterosis over better parent (HB) was found in Punjab Sadabahar x Pant Rituraj (i.e. 72.26%) followed by the hybrid Pusa Purple Long x Pant Rituraj and NDB-2 x Pant Rituraj for the character yield. Besides, D. Rameshkumar & I. Vethamonai (2020) found that the hybrid Seetipulam Local x Sevathampatti Local was the superior cross combination for most of the studied characters like earliness and yield per plant considering better parent and standard heterosis. S. Mishra *et al.* (2023) revealed that the crosses BBSR-08-2 x selection from BBSR-145-1, BBSR-08-2 × BBSR-10-26 and the cross BBSR-08-2 × BBSR-10-25 showed significant positive heterosis for the trait fruit yield attributing traits, fruit yield and also for vegetative traits over relative heterosis, heterobeltosis and standard heterosis. The researchers, H. Thota & I. Delvadiya (2025) exhibited the highest significant and positive standard heterosis from the cross combination JBR-3 x JBR-5 for the character total yield per plant i.e. 154.49%. A. Kumari *et al.* (2025) recorded in the findings that the cross, PPL x Arka harshita, PPL x Pusa Anupam and PPL x PPC exhibited fruitful heterosis and appreciable heterobeltosis for the character yield and earliness. Z. Khasdhar *et al.* (2024) emphasised in the research that the highest value of standard heterosis for the character fruit yield per plant was recorded from the cross AB-08-14 x GBL-3 over standard check. The researchers Rajashree *et al.* (2023) found in the research that the highest positive heterosis from the cross combination KRCCH-11 x GL, KRCCH-12 x GL and KRCCH-10 x GL for the character earliness and yield parameters whereas KRCCH-11 × BL and KRCCH-11 x GL showed superior for quality trait. The main objectives of any hybridisation program are to create genetically modified and potential lucrative genotypes through accumulation of stable gene effects. Thus, it is critical to identify firstly more or less homozygous lines and flexible parental lines selection. Keeping this in mind, both heterosis and combining ability study are very much important for each plant breeding program due to providing necessary information for varietal improvement and commercial utilisation of heterosis (Quamruzzaman *et al*., 2020).

This research was done to select the best hybrid from 55 hybrid combination that was developed by the researcher from 11 × 11 half diallel method of breeding with standard check varieties and to select the best hybrids (high yield and high quality) which can be used to mitigate nutritional security.

MATERIALS AND METHODS

Experiment site. The experiment was conducted with two locations (at field 10 and field 15) in one season at Universiti Putra Malaysia simultaneously from November 2020 to January 2021. Plant materials. Eleven eggplant genotypes were used as parents in 11 × 11 half diallel method (excluding reciprocal) to develop 55 F_1 hybrids in this research. These 11 genotypes were BB1, BB12, BB23, BB26, BB31, BT6, BT13, BT15, BT17, BM5 and BM9. Layout and design of experiment. This study was carried out in a RCB design (randomised complete block design) with three times replication. There were 5 plants in each replication. Spacing was maintained 60 cm between plants and 80 cm between rows. A well drainage system was kept in the field. Data collection. Data of 12 quantitative trait were taken from five plants in each genotype per replication. Quantitative trait likely days to first flower opening, days to 50% flower opening, plant height, stem diameter, no. of primary branches/plant, fruit diameter, fruit length, fruit girth, ratio of length to width of fruit, individual fruit weight, yield of fruit/plant, no. of fruits /plant, TSS (Total soluble solid), TPC (Total phenol content) and DPPH (Antioxidant activity) etc.

Statistical analysis. Heterosis estimation: expression of heterosis as % of increase of F_1 over mid parent, better parent and commercial check were determined for each trait by using the following formulae (Mohsin *et al*., 2022):

$$\text{relative heterosis (MP)} = \frac{F1-MP}{MP} \times 100. \qquad (1)$$

$$\text{Heterobeltosis (HB)} = \frac{F1-BP}{BP} \times 100. \qquad (2)$$

$$\text{Standard heterosis} = \frac{F1-CV}{CV} \times 100, \qquad 3)$$

where F_1, MP, BP, and CV are the average of F_1, two parent (MP), better parent (BP) and check variety (CV) respectively.

Significant difference of F_1 were calculated with MP, BP, and CV by using "t" test. The following formula was used:

$$[t] = \frac{F1-MP}{SED} \times 100, \qquad (4)$$

where $SED = \sqrt{\frac{2EMS}{r}}$.

$$[t] = \frac{F1-BP}{SED} \times 100, \qquad (5)$$

where $SED = \sqrt{\frac{2EMS}{r}}$.

$$[t] = \frac{F1-CV}{SED} \times 100, \qquad (6)$$

where $SED = \sqrt{\frac{2EMS}{r}}$.

Here, SED means standard error of difference; EMS = error mean square; r = replication.

Besides, $SED = \sqrt{\frac{Variance}{Sample\ Size}}$.

The study was conducted in accordance with the ethical standards of the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1976).

RESULTS AND DISCUSSION

Heterosis were calculated for each crosses of 55 hybrids for yield, yield related characters and some biochemical characters over mid parent, better parent and standard variety. Here, heterosis results have been shown in Tables 1-4. All types of heterosis (mid, better, and standard) were discussed individual trait-wise in the following way. Fruit length. The fruit length is an important character to develop high yielding variety. Out of 55 hybrids, 33 hybrids, 15 hybrids and 6 hybrids showed significant positive relative heterosis, heterobeltosis and standard heterosis respectively. The rest of the hybrids showed significant negative heterosis. The hybrid BM5 × BT13 had the highest value of relative heterosis that is 57.60% and the least value of relative heterosis was -38.33% recorded from the hybrid BM5 × BT15 (Table 1). On the other hand, the highest and the lowest value of heterobeltosis was 31.94% (BM9 × BB1) and -64.01% (BM5 × BT15) respectively. Besides, the hybrid's standard heterobeltosis value was ranged from -71.09% (BB12 × BT15) to 21.73% (BB31 × BT13). Considering all three types of heterosis, hybrids BM9 × BT13, BB26 × BM5, BB31 × BT13 and BM5 × BT13 were found as the best hybrids due to the positive heterosis over the mid parent, better parent and check variety across the environment.

Fruit diameter. For this character, relative heterosis varied from -43.39 to 28.98% for the hybrids BB12 × BT17 and BB1 × BB31, respectively. Out of 55 hybrids – 18 hybrids, 7 hybrids and 31 hybrids showed significant positive relative heterosis, heterobeltosis and standard heterosis respectively. The heterobeltosis value for this trait varied from -58.77 to 20.795% for the hybrids BB12 × BT17 and BM9 × BB1, respectively. Besides, standard heterosis for this trait varied from -35.05 (BT13 × BT15) to 60.28% (BT17 × BB1). Considering all types of heterosis, the crosses BM9 × BB26, BM9 × BB1, BB1 × BB26 and BB1 × BB31 performed positive over all types of heterosis among all the studied hybrids. Fruit girth. In this trait, all the hybrids showed highly significantly values for relative heterosis and standard heterosis but in case of heterobeltosis all hybrids performed significantly except two hybrids (BB12 × BM5 and BB12 × BT13) showed non-significant values. The highest value for relative heterosis was found by BB31 × BT6 with the value of 37.29% and the least value was recorded by BM9 × BB23 with the value of -44.21%. The value of HB was ranged from -60.65 to 15.18% from the hybrids BM9 × BB23 and BM9 × BB26 respectively. The SH value ranged from -33.14 (BM9 × BB23) to 79.91% (BM9 × BB1) for fruit girth.

Fruit length to width ratio. Most of the hybrids showed highly significant values, except three crosses in case of relative heterosis (RH). These three crosses showed non-significant values. The value of RH for this trait varied from -40.29 (BB1 × BB31) to 143.01% (BM9 × BT13). The HB value for ranged from -61.07 (BM5 × BT15) to 54.87% (BM9 × BB31), and the standard heterosis value varied from -71.05 (BT17 × BT6) to 56.75% (BM9 × BB31). The hybrids namely; BM9 × BB23, BM9 × BB31, BM9 × BT13, BB26 × BM5, BB31 × BM5, BB31 × BT13 and BM5 × BT13 had a positive significant value for all three types of heterosis. Individual fruit weight. Most of the hybrids showed positively significant values for relative heterosis (RH) except four. These four hybrids were non-significant for RH. The RH value ranged from -60.15 (BM5 × BT15) to 153.30% (BT13 × BT 6). The HB varied from -79.08 (BM5 × BT15) to 99.73% (BT13 × BT6). The SH was -84.93 (BB12 × BT15) to 105.04% (BM9 × BB1) (Table 2). The crosses BM9 × BB1, BM9 × BB26, BT17 × BB26, and BB26 × BM5 had the significant positive value for all types of heterosis namely; RH, HB and SH.

Yield per plant. The highest RH value was performed with the hybrid BM9 × BB26 (466.53%), and the minimum value was recorded from the hybrid BT6 × BT15 (-74.83%). The value of HB ranged from 315.07 (BM9 × BB26) to -81.15% (BT6 × BT15). The heterosis over check variety was performed from 130.79 (BM9 × BB26) to 82.63% (BT6 × BT15) (Tables 1-4). The hybrids BB12 × BB1, BB12 × BT6, BT17 × BB1, BM9 × BB26, BM9 × BM5, BB23 × BB31, BB23 × BM5, BB26 × BM5, BB31 × BM5, BB31 × BT13, BB31 × BT6 and BB31 × BT15 performed positively significant for all types of heterosis (Table 5). Number of primary branches per plant (PB). The extent of RH for the trait PB ranged from 57.66 (BB12 × BT15) to -52.75% (BB1 × BT6). Besides, the value of HB and SH 41.51 to -61.35% and 91.34 to -51.41% respectively. Fourteen hybrids were found to be good over MP, BP, and CV for this character (Tables 1-4). Days to first flower opening (DF). The values of SH, HB and RH ranged from -27.91 to 53.49%, -37.87 to 71.45% and -54.32 to 71.45% respectively. The cross BB1 × BT6 showed the highest value for all heterosis. The least value of HB and RH was found from the crosses BM5 × BT15 and BB23 × BB31, respectively. On the other side, the lowest value for SH was performed from the cross BM5 × BT15. Days to 50% flower opening (DFF). The maximum value of SH, HB and RH for this character found from the cross BB1 × BT6 with the value of 53.59%, 42.18% and 63.96% respectively.

Similarly, the minimum value of SH, HB and RH was found from the cross BM5 × BT 15 with the value of -29.53%, -38.83% and -38.60% respectively (Table 3). Besides, no hybrid performed non-significant relation with all three types of heterosis.

Number of fruits per plant (NF). All the hybrids showed positively significant value for all SH, HB and RH except BB23 × BT6, which showed non-significant value for SH. The RH value varied from 315.14 (BM9 × BB26) to -90.80% (BT6 × BT15). The HB value varied from 206.71 (BB31 × BM5) to -94.79% (BT17 × BT15). On the other hand, the extent of SH from 354.46 (BT13 × BT15) to -79.55% (BB1 × BB26) (Tables 1-4). Plant height (PH). The magnitude of RH, HB and SH valued from 61.56 to –24.92% (BB23 × BT15 to BB1 × BB26), 54.24 to -33.15% (BB23 × BT15 to BB1 × BB26) and 41.45 to 18.34% (BM9 × BB26 to BB1 × BT13) respectively (Table 3). Besides, all the hybrids showed positively significant value except two hybrids for standard heterosis, which showed non-significant value. Stem diameter (SD). The maximum value (27.05%) of RH was recorded from the several hybrids like BT17 × BB1, BB12 × BB1, BM9 × BB23, BB31 × BT13, BB23 × BT6 and BB1 × BB31 (Table 3). Other side, the lowest value(-25.40%)ofRHwasrecordedfromthecrosses BB12 × BM9, BT17 × BM9, BM9 × BB1, BB1 × BB26, BB23 × BT13, BB31 × BM5 and BT13 × BT15. Besides, the HB for this trait ranged from -8.56 to -19.55%, in which none of the crosses showed positive heterobeltosis. Here, the standard heterosis (SH) lied in between 32.48 to 19.59%, whereas, none crosses showed negative value of SH.

Total soluble solid (TSS) (Table 4). The value of RH, HB and SH range varied from 16.09 (BM9 × BB26) to -15.01% (BT17 × BT15), 8.24 (BB12 × BM9) to -29.91% (BM9 × BT15) and 17.69 (BB1 × BT15) to -7.86% (BB26 × BT13) respectively. Total phenol content (TPC). The RH for this character ranged from 71.98 to -76.52% whereas, the HB ranged from 71.29 to -81.30%. But a wide range of variation was recorded for SH from 192.43 to -71.32%. The highest and the lowest value was found from the hybrid BT6 × BT15 and BB31 × BT13 respectively for RH, HB and SH. DPPH (antioxidant activity). This character was shown relative heterosis (RH) ranged from 53.45 to -37.02% from the cross BM5 × BT15 and BB26 × BT13 respectively. The value of HB for DPPH ranged from 33.34 (BM5 × BT15) to -39.01% (BB26 × BT13) (Table 3). Besides, depend on standard heterosis, the top hybrid for all the studied traits is shown in Table 5.

Table 1. Percentage of heterosis (mid-parent, better-parent and standard heterosis) for fruit morphology traits in eggplant hybrids

Crosses	FL			FD			FG			FLWR		
	SH (%)	HB (%)	RH (%)	SH (%)	HB (%)	RH (%)	SH (%)	HB (%)	RH (%)	SH (%)	HB (%)	RH (%)
BB12 × BT17	-49.37**	-14.00**	-7.59**	28.97**	-58.77**	-43.39**	-14.37**	-53.83**	-35.75**	-32.02**	5.61**	39.93**
BB12 × BM9	-43.98**	-9.79**	-0.67**	4.44**	-36.34**	-21.96**	-17.71**	-36.51**	-21.89**	-29.96**	8.81**	14.57**
BB12 × BB1	-47.20**	-13.80**	-5.67**	12.38**	-27.75**	-2.22 NS	14.93**	-32.37**	-8.44**	-52.87**	-26.78**	-14.08**
BB12 × BB23	-42.86**	-12.91**	-1.74**	-15.65**	-3.82**	-0.09**	5.10**	-4.55**	9.93**	-33.06**	-12.29**	-4.71**
BB12 × BB26	-34.10**	14.34**	21.67**	10.05**	-25.38**	-5.73**	13.43**	-18.78**	2.76**	-36.98**	-2.10**	18.83**
BB12 ×BB31	-20.95**	-25.80**	0.52**	-7.01**	-15.55**	-4.73**	-10.50**	-18.80**	-6.44**	-11.40**	-12.47**	7.01**
BB12 × BM5	-22.04**	-28.38**	-2.27**	-16.12**	-6.85**	-3.48**	-8.55**	-0.35 NS	5.80**	-3.48**	-23.83**	1.02**
BB12 × BT13	-18.26**	-2.86**	21.24**	-25.23**	-9.46**	-1.82*	-19.19**	-0.38NS	7.69**	12.58**	-6.68**	21.70**
BB12 × BT6	-63.32**	-27.72**	-14.51**	-24.53**	-26.18**	-20.69**	-23.09**	-5.18**	0.45**	-40.28**	-7.23**	4.24**
BB12 × BT15	-71.09**	-43.02**	-16.18**	-28.74**	-16.76**	-5.30**	-21.71**	-3.48**	8.61**	-57.66**	-34.22**	-9.45**
BT17 × BM9	-38.55**	-1.05**	1.60**	52.57**	-33.80**	-23.15**	27.01**	-31.51**	-19.38**	-48.72**	-11.42**	13.10**
BT17 × BB1	-27.28**	18.74**	21.08**	60.28**	-12.60**	-3.43**	62.26**	-12.50**	-8.66**	-53.54**	2.46**	18.91**
BT17 × BB23	-27.91**	9.87**	15.83**	32.24**	-36.32**	-14.72**	31.13**	-29.29**	-11.25**	-34.58**	-14.28**	19.69**
BT17 × BB26	-37.37**	6.39**	7.52**	57.94**	-12.53**	-1.92**	58.32**	-14.63**	-2.58**	-60.29**	-4.77**	6.61**
BT17 × BB31	-14.47**	-19.71**	3.46**	40.89**	-34.67**	-17.88**	23.72**	-33.28**	-16.30**	-25.07**	-25.97**	11.83**
BT17 × BM5	-14.09**	-21.08**	2.45**	32.01**	-51.80**	-35.34**	-9.50**	-51.20**	-34.71**	2.83**	-18.85**	28.93**
BT17 × BT13	-22.02**	-7.33**	9.05**	22.90**	-42.81**	-17.59**	0.74**	-45.68**	-20.81**	-23.14**	-36.30**	0.18NS
BT17 × BT6	-58.66**	-29.78**	-12.03**	23.36**	-19.74**	15.21**	47.14**	-20.65**	14.28**	-71.05**	-42.57**	-30.58**
BT17 × BT15	-61.19**	-34.07**	0.72**	19.16**	-31.68**	1.54**	28.27**	-30.83**	3.25**	-68.39**	-4.19**	2.07**
BM9 × BB1	-18.06**	31.94**	32.86**	35.75**	20.79**	27.85**	79.91**	5.87**	20.16**	-52.50**	-17.95**	-7.61**
BM9 × BB23	-37.91**	-5.37**	-2.77**	7.71**	-50.79**	-41.50**	-33.14**	-60.65**	-44.21**	0.98**	32.32**	50.70**
BM9 × BB26	-24.51**	21.56**	26.10**	33.41**	8.77**	13.34**	60.87**	15.18**	19.52**	-48.99**	-11.89**	2.44**

Table 1, Continued

Crosses	FL			FD			FG			FLWR		
	SH (%)	HB (%)	RH (%)	SH (%)	HB (%)	RH (%)	SH (%)	HB (%)	RH (%)	SH (%)	HB (%)	RH (%)
BM9 × BB31	3.59**	-2.76**	22.90**	16.36**	-45.07**	-39.56**	-14.18**	-33.78**	-28.43**	56.75**	54.87**	97.03**
BM9 × BM5	-5.39**	-13.09**	10.68**	7.48**	-32.48**	-19.57**	-7.21**	-28.41**	-16.18**	9.89**	-13.29**	19.04**
BM9 × BT13	4.01**	23.61**	42.25**	-1.64**	-37.90**	-19.16**	-15.58**	-34.86**	-14.99**	31.34**	8.86**	143.01**
BM9 × BT6	-36.12**	2.87**	31.43**	-1.17**	-44.89**	-28.61**	-24.74**	-41.93**	-25.36**	-10.90**	53.90**	64.86**
BM9 × BT15	-66.32**	-45.77**	-16.11**	-5.37**	-45.68**	-26.50**	-19.69**	-38.04**	-16.62**	-47.30**	-8.97**	21.09**
BB1 × BB23	-46.49**	-18.45**	-15.64**	15.65**	-10.03**	11.78**	31.38**	-22.68**	-6.16**	-59.51**	-46.95**	-33.33**
BB1 × BB26	-37.61**	1.87**	4.97**	41.36**	2.82**	4.52**	55.58**	-8.44**	0.53**	-57.49**	-6.25**	-2.33**
BB1 × BB31	-28.79**	-33.15**	-15.08**	24.30**	11.57**	28.98**	59.87**	-5.92**	14.19**	-56.24**	-56.77**	-40.29**
BB1 × BM5	-29.36**	-35.10**	-16.94**	15.19**	-8.02**	14.74**	36.38**	-19.74**	4.26**	-45.18**	-56.74**	-36.27**
BB1 × BT13	-42.75**	-31.96**	-21.24**	6.07**	-39.38**	-17.88**	0.18**	-41.04**	-16.10**	-31.17**	-42.95**	-17.07**
BB1 × BT6	-43.17**	-7.20**	17.97**	6.78**	-12.63**	17.58**	21.58**	-28.45**	0.53**	-55.36**	-11.45**	-6.57**
BB1 × BT15	-65.51**	-43.69**	-13.18**	2.57**	-31.76**	-4.40**	6.24**	-37.48**	-8.79**	-64.81**	-22.40**	-5.53**
BB23 × BB26	-26.26**	12.38**	19.66**	13.32**	-17.65**	1.03**	5.41**	-24.53**	-15.59**	-35.05**	-14.90**	10.25**
BB23 × BB31	-18.32**	-23.33**	-5.08**	-3.74**	-3.34**	5.34**	-0.54**	-9.76**	-9.68**	-17.95**	-18.93**	-7.46**
BB23 × BM5	-6.56**	-14.16**	7.11**	-12.85**	-7.07**	-6.57**	-8.16**	-16.59**	-8.99**	18.93**	-6.15**	17.27**
BB23 × BT13	-13.41**	2.91**	15.64**	-21.96**	9.16**	22.55**	-1.73**	-10.75**	9.78**	-9.11**	-24.66**	-7.61**
BB23 × BT6	-42.84**	-12.89**	13.49**	-21.26**	-13.33**	-3.56**	-10.51**	-18.73**	-1.71**	-17.27**	8.40**	30.56**
BB23 × BT15	-70.41**	-54.90**	-29.38**	-25.47**	-26.27**	-13.32**	-17.37**	-24.95**	-4.57**	-54.22**	-40.01**	-13.01**
BB26 × BB31	-10.84**	-16.30**	8.66**	21.96**	-10.87**	1.53**	22.02**	-12.64**	-2.29**	-28.10**	-28.97**	0.61NS
BB26 × BM5	9.38**	0.49**	31.40**	12.85**	-36.74**	-22.12**	6.72**	-23.59**	-7.74**	32.59**	4.63**	57.45**
BB26 × BT13	-37.01**	-25.15**	-11.15**	3.74**	-50.20**	-33.30**	4.90**	-24.90**	0.60**	-9.75**	-25.20**	11.18**
BB26 × BT6	-50.94**	-14.88**	5.79**	4.44**	-39.10**	-18.98**	-2.52**	-30.21**	-7.87**	-41.84**	15.39**	26.58**
BB26 × BT15	-65.31**	-39.80**	-8.50**	0.23**	-30.55**	-3.73**	2.27**	-26.78**	0.90**	-64.64**	-14.80**	-0.19NS
BB31 × BM5	7.90**	-0.87**	0.22*	-4.21**	-20.18**	-12.52**	-16.17**	-23.94**	-16.99**	27.77**	0.83**	12.11**
BB31 × BT13	21.73**	14.27**	27.72**	-13.32**	-19.62**	-2.65**	-13.54**	-21.56**	-3.49**	42.38**	18.01**	28.35**
BB31 × BT6	-26.81**	-31.29**	3.39**	-12.62**	3.26**	24.06**	25.10**	13.50**	37.29**	-30.57**	-31.40**	-8.29**
BB31 × BT15	-58.69**	-61.22**	-33.78**	-16.82**	-9.94**	13.67**	-6.67**	-15.33**	7.78**	-56.07**	-56.60**	-32.61**
BM5 × BT13	14.64**	5.32**	57.60**	-22.20**	-8.25**	2.35**	-18.57**	-11.27**	1.30**	44.67**	14.16**	16.97**
BM5 × BT6	-15.76**	-22.61**	17.03**	-21.73**	-16.78**	-7.71**	-28.30**	-21.87**	-12.47**	17.95**	-6.92**	33.33**
BM5 × BT15	-60.83**	-64.01**	-38.33**	-25.93**	-9.47**	6.10**	-22.14**	-15.16**	0.61**	-50.67**	-61.08**	-36.71**
BT13 × BT6	-36.97**	-25.09**	5.70**	-30.84**	-1.95**	-0.96**	-19.92**	11.18**	13.56**	-5.94**	-22.04**	10.11**
BT13 × BT15	-62.18**	-55.05**	-26.09**	-35.05**	-4.71**	0.78*	-22.34**	7.83**	17.70**	-41.09**	-51.17**	-21.35**
BT6 × BT15	-63.67**	3.52**	36.30**	-34.35**	19.84**	12.16**	-21.45**	9.06**	16.34**	-50.57**	-1.94**	24.57**

Note: DFF – days to 50% flower opening, NF – number of fruits per plant, PH – plant height, SD – stem diameter, RH – relative heterosis, HB – heterobeltosis, SH – standard heterosis
Source: research by the authors

Table 2. Percentage of heterosis for yield components in eggplant hybrids

Crosses	FW			PB			YPP			DF		
	SH (%)	HB (%)	RH (%)	SH (%)	HB (%)	RH (%)	SH (%)	HB (%)	RH (%)	SH (%)	HB (%)	RH (%)
BB12 × BT17	-64.99**	-72.46**	-54.85**	38.52**	-21.15**	-11.81**	-27.70**	-34.49**	1.14*	-2.33**	-10.64**	-6.04**
BB12 × BM9	-63.80**	-62.69**	-42.05**	8.48**	-21.68**	-17.90**	-11.65**	171.02**	202.21**	-2.79**	-16.40**	-9.52**
BB12 × BB1	-49.19**	-60.19**	-34.67**	-17.22**	-40.24**	-24.24**	43.16**	268.33**	300.62**	-19.07**	-23.01**	-20.55**
BB12 × BB23	-43.26**	-19.05**	15.78**	25.71**	-9.25**	18.12**	-31.19**	82.00**	95.46**	-3.26**	-11.11**	-6.71**
BB12 × BB26	-46.73**	-31.85**	0.42NS	-34.28**	-52.55**	-40.54**	-59.88**	-27.84**	-9.02**	0.00NS	-14.68**	-7.31**
BB12 × BB31	-37.28**	-54.61**	-24.49**	8.57**	-21.62**	-1.78**	-25.16**	-14.42**	24.68**	-0.93**	0.47**	1.92**
BB12 × BM5	-46.45**	-54.19**	-26.05**	5.66**	-23.72**	-11.42**	-26.29**	11.05**	48.94**	2.33**	-15.06**	-6.58**
BB12 × BT13	-53.04**	20.63**	40.48**	8.48**	-21.68**	-20.38**	-70.75**	-70.79**	-55.92**	-9.30**	-8.02**	-6.02**
BB12 × BT6	-78.72**	-23.81**	-15.55**	91.43**	38.20**	44.88**	10.12**	140.13**	180.70**	-7.91**	24.53**	6.76**
BB12 × BT15	-84.93**	-46.05**	-10.84**	79.95**	29.91**	57.66**	-20.62**	-13.86**	27.25**	-12.09**	-21.25**	-16.36**
BT17 × BM9	-27.73**	-43.16**	-35.51**	65.64**	-5.71**	9.95**	-46.59**	-51.61**	-21.60**	14.42**	4.68**	1.43**
BT17 × BB1	20.90**	-5.26**	-5.09**	25.71**	-28.44**	-1.61**	66.27**	50.66**	122.84**	0.93**	-13.20**	-5.87**
BT17 × BB23	6.60**	-16.16**	8.10**	17.14**	-33.32**	-6.24**	-13.85**	-21.94**	16.29**	21.40**	11.31**	11.31**
BT17 × BB26	30.65**	2.76**	27.27**	-20.05**	-54.49**	-38.05**	-43.13**	-48.47**	-31.47**	-0.93**	-12.52**	-12.52**
BT17 × BB31	24.90**	-9.61**	-5.85**	14.22**	-34.98**	-11.49**	6.72**	-3.31**	7.90**	6.51**	-7.29**	3.85**
BT17 × BM5	-29.91**	-44.87**	-42.56**	0.00NS	-43.07**	-27.43**	-22.60**	-29.87**	-12.41**	21.86**	6.06**	6.06**
BT17 × BT13	-35.19**	-49.03**	-21.95**	-8.57**	-47.95**	-40.92**	-15.40**	-23.34**	-19.62**	-5.58**	-7.31**	-7.31**
BT17 × BT6	-6.38**	-26.37**	25.15**	5.66**	-39.85**	-29.86**	-16.17**	-24.04**	7.32**	1.40**	10.67**	10.67**
BT17 × BT15	-54.43**	-64.16**	-31.48**	7.11**	-39.02**	-19.25**	-59.97**	-63.73**	-60.46**	0.00NS	-9.47**	-9.47**
BM9 × BB1	105.04**	60.67**	82.57**	0.00NS	-20.45**	-2.75**	-31.16**	77.12**	112.67**	11.16**	0.41**	0.41**
BM9 × BB23	-56.95**	-55.62**	-48.47**	31.36**	4.50**	31.36**	-81.25**	-50.41**	-41.11**	2.79**	-8.67**	-8.67**

Table 2, Continued

Crosses	FW			PB			YPP			DF		
	SH (%)	HB (%)	RH (%)	SH (%)	HB (%)	RH (%)	SH (%)	HB (%)	RH (%)	SH (%)	HB (%)	RH (%)
BM9 × BB26	42.83**	47.24**	63.07**	25.71**	0.00NS	20.74**	130.79**	315.07**	466.53**	3.26**	-11.55**	-11.55**
BM9 × BB31	-1.33**	-28.60**	-16.09**	2.83**	-18.20**	-1.23**	-66.00**	-61.12**	-40.00**	6.98**	0.88**	0.88**
BM9 × BM5	-12.16**	-24.86**	-17.87**	28.53**	2.25**	11.36**	0.02NS	50.68**	116.85**	-8.84**	-22.99**	-22.99**
BM9 × BT13	-15.71**	-13.11**	24.02**	0.00NS	-25.53**	-22.97**	-23.69**	-23.78**	21.13**	-20.93	-24.94**	-24.94**
BM9 × BT6	-56.98**	-55.66**	-27.99**	54.24**	22.70**	22.70**	-77.13**	-50.12**	-36.23**	10.23**	15.90**	15.90**
BM9 × BT15	-78.76**	-78.11**	-58.72**	26.39**	0.55**	17.34**	-59.30**	-55.84**	-31.04**	-6.98**	-18.36**	-18.36**
BB1 × BB23	-26.46**	-42.38**	-25.61**	-34.28**	-17.79**	-6.00**	-73.27**	-31.22**	-30.26**	20.47**	12.62**	12.62**
BB1 × BB26	16.17**	-8.97**	12.90**	-37.19**	-24.12**	-22.68**	-72.30**	-50.18**	-41.36**	-4.65**	-14.22**	-14.22**
BB1 × BB31	33.99**	-3.04**	0.82NS	-51.41**	-41.30**	-40.19**	-40.73**	-32.23**	-6.16**	18.14**	17.59**	17.59**
BB1 × BT13	-39.82**	-52.84**	-27.73**	-10.03**	-32.99**	-15.87**	-57.90**	-57.96**	-39.43**	4.19**	4.43**	4.43**
BB1 × BT6	-25.37**	-41.52**	-0.54NS	-51.41**	-61.35**	-52.75**	-57.31**	-6.90**	0.78NS	53.49**	71.45**	71.45**
BB1 × BT15	-69.52**	-76.12**	-54.33**	-8.57**	1.67**	7.78**	-11.19**	-3.62**	35.57**	-27.44**	-33.04**	-33.04**
BB23 × BB26	-31.44**	-12.29**	-7.51**	-20.05**	-3.42**	1.97**	-75.66**	-56.22**	-47.88**	22.33**	8.23**	8.23**
BB23 × BB31	-19.95**	-42.07**	-23.13**	-11.48**	6.94**	12.90**	18.10**	35.05**	88.57**	-6.51**	-8.64**	-54.32**
BB23 × BM5	-11.88**	-24.62**	-5.74**	25.71**	25.71**	44.25**	46.05**	120.03**	180.37**	-15.35**	-26.16**	-26.16**
BB23 × BT13	-17.91**	17.12**	50.61**	40.02**	4.28**	34.49**	-30.82**	-30.91**	0.31NS	19.07**	17.18**	17.18**
BB23 × BT6	-58.64**	-40.98**	-10.61**	28.53**	2.25**	28.53**	-53.49**	1.43**	11.19**	-8.37**	0.25NS	0.25NS
BB23 × BT15	-83.78**	-76.86**	-57.30**	17.14**	30.25**	42.84**	-55.65**	-51.87**	-31.75**	-9.30**	-17.72**	-17.72**
BB26 × BB31	12.76**	-18.40**	4.23**	17.14**	41.51**	41.51**	-41.57**	-33.19**	-18.31**	3.26**	-3.04**	-3.04**
BB26 × BM5	20.88**	3.40**	23.93**	-34.28**	-34.28**	-27.98**	73.75**	161.77**	184.89**	5.12**	-11.54**	-11.54**
BB26 × BT13	-35.34**	-17.29**	10.44**	-37.19**	-53.22**	-42.10**	-78.76**	-78.79**	-72.72**	23.26**	16.50**	16.50**
BB26 × BT6	-58.64**	-47.09**	-17.80**	17.14**	-6.82**	12.79**	-18.93**	45.80**	59.81**	-5.12**	-0.73**	-0.73**
BB26 × BT15	-73.22**	-65.74**	-36.27NS	17.14**	30.25**	35.62**	-61.54**	-58.27**	-47.94**	-2.33**	-14.63**	-14.63**
BB31 × BM5	-22.84**	-44.16**	-39.51**	17.14**	17.14**	28.36**	48.74**	70.09**	93.39**	-8.84**	-15.70**	-15.70**
BB31 × BT13	-15.17**	-38.61**	-4.20**	-11.48**	-34.08**	-18.40**	2.99**	2.86**	9.81**	3.26**	8.57**	8.57**
BB31 × BT6	-7.53**	-33.08**	15.12**	5.66**	-15.95**	1.48**	3.54**	18.40**	55.34**	-8.84**	7.42**	7.42**
BB31 × BT15	-66.59**	-75.82**	-53.62**	-17.22**	-7.96**	-4.17**	6.12**	15.16**	18.17**	-16.74**	-19.72**	-19.72**
BM5 × BT13	-21.68**	-33.00**	0.52NS	51.41**	12.76**	29.45**	-3.55**	-3.67**	15.85**	-10.70**	-16.88**	-16.88**
BM5 × BT6	-50.88**	-57.98**	-29.50**	17.14**	-6.82**	3.80**	-55.57**	-33.06**	-20.82**	31.16**	34.94**	34.94**
BM5 × BT15	-75.54**	-79.08**	-60.16**	0.00NS	0.00NS	5.42**	-19.02**	-12.13**	2.16**	-27.91**	-37.87**	-37.87**
BT13 × BT6	-22.25**	99.73**	153.30**	-11.48**	-34.08**	-31.82**	-19.84**	-19.94**	9.82**	-2.33**	16.05**	16.05**
BT13 × BT15	-79.55**	-47.46**	-8.68**	59.90**	19.08**	27.98**	-4.77**	-4.89**	-0.94**	-14.42**	-16.92**	-16.92**
BT6 × BT15	-80.16**	-11.67**	40.08**	-20.05**	-36.40**	-25.78**	-82.63**	-81.15**	-74.83**	-17.67**	-11.28**	-11.28**

Note: FW – individual fruit weight, PB – number of primary branches per plant, YPP – yield per plant, DF – days to first flower opening, RH – relative heterosis, HB – heterobeltosis, SH – standard heterosis
Source: collected from authors' research

Table 3. Percentage of heterosis for flowering and fruiting traits in eggplant hybrids

Crosses	DFF			NF			PH			SD		
	SH (%)	HB (%)	RH (%)	RH (%)	HB (%)	SH (%)	SH (%)	HB (%)	RH (%)	SH (%)	HB (%)	RH (%)
BB12 × BT17	-5.91**	-10.80**	-8.70**	35.17**	38.28**	38.28**	-12.46**	-17.13**	-12.21**	-25.67**	-33.65**	-20.44**
BB12 × BM9	-8.02**	-19.56**	-12.45**	122.67**	127.79**	273.53**	-1.66**	-7.15**	-1.51**	-32.48**	-36.28**	-25.40**
BB12 × BB1	-15.19**	-21.48**	-16.77**	139.71**	145.22**	294.67**	17.04**	19.18**	21.92**	5.72**	16.17**	27.05**
BB12 × BB23	-6.33**	-13.62**	-8.26**	10.74**	13.28**	52.11**	-1.44**	5.09**	18.43**	-8.27**	-9.81**	3.86**
BB12 × BB26	-2.95**	-16.97**	-8.73**	-37.53**	-36.09**	-17.88**	7.95**	-14.17**	-1.67**	-18.49**	-13.77**	-4.56**
BB12 × BB31	-2.95**	1.32**	1.32**	9.65**	12.17**	48.11**	9.73**	-9.52**	2.04**	-9.61**	-25.47**	-8.27**
BB12 × BM5	-3.80**	-16.48**	-8.80**	31.22**	34.24**	69.75**	24.46**	23.99**	28.20**	-7.42**	10.61**	-20.44**
BB12 × BT13	-10.55**	-7.42**	-7.02**	-51.12**	-79.56**	-70.96**	0.87NS	-3.08**	1.96**	17.40**	23.72**	-20.44**
BB12 × BT6	-8.02**	-3.96**	-3.96**	280.57**	68.42**	134.97**	1.14**	-3.35**	1.94**	-4.62**	9.49**	-20.44**
BB12 × BT15	-8.44**	-19.93**	-12.85**	351.02**	-68.42**	-40.87**	12.09**	19.51**	40.23**	19.59**	57.78**	-20.44**
BT17 × BM9	10.97**	-2.95**	0.96**	-25.56**	-11.44**	41.09**	10.31**	4.15**	4.29**	-4.74**	-14.98**	-25.40**
BT17 × BB1	-0.84**	-8.20**	-7.11**	15.34**	37.23**	114.45**	22.79**	16.24**	20.48**	19.46**	6.62**	27.05**
BT17 × BB23	12.66**	3.89**	5.33**	-11.38**	5.43**	34.58**	11.60**	5.66**	25.19**	13.14**	0.97NS	3.86**
BT17 × BB26	-6.75**	-20.22**	-16.13**	-63.63**	-56.73**	-47.54**	14.25**	-9.15**	-1.25**	8.88**	-2.82**	-4.56**
BT17 × BB31	2.53**	-2.81**	2.10**	-29.58**	-16.22**	4.66**	7.62**	-11.25**	-5.14**	1.95	-15.86**	-8.27**
BT17 × BM5	14.35**	-0.73**	3.63**	17.01**	39.21**	66.33**	6.92**	1.22**	3.79**	7.18**	-4.65**	-20.44**
BT17 × BT13	-5.91**	-10.80**	-6.89**	36.91**	-42.73**	-15.25**	9.28**	3.46**	4.22**	4.01**	-7.47**	-20.44**
BT17 × BT6	-0.84**	-6.00**	7.31**	-24.44**	-66.56**	-51.25**	14.44**	8.35**	8.85**	7.91**	-4.00**	-20.44**
BT17 × BT15	0.84**	-11.81**	-8.25**	-25.56**	-94.79**	-90.15**	9.04**	3.23**	27.00**	-9.49**	-19.48**	-20.44**
BM9 × BB1	8.86**	-4.80**	-2.09**	-68.20**	34.05**	41.36**	27.05**	19.95**	24.48**	-3.77**	-9.18**	-25.40**
BM9 × BB23	3.38**	-9.60**	-7.20**	-67.08**	-30.90**	-4.73**	-6.49**	-11.72**	4.72**	-16.55**	-21.24**	27.05**
BM9 × BB26	2.53**	-12.28**	-11.31**	57.91**	189.20**	315.14**	41.45**	12.47**	22.10**	8.39**	2.29NS	3.86**
BM9 × BB31	1.27**	-11.45**	-3.42**	-67.08**	-34.82**	-8.52**	-8.38**	-24.45**	-19.35**	-3.89**	-20.76**	-4.56**

Table 3, Continued

Crosses	DFF			NF			PH			SD		
	SH (%)	HB (%)	RH (%)	RH (%)	HB (%)	SH (%)	SH (%)	HB (%)	RH (%)	SH (%)	HB (%)	RH (%)
BM9 × BM5	-5.06**	-17.58**	-17.28**	4.53**	83.87**	167.63**	12.03**	5.77**	8.61**	9.25**	3.10**	-8.27**
BM9 × BT13	-19.83**	-29.89**	-24.00**	-22.73**	-67.68**	-40.69**	1.56**	-4.11**	-3.27**	4.26**	-1.61NS	-20.44**
BM9 × BT6	5.49**	-7.76**	8.93**	-62.51**	-83.41**	-69.70**	2.32**	-3.40**	-2.81**	-13.38**	-18.25**	-20.44**
BM9 × BT15	-1.69**	-14.03**	-14.02**	22.70**	-91.41**	-83.07**	4.59**	-1.25**	21.62**	-8.27**	-13.43**	-20.44**
BB1 × BB23	16.46**	7.40**	7.60**	-67.08**	-30.90**	-7.47**	-17.20**	-15.67**	-3.08**	-13.87**	-15.31**	-20.44**
BB1 × BB26	-0.84**	-15.15**	-11.82**	-79.55**	-62.55**	-47.64**	-15.92**	-33.15**	-24.92**	-22.75**	-18.27**	-25.40**
BB1 × BB31	18.57**	9.76**	16.60**	-69.33**	-39.27**	-17.13**	1.56**	-16.25**	-7.45**	-2.19	-19.36**	27.05**
BB1 × BM5	-18.57**	-29.30**	-27.03**	-21.06**	38.85**	95.94**	11.37**	10.95**	12.17**	-12.77**	-4.14**	3.86**
BB1 × BT13	13.08**	4.68**	10.52**	-28.43**	-70.06**	-45.48**	-18.34**	-21.52**	-19.25**	-16.55**	-12.05**	-4.56**
BB1 × BT6	53.59**	42.18**	63.96**	-60.22**	-82.40**	-68.11**	-16.91**	-20.59**	-18.07**	-15.09**	-6.68**	-8.27**
BB1 × BT15	-20.25**	-30.26**	-28.27**	117.01**	-84.80**	-70.10**	13.40**	15.49**	38.06**	-14.48**	-6.02**	-20.44**
BB23 × BB26	20.68**	3.24**	7.12**	-71.57**	-47.94**	-44.40**	0.62NS	-20.00**	1.41**	5.60**	3.83**	-20.44**
BB23 × BB31	-4.64**	-12.06**	-6.42**	31.22**	159.78**	167.36**	10.37**	-8.98**	13.83**	-0.97	-18.35**	-20.44**
BB23 × BM5	-7.17**	-19.41**	-16.98**	49.97**	163.79**	187.58**	7.86**	7.46**	24.67**	-1.95**	-3.59**	-20.44**
BB23 × BT13	13.92**	5.07**	11.11**	-10.26**	-62.46**	-37.40**	2.51**	-1.50**	16.00**	-0.36NS	-2.03**	-25.40**
BB23 × BT6	10.55**	1.95**	17.75**	0.00NS	-55.75**	-26.91**	-5.12**	-9.33**	7.03**	-14.11**	-15.55**	27.05**
BB23 × BT15	-9.28**	-20.67**	-18.56**	140.83**	-83.14**	-67.36**	12.08**	54.24**	61.56**	-14.48**	-15.90**	3.86**
BB26 × BB31	16.88**	22.57**	10.14**	-55.69**	-12.28**	-15.69**	33.58**	6.21**	8.15**	3.04**	-15.04**	-8.27**
BB26 × BM5	9.70**	-4.76**	-5.45**	42.02**	149.82**	155.33**	22.45**	-2.64**	8.29**	-5.35**	0.13NS	-20.44**
BB26 × BT13	32.49**	37.12**	24.11**	-72.73**	-88.59**	-81.43**	-7.06**	-26.10**	-19.13**	-25.06**	-20.72**	-20.44**
BB26 × BT6	-5.91**	18.62**	-4.09**	81.77**	-19.56**	29.57**	40.41**	11.64**	21.88**	-6.57**	-1.15**	-20.44**
BB26 × BT15	-3.38**	-15.50**	-16.42**	32.92**	-90.69**	-82.07**	29.70**	3.13**	35.21**	-6.45**	-1.03**	-20.44**
BB31 × BM5	5.06**	-8.79**	-0.20NS	74.37**	206.71**	225.45**	16.82**	-3.67**	5.41**	1.82	-16.04**	-25.40**
BB31 × BT13	6.75**	10.48**	11.21**	-2.90**	-59.38**	-32.93**	1.51**	-16.29**	-9.90**	4.01**	-14.24**	27.05**
BB31 × BT6	-0.42**	4.42**	4.42**	13.05**	-49.97**	-18.22**	7.89**	-11.03**	-4.48**	-0.73**	-18.15**	3.86**
BB31 × BT15	-15.19**	-25.83**	-19.11**	189.16**	-79.75**	-60.89**	26.67**	4.45**	35.22**	-6.33**	-22.77**	-4.56**
BM5 × BT13	-2.95**	-15.75**	-8.37**	25.53**	-47.49**	-15.10**	2.70**	-1.32**	0.46NS	5.11**	10.77**	-20.44**
BM5 × BT6	25.74**	9.16**	29.28**	5.08**	-53.50**	-25.64**	-7.72**	-11.82**	-9.98**	12.41**	29.05**	-20.44**
BM5 × BT15	-29.54**	-38.83**	-38.60**	197.10**	-79.19**	-59.98**	17.00**	16.57**	40.58**	5.60**	26.16**	-20.44**
BT13 × BT6	-3.80**	-0.45**	9.35**	64.76**	-31.08**	-29.14**	16.34**	11.18**	11.48**	5.72**	11.41**	-20.44**
BT13 × BT15	-9.28**	-20.66**	-14.00**	354.46**	-68.18**	-45.48**	14.63**	10.15**	34.74**	-4.50**	0.64NS	-25.40**
BT6 × BT15	-8.44**	-19.93**		-23.89**	-94.67**	-90.80**	-3.84**	-8.10**	12.67**	-20.07**	-8.24**	14.06**

Note: DFF – days to 50% flower opening, NF – number of fruits per plant, PH – plant height, SD – stem diameter, RH – relative heterosis, HB – heterobeltosis, SH – standard heterosis
Source: collected from authors' research

Table 4. Percentage of heterosis for vegetative growth traits in eggplant hybrids

Crosses	TSS			TPC			DPPH (antioxidant activity)		
	SH (%)	HB (%)	RH (%)	SH (%)	HB (%)	RH (%)	SH (%)	HB (%)	RH (%)
BB12 × BT17	0.98**	-3.86**	2.30**	-1.79**	-20.70**	-13.06**	23.81**	8.13**	11.85**
BB12 × BM9	0.00NS	8.24**	8.68**	24.59**	-10.09**	-5.05**	17.98**	3.04**	7.90**
BB12 × BB1	-3.44**	-2.96**	0.64NS	-19.98**	-35.39**	-23.87**	-6.09**	-17.98**	-8.87**
BB12 × BB23	-4.18**	1.04**	2.36**	56.91**	26.69**	28.59**	5.20**	-8.12**	-5.43**
BB12 × BB26	-4.91**	2.93**	6.03**	48.48**	15.94**	17.88**	14.67**	-3.35**	-1.64**
BB12 × BB31	-5.16**	-1.53**	0.52**	6.35**	-14.14**	-0.95**	19.93**	3.86**	4.30**
BB12 × BM5	-3.44**	4.52**	6.07**	-3.13**	-21.79**	-13.82**	5.37**	-7.98**	1.60**
BB12 × BT13	-1.65**	-2.84**	1.60**	-12.08**	-42.67**	-36.56**	2.07**	-10.85**	-9.52**
BB12 × BT6	7.37**	5.30**	10.49**	59.60**	-5.75**	8.87**	0.12NS	-18.68**	-15.73**
BB12 × BT15	11.06**	-21.39**	-4.94**	49.70**	-12.32**	1.64**	16.00**	1.31**	26.74**
BT17 × BM9	-0.74**	-5.50**	0.94**	-20.42**	-42.57**	-5.05**	8.86**	1.86**	3.16**
BT17 × BB1	1.11**	-3.74**	-1.14**	-11.20**	-13.02**	-23.87**	-2.08**	-8.37**	-1.34**
BT17 × BB23	-4.18**	-8.77**	-4.12**	44.83**	20.53**	28.59**	-1.25**	-7.60**	-8.08**
BT17 × BB26	1.97**	-2.92**	6.21**	63.16**	27.41**	17.88**	2.83**	-13.33**	-8.80**
BT17 × BB31	-5.41**	-9.94**	-6.04**	-9.47**	-11.32**	-13.06**	-10.82**	-22.77**	-19.79**
BT17 × BM5	-4.91**	-9.47**	-2.33**	16.68**	14.30**	-5.05**	14.59**	7.23**	14.70**
BT17 × BT13	4.18**	-0.82**	1.01**	-21.37**	-48.72**	-23.87**	-5.78**	-15.23**	-13.57**
BT17 × BT6	-2.70**	-7.37**	-5.99**	9.36**	-35.42**	28.59**	0.55**	-18.33**	-12.56**
BT17 × BT15	4.67**	-25.91**	-15.01**	50.91**	-11.59**	17.88**	-2.71**	-8.96**	10.90**
BM9 × BB1	-4.91**	-4.44**	-0.51**	21.64**	-12.23**	-13.82**	3.35**	-0.80**	5.58**
BM9 × BB23	3.32**	3.83**	10.80**	41.27**	1.94**	-36.56**	28.28**	18.80**	20.94**
BM9 × BB26	3.69**	4.20**	16.09**	10.60**	-20.19**	8.87**	4.78**	-11.69**	-5.96**
BM9 × BB31	-5.16**	-4.69**	0.92**	-6.51**	-32.54**	1.64**	-9.00**	-21.19**	-17.13**
BM9 × BM5	-3.93**	-3.46**	5.96**	6.08**	-23.45**	-11.42**	1.02**	-3.03**	2.51**
BM9 × BT13	5.16**	3.88**	9.04**	65.08**	7.65**	-5.05**	20.26**	8.20**	11.69**

Table 4, Continued

Crosses	TSS			TPC			DPPH (antioxidant activity)		
	SH (%)	HB (%)	RH (%)	SH (%)	HB (%)	RH (%)	SH (%)	HB (%)	RH (%)
BM9×BT6	0.00NS	-1.93**	3.30**	-38.05**	-63.41**	-23.87**	5.43**	-14.37**	-7.23**
BM9×BT15	-0.98**	-29.91**	-14.98**	95.19**	14.33**	28.59**	13.08**	8.55**	30.91**
BB1×BB23	-4.42**	-3.95**	-1.64**	-37.70**	-48.15**	-13.06**	1.46**	-6.05**	1.66**
BB1×BB26	-1.72**	-1.23**	5.40**	13.21**	-11.60**	-5.05**	-5.99**	-20.76**	-10.56**
BB1×BB31	-1.72**	-1.23**	0.38**	9.73**	20.74**	-23.87**	-2.42**	-15.50**	-5.76**
BB1×BM5	-1.23**	-0.74**	4.42**	-8.25**	-9.12**	28.59**	-1.40**	6.11**	6.86**
BB1×BT13	-3.69**	-4.85**	-4.04**	-16.59**	-45.61**	17.88**	7.48**	-3.30**	6.02**
BB1×BT6	-2.95**	-4.82**	-3.66**	-28.41**	-57.72**	-0.95**	-11.06**	-27.76**	-17.16**
BB1×BT15	17.69**	-16.70**	-2.24**	58.55**	-7.13**	-13.82**	9.99**	20.06**	37.33**
BB23×BB26	-3.19**	2.07**	6.49**	-2.43**	-23.81**	-0.01NS	-4.03**	-19.11**	-15.30**
BB23×BB31	-6.39**	-1.30**	-2.06**	12.60**	-6.29**	0.01NS	-4.15**	-17.00**	-14.22**
BB23×BM5	-2.21**	1.53**	5.99**	76.54**	46.92**	59.69**	-6.15**	-13.09**	-6.57**
BB23×BT13	-1.23**	-2.47**	0.75**	6.69**	-30.42**	-21.99**	-12.01**	-20.83**	-19.69**
BB23×BT6	3.69**	1.69**	5.37**	81.41**	7.13**	0.00NS	2.09**	-17.08**	-11.65**
BB23×BT15	17.44**	-16.87**	-0.52**	87.66**	9.92**	0.00NS	25.27**	16.00**	41.90**
BB26×BB31	-7.00**	-3.44**	1.47**	-26.84**	-42.87**	-13.06**	-1.94**	-17.35**	-16.24**
BB26×BM5	1.97**	5.87**	15.44**	-40.74**	-53.73**	-5.05**	-15.16**	-28.49**	-19.79**
BB26×BT13	-7.86**	-9.02**	-2.09**	-22.58**	-49.52**	-23.87**	-27.64**	-39.01**	-37.02**
BB26×BT6	7.37**	5.30**	13.65**	25.37**	-25.96**	28.59**	5.98**	-13.93**	-12.34**
BB26×BT15	5.65**	-25.22**	-7.43**	0.26NS	-41.27**	17.88**	-7.52**	-22.05**	-1.21**
BB31×BM5	-5.90**	-2.30**	1.19**	-41.35**	-41.91**	-38.85**	8.41**	-6.12**	4.04**
BB31×BT13	-4.42**	-5.58**	-3.23**	-71.32**	-81.30**	-76.52**	-26.37**	-36.23**	-35.01**
BB31×BT6	3.19**	1.20**	4.09**	2.09**	-39.71**	-21.54**	-8.54**	-25.71**	-23.33**
BB31×BT15	7.13**	-24.17**	-9.82**	124.67**	31.60**	71.77**	23.88**	7.27**	34.62**
BM5×BT13	-1.23**	-2.43**	3.47**	-4.69**	-37.85**	-29.84**	5.98**	-4.65**	3.87**
BM5×BT6	0.25**	-1.69**	4.62**	39.19**	-17.80**	37.86**	26.01**	2.35**	16.66**
BM5×BT15	10.93**	-21.48**	-3.94**	45.27**	-14.91**	43.89**	23.90**	33.34**	53.45**
BT13×BT6	4.67**	2.65**	3.05**	104.61**	20.83**	-13.06**	6.54**	-13.47**	-9.04**
BT13×BT15	4.91**	-25.74**	-13.53**	88.37**	10.33**	-5.05**	-4.91**	-14.44**	5.83**
BT6×BT15	11.06**	-21.36**	-8.69**	192.43**	71.29**	71.98**	7.31**	-12.84**	11.96**

Note: TSS – total soluble solid, TPC – total phenol content, RH – relative heterosis, HB – heterobeltosis, SH – standard heterosis

Source: collected from authors' research

Table 5. Best hybrids for different traits based on standard heterosis

Crosses	Traits
BM9×BB26	Plant height, and yield per plant
BB12×BT6	Number of primary branches per plant
BM5×BT15	Days to first flower opening and days to 50% flower opening
BB12×BT15	Stem diameter
BT13×BT15	Number of fruits per plant
BB31×BT13	Fruit length
BM9×BB1	Individual fruit weight and fruit girth
BT17×BB1	Fruit diameter
BB1×BT15	Total soluble solid
BT6×BT15	Total phenol content
BM9×BB23	DPPH (antioxidant activity)

Source: compiled by the authors from their research

The information of heterosis is a prerequisite to develop hybrids is well known. A hybrid is good when it has abundant of heterosis for exploitation of commercially. Here, fruit length is a significant character which is directly correlated with yield. That's why positive heterosis is considerable for this trait, though fruit size varied on consumer's choice. The greatest value of RH, HB and SH was found from the hybrids BM5 × BT13, BM9 × BT13 and BB31 × BT13 with the value of 57.60%, 42.25% and 21.73% respectively which were considered the best hybrids over the environment. The researcher T. Sharma *et al.* (2016) reported more or less similar results that supported the above results. The top values of fruit diameter were found from the hybrids BT17 × BB1, BM9 × BB1 and BB1 × BB31 for SH, HB and RH respectively. Besides, regarding fruit girth, the hybrids BB31 × BT6, BM9 × BB26 and BM9 × BB1 performed the highest positive heterosis value for RH, HB and SH respectively. The findings of C. Mistry *et al.* (2018) support this researcher result for HB and RH. On the other hand, the character fruit length to width ratio BM9 × BT13 hybrid performed the best for RH and BM9 × BB31 hybrid recorded the best for HB and SH. The character individual fruit weight is directly connected to the trait yield per plant. Thus, the trait individual fruit weight is also crucial trait, as yield per plant is the target. The hybrid BT13 × BT6 registered the best for RH, and BM9 × BB1 hybrid found the best for SH and HB. Hence, it can be counted these hybrids for individual fruit weight. Besides, the final objective of the breeding program is to increase yield for each plant. As the character yield is a complex trait, so the trait yield for each plant is the final result of its components. Besides, heterosis plays a major part in it. Considering all types of heterosis, the hybrid BM9 × BB26 found the best. Breeding between various parents has been attempted, and non-additive gene action brightens a high heterosis value for fruit output per plant.

Findings of this result that is high heterosis are almost same findings with the researcher J. de Sousa & W. Maluf (1998). Hybrids namely BB12 × BT15, BB26 × BB31, and BB12 × BT6 were found as good for RH, HB and SH respectively considering the character number of primary branches per plant. This character performed low heterosis compared to others such as yield per plant, number of fruits per plant and individual fruit weight. This finding is similar to the previous researchers N. Dharwad *et al.* (2012) and J. Prohens *et al.* (2013). Earliness is one of the most crucial factors in the breeding program, in which days to first flower opening and days to 50% flower opening are two important characters that assess earliness. In this case, negative heterosis is desirable over mid parent, better parent and standard variety. Here, the majority of the hybrids displayed negative heterosis, meaning earliness. Among all the studied hybrid, the BM5 × BT15 cross was the earliest hybrid, as it had the lowest value of heterosis for both DF and DFF. Early flowering of eggplant occurs due to negative effect of heterosis has been reported by previous reporters S. Kumar & T. Arumugam (2013) and T. Sharma *et al.* (2016).

The trait number of fruits per plant is one of the important characters to enhance yield per plant in eggplant. 28 hybrids showed positive standard heterosis for this character. In case of number of fruits per plant, BT13 × BT15 performed the best, considering standard heterosis. Besides, the hybrid BB12 × BB1 and BB31 × BM5 showed the highest value of RH and HB. Similar findings were also reported by S. Dash (2017). The BM9 × BB26 hybrid performed the highest heterosis value for plant height over check variety meaning it would be preferable to generate taller plants over check variety and to develop shorter plant than the check variety, cross BB1 × BT13 perform the better. M. Shahjahan *et al.* (2016) found both positive and negative heterosis values for RH and HB. Regarding stem diameter, the hybrid BB12 × BT15 performed the best positive value of SH following the hybrid BT17 × BB1. Besides, no hybrid performed positive HB value. Considering the trait TSS, the hybrids BB1 × BT15, BB12 × BM9 and BM9 × BB26 showed the greatest value of SH, HB and RH respectively and these three hybrids can consider promising hybrids for the trait TSS. This result is supported by the earlier researcher A. Patel *et al.* (2017). Moreover, the negative heterosis signified low phenol content in hybrids (Lokesh *et al.*, 2025). Thus, BT6 × BT15 hybrid could be advised as the best for the trait TPC regarding all types of heterosis. Conversely, the highest value for HB and RH is found in the hybrid BM5 × BT15 and the hybrid BM9 × BB23 was best over SH for DPPH (antioxidant activity). Hence, these two hybrids could be considered to get higher antioxidant activity in eggplants.

CONCLUSIONS

The developed 55 hybrids for achieving high yield and high quality showed highly significant heterosis. Among these, the hybrid BM9 × BB26, considered the best hybrid, showed significant positive heterosis (130.79%) over check variety for yield per plant. Besides, the hybrid BT13 × BT15 (354.46%) and BM9 × BB1 (105.04%) performed the best significant positive standard heterosis for the character number of fruits per plant and individual fruit weight respectively. Additionally, the combination BT17 × BB1, BM9 × BB1, and BM9 × BB31 showed highly significant standard heterosis for the character fruit diameter, fruit girth, and fruit length to width ratio with the value of 60.28%, 79.915 and 56.75% respectively. On the other side, considering quality of the combination the hybrid BB1×BT15 and BT6×BT15 exhibited the best significant positive heterosis over check for the character of total soluble solid (17.69%) and total phenol content (192.43%) respectively. Besides, the cross combinations of BM9 × BB23 showed the best performance for the character DPPH over the check variety. These findings record a strong foundation for more research and the development of new hybrids with enhanced quality characters. Further research could be focused on analysing other quality traits in these hybrids to more comprehensively assess quality and further confirmation of yield and other yield related traits. After analysis of stability for yield and other yield related performances, it can be commercially exploited. Moreover, multi-location and multi-season trials are recommended to validate the consistency of heterotic performance under diverse agro-climatic conditions.

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CONFLICT OF INTEREST

There is no conflict of interest.

REFERENCES

[1] Anvesh, S., Delvadiya, I.R., Thota, H., & Yasaswini, M. (2025). Analyzing genetic variation and graphical representation (Wr-Vr) in brinjal (*Solanum melongena* L.) using the Hayman approach in the northwestern region of India. *Indian Journal of Agricultural Research*, 59(3), 447-453. doi: 10.18805/IJARe.A-6231.

[2] Convention on Biological Diversity. (1992, June). Retrieved from https://surl.li/bbovxp.

[3] Convention on the Trade in Endangered Species of Wild Fauna and Flora. (1976, March). Retrieved from https://surl.lu/bmdbca.

[4] Dash, S.P. (2017). *Divergence, combining ability and heterosis for fruit yield and its components in brinjal (Solanum melongena L.)*. (Doctoral dissertation, Indira Gandhi Krishi Vishwavidhyalaya, Purena, India).

[5] De Sousa, J.A., & Maluf, W.R. (1998). Expression of heterosis for productive traits in F_1 eggplant (*Solanum melongena* L.) hybrids. *Genetics and Molecular Biology*, 21(1). doi: 10.1590/S1415-47571998000100017.

[6] Dharwad, N.A., Patil, S., & Salimath, P.M. (2012). Heterosis and combining ability analysis for productivity traits in brinjal (*Solanum melongena* L.). *Karnataka Journal of Agricultural Sciences*, 24(5), 622-625.

[7] Hassan, E.O. (2021). Determination of heterosis in eggplant (*Solanum melongena* L.) hybrids. *Journal of Applied Sciences*, 36(3), 25-42. doi: 10.21608/EJAS.2021.163325.

[8] Khasdhar, Z.F., Patel, N., Patel, A., & Patel, N.A. (2024). Standard heterosis for yield and its attributing traits in brinjal (*Solanum melongena* L.). *International Journal of Research in Agronomy*, 7(1), 100-103. doi: 10.33545/2618060X.2024.v7.i1b.194.

[9] Kumar, S.R., & Arumugam, T. (2013). Correlation and path coefficient analysis for some yield-related traits in F_2 segregating population of eggplant. *International Journal of Vegetable Science*, 19(4), 334-341. doi: 10.1080/19315260.2012.731680.

[10] Kumari, A., Dogra, B.S., Dhiman, S., & Thakur, A. (2025). Exploring the impact of heterosis in brinjal (*Solanum melongena* L.) cultivation and yield quality. *Bangladesh Journal of Botany*, 54(3), 447-453. doi: 10.3329/bjb.v54i3.82028.

[11] Lokesh, Y., Singh, B., Jha, A., Ram, C.N., & Upadhyay, D.K. (2025). Genetics and heterosis of quality and yield of brinjal (*Solanum melongena* L.). *Plant Science Today*, 12(2), 1-9. doi: 10.14719/pst.6176.
[12] Mishra, S., Tripathy, P., Gouri, S., Lenka, D., Mishra, M.K., Tripathy, S.K., Padhiary, G.G., Mohanty, A., & Das, S. (2023). Study of heterosis, combining ability and gene action in brinjal (*Solanum melongena* L.) landraces of Odisha. *Electronic Journal of Plant Breeding*, 14(2), 572-583. doi: 10.37992/2023.1402.068.
[13] Mistry, C.R., Kathiria, K.B., Sabolu, S., & Kumar, S. (2018). Heterosis and inbreeding depression for fruit yield attributing traits in eggplant. *Current Plant Biology*, 16, 27-31. doi: 10.1016/j.cpb.2018.10.004.
[14] Mohsin, G., Rahman, S., Ahamed, F., & Hasanuzzaman. (2022). Heterosis analysis in pumpkin (*Cucurbitamoschata Duch*. Ex. Poir). *Dhaka University Journal of Biological Sciences*, 31(1), 117-136. doi: 10.3329/dujbs.v31i1.57921.
[15] Patel, A.A., Gohil, D.P., Dhruve, J.J., & Damor, H.I. (2017). Heterosis for fruit yield and its quality characters in brinjal (*Solanum melongena* L.). *Journal of Pharmacognosy and Phytochemistry*, 6(6), 975-978.
[16] Prohens, J., Whitaker, B.D., Plazas, M., Vilanova, S., Hurtado, M., Blasco, M., Gramazio, P., & Stommel, J.R. (2013). Genetic diversity in morphological characters and phenolic acids content resulting from an interspecific cross between eggplant, *Solanum melongena*, and its wild ancestor (*S. incanum*). *Annals of Applied Biology*, 162(2), 242-257. doi: 10.1111/aab.12017.
[17] Quamruzzaman, A.K.M., Salim, M.M.R., Akhter, L., Rahman, M.M., & Chowdhury, M.A.Z. (2020). Expression of heterosis for productive traits in bottle gourd hybrids. *Journal of Botanical Research*, 2(2), 1-7. doi: 10.30564/jrb.v2i2.1828.
[18] Rajashree, Kamble, C.S., Tirakannanavar, S., Gasti, V.D., Nishani, S., Koulagi, S., & Bhavidoddi, A. (2023). Heterosis studies for growth, flower and yield characters in brinjal (*Solanum melongena* L.). *Biological Forum – An International Journal*, 15(11), 13-20.
[19] Rameshkumar, D., & Vethamonai, I.P. (2020). Heterosis for quantitative and qualitative traits in brinjal (*Solanum melongena* L.). *Vegetable Science*, 47(1), 55-61. doi: 10.61180/vegsci.2020.v47.i1.10.
[20] Shahjahan, M., Kabir, K., Zomo, S.A., Sarkar, D., & Fazlullah, M.U. (2016). Evaluation of heterosis in exotic eggplant. *International Research Journal of Agricultural and Food Sciences*, 1(2), 23-32.
[21] Sharma, T.K., Pant, S.C., Kumar, K., Kurrey, V.K., Pandey, P.K., & Bairwa, P.L. (2016). Studies on heterosis in brinjal (*Solanum melongena* L.). *International Journal of Bio-Resource and Stress Management*, 7(5), 964-969. doi: 10.23910/IJBSM/2016.7.5.1636a.
[22] Thota, H.S., & Delvadiya, I. (2025). Harnessing heterosis in eggplant (*Solanum melongena* L.). *Electronic Journal of Plant Breeding*, 16(1), 110-120. doi: 10.37992/2025.1601.005.

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Аналіз гетерозису врожайності та якості баклажанів (*Solanum melongena* L.)

Анотація. Дослід було проведено з 55 гібридами баклажана, отриманими в результаті 11 × 11 напівдіалельних схрещувань, разом зі стандартним сортом на дослідних полях 10 і 15 Університету Путра Малайзія (Серданг, штат Селангор, Малайзія) протягом одного сезону – з листопада 2020 року по січень 2021 року. Метою дослідження було створення високоврожайних і високоякісних гібридів баклажана. Дослідження проводили за схемою рандомізованого повного блокового дизайну з трьома повтореннями у двох локаціях. Для оцінки гетерозису визначали 15 морфологічних і біохімічних ознак. Серед досліджуваних гібридів BM9 × BB26 був визначений як найкращий за врожайністю з однієї рослини з урахуванням стандартного гетерозису, гетеробельтозису та відносного гетерозису. Крім того, гібрид BB1 × BT15 виявився найкращим за вмістом загальних розчинних сухих речовин порівняно зі стандартним сортом, а гібрид BT6 × BT15 – найкращим за вмістом загальних фенольних сполук з урахуванням усіх трьох типів гетерозису: відносного, гетеробельтозису та стандартного гетерозису. Натомість найвищі значення гетеробельтозису та відносного гетерозису за антиоксидантною активністю (DPPH) були виявлені у гібриду BM5 × BT15, тоді як гібрид BM9 × BB23 показав найкращі результати за стандартним гетерозисом. Отже, ці два гібриди можна рекомендувати для отримання баклажанів з підвищеною антиоксидантною активністю. Отримані результати можуть бути використані селекціонерами, агрономами та фахівцями з овочівництва для відбору найкращих гібридів у подальших практичних дослідженнях

Ключові слова: гібриди; напівдіалельні схрещування; власна продуктивність; гетерозис за кращим батьківським компонентом; антиоксидантна активність

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