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Dmytro Pyshcholka
Postgraduate Student
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
http://orcid.org/0009-0001-9025-4463

Volodymyr Mezhenskyj*
Doctor of Agricultural Sciences, Senior Researcher
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0000-0002-3154-1120

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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*Corresponding author

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 ± 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±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 ≤ 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.

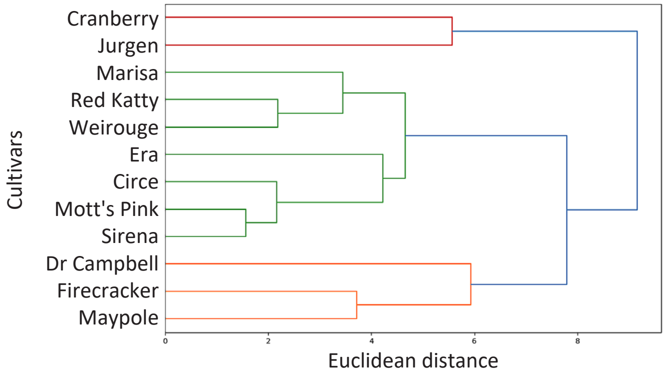

Figure 1. Dendrogram of cultivars clustering based on all biochemical characteristics
Source: compiled by the authors

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).

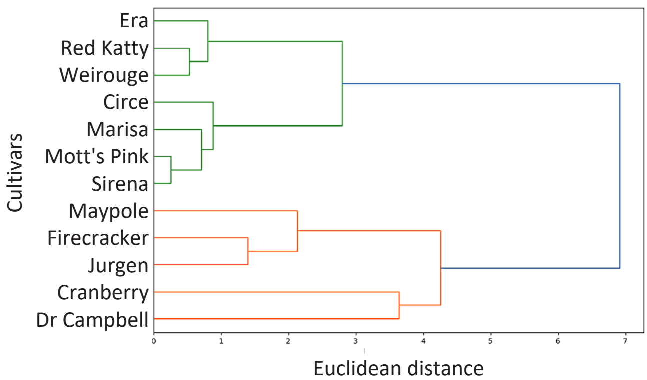

Figure 2. Dendrogram of cultivars clustering based on antioxidant traits
Source: compiled by the authors

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.

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Дмитро Пищолка
Аспірант
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
http://orcid.org/0009-0001-9025-4463

Володимир Меженський
Доктор сільськогосподарських наук, старший науковий співробітник
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
https://orcid.org/0000-0002-3154-1120

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