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BIOCHEMICAL COMPOSITION AND BIOLOGICALLY ACTIVE SUBSTANCES IN TUBERS OF KAZAKH-RUSSIAN BREEDING COLORED POTATO

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ABSTRACT

Colored-flesh potato is a promising source of natural antioxidants, but the yield stability and biochemical value of newly introduced Kazakh–Russian breeding materials under contrasting environments remain insufficiently characterized. The aim of this study was to evaluate yield performance and 17 tuber biochemical parameters related to nutritional quality and the accumulation of bioactive compounds. The field comparison included six potato genotypes: four colored-flesh Kazakh–Russian materials (Kiru, Travnik, Tanyusha, and Olyushka), the light-fleshed Kazakh cultivar Udovitsky, and the regional purple-fleshed standard Fioletovyi. Trials were conducted at two contrasting locations: Terra farm, Kostanay Region, Republic of Kazakhstan, in 2024, and VIR Pushkin Laboratories, Leningrad Region, Russian Federation, in 2022–2024; biochemical profiling of five Kazakh-bred genotypes included harvests from Kostanay in 2021–2024 and from Leningrad in 2022–2024. All biochemical traits were determined on a fresh-weight basis. Yield ranged from 285.7 ± 58.1 to 884.95 ± 96.55 g/plant; Kiru had the highest mean yield at both sites, reaching 777.25 ± 75.60 g/plant in Kostanay and 884.95 ± 96.55 g/plant in Leningrad. The main bioactive compounds varied widely: anthocyanins ranged from 2.91 to 101.43 mg/100 g FW, total phenolics from 13.97 to 59.34 mg GAE/100 g FW, and antioxidant capacity from 2.82 to 33.09 mg AAE/100 g FW. The maximum values for anthocyanins, phenolics, and antioxidant capacity were recorded in Olyushka grown in the Leningrad Region: 101.43 ± 11.21 mg/100 g FW, 59.34 ± 12.51 mg GAE/100 g FW, and 33.09 ± 6.59 mg AAE/100 g FW, respectively. DPPH radical-scavenging activity reached 14.69 ± 0.80% in Travnik. The novelty of this work is the integrated yield–biochemical characterization of recently introduced Kazakh–Russian colored-flesh potato materials across continental and temperate environments. The results identify Olyushka as a promising source of anthocyanins and phenolics for breeding and functional potato products in northern Kazakhstan, whereas Travnik and Tanyusha are promising high-yielding, nutritionally valuable materials for northwestern Russia.

Keywords: Nutritional value, Colored-flesh potato, Bioactive compounds, Anthocyanins, Carotenoids.

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1. INTRODUCTION

Potato is one of the major food crops globally and the most important non-cereal crop, cultivated on approximately 20 million hectares and consumed by around 1.3 billion people worldwide. According to the latest FAOSTAT data, global potato production reached approximately 390 million tons in 2024, with a harvested area of about 17.1 million ha and an average yield of about 22.9 t/ha. Potatoes, therefore, remain one of the key global staple crops, and their importance is increasing not only for food security but also for the development of nutrient-dense and value-added products (Food and Agriculture Organization of the United Nations, 2025). In the Russian Federation, per capita potato consumption in 2021 was 52 kg per year (Kuzmin et al., 2024). As the global consumer trend preferences gradually shift towards the health and wellness market in the next coming years, pigmented potatoes have shown traits of a promising future for non-traditional, available food sources and a source of enhanced nutritional content due to their antioxidant levels, which are comparably higher than the white potato variety (Azhimakhan et al., 2025). Pino and Vergara (2021) also mentioned that, aside from being an aesthetically pleasing, healthy solution to starvation and imminent world hunger, the flesh of these pigmented potatoes has shown potential to be used as raw materials for natural color extraction and food coloring ingredients.

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At the global statistical level, colored-flesh potato remains a niche but strategically important segment of potato production (Johansson et al., 2025). Official agricultural databases usually report potato as a single crop category and do not disaggregate global production or harvested area by tuber flesh color; therefore, reliable worldwide acreage data specifically for colored potatoes are not available. Nevertheless, the broader market context supports the relevance of this breeding direction. World fruit and vegetable production, which represents the main agricultural group of antioxidant-rich plant foods, reached 2.1 billion tonnes in 2023, while the global functional foods market was estimated at USD 280.7 billion in 2021 and is projected to grow at an annual rate of 8.5% through 2030. In this context, red- and purple-fleshed potatoes are important because they combine the advantages of a staple crop with a naturally increased content of anthocyanins, phenolic compounds, carotenoids, and other bioactive substances relevant to functional food development (Xu et al., 2023; Rashidinejad, 2024; Food and Agriculture Organization of the United Nations, 2025).

Pigmented potatoes are also globally important due to their latent health benefits. Bvenura et al. (2022) reported that consuming these carotenoid-rich potatoes may serve as a safeguard against lifestyle- and diet-related diseases and assist in the management and treatment of vision-related disorders. Other in vitro studies claim that the anthocyanins in pigmented potatoes can inhibit cancer cell proliferation; another school of thought believes in the medical capacity of pigmented potatoes to reduce chronic cardiovascular diseases and manage diabetes (Singh et al., 2020; Mattoo et al., 2022).

The biochemical activities of pigmented potatoes vary across boards but are closely linked to the presence of anthocyanins and carotenoids. Zhang et al. (2023) highlighted in their study that for most pigmented varieties, cyanidin and pelargonidin derivatives were responsible for the redness, while malvidin, petunidin, and delphinidin compounds contributed to the purple color. Violaxanthin compounds determined the light-yellow hue, while zeaxanthin and antheraxanthin derivatives increased the deep-yellow deposition. Integrated transcriptome and proteome analysis revealed that F3′5′H significantly increased anthocyanin production in purple flesh, which was responsible for metabolic differences between red and purple samples (Zhang et al., 2023). BCH2 dramatically increased carotenoid production in yellow samples, and together with ZEP, NCED1, and CCD1 genes, determined metabolic divergence between light and deep-yellow samples. In another unrelated study, Wang et al. (2023) explained that the biochemical activity of pigmented potatoes allowed them to thrive in high saline soil. Bvenura et al. (2022) also added that the in vitro study showed that the ethanolic extracts were minimally active against the hepatocellular carcinoma cell lines. Studies also showed a reduction in cancer incidence and multiplicity, but in vivo, when extracts of pigmented potatoes were used. Other studies also revealed that the extracts of some pigmented potatoes were lethal against the hepatocarcinoma (Hep3B) cell lines, and skin and flesh extracts of some cultivars possessed some antibacterial properties against E. coli.

Recent studies published in 2020–2025 have further confirmed that the nutritional and functional value of pigmented potatoes is determined by both genotype and growing environment. Colored-flesh potato accessions generally show higher levels of phenolics, anthocyanins, flavonoids, and antioxidant activity than white- or yellow-fleshed materials, but the magnitude of these differences depends on cultivar, year, location, altitude, temperature, and water availability (Samaniego et al., 2020; Hellmann et al., 2021; Bvenura et al. 2022; Mattoo et al., 2022; Liu et al. 2023; Wu and Xiao, 2024). Molecular and multi-omics studies have also identified key regulatory mechanisms involved in tuber pigmentation, including anthocyanin- and carotenoid-related pathways, which makes colored-flesh potato a relevant object for both biochemical evaluation and breeding-oriented research (Zhang et al., 2023; Kim et al., 2025; Sturaro, 2025).

In 2024, the total area under potato cultivation in the Republic of Kazakhstan amounted to 122.6 thousand hectares. According to the Ministry of Agriculture of the Republic of Kazakhstan, the gross potato harvest in the same year reached 2.9 million tons, including 300 thousand tons of early-season potatoes. Based on the Order of the Minister of National Economy of the Republic of Kazakhstan No.503 dated December 9, 2016, "On the Approval of Scientifically Based Physiological Standards for Food Consumption," the recommended per capita annual consumption of potatoes is 100 kilograms. Given the country's population size, domestic demand for potatoes is estimated at approximately 2 million tons per year (Bureau of National Statistics, 2024; Ministry of Agriculture of the Republic of Kazakhstan, 2024). The high nutritional value and balanced composition of essential components in potato tubers are important for a healthy modern diet. Potato tubers contain carbohydrates, protein, fats, dietary fiber, vitamins, minerals, and antioxidants. Phenolic compounds, storage proteins, anthocyanins, vitamins, and carotenoids found in potatoes may have beneficial effects on human health, exhibiting anticancer, hypocholesterolemic, anti-inflammatory, and antidiabetic properties (Hellmann et al., 2021). Potato varieties with red and purple flesh have particularly high dietary value, as they are rich sources of polyphenolic compounds with antioxidant activity, primarily anthocyanins (Polivanova & Gins 2019). Aside from phenolic and polyphenolic contents, pigmented potatoes are rich sources of macro- and micronutrients. According to the Bellumori et al. (2020) study on pigmented Andean potatoes, potassium was the highest nutrient in both the skin and flesh for most species. Calcium, an essential mineral involved in neuromuscular function, blood clotting, and many metabolic processes, was also found in abundance in the skin of the pigmented potatoes. Micronutrients, iron, and zinc were found in lower concentrations, with a positive correlation existing between calcium and iron. Bellumori et al. (2020) went further to state that, in agreement with previous studies, all mineral elements (macro- and micro-) exhibited elevated amounts in the skin samples compared to the flesh samples across all investigated genotypes.

The study of environmental conditions that influence pigmented cultivars, yields a variety of findings. According to research, root zone temperature has a considerable influence on plant height and tuber weight, although the impact on anthocyanins and polyphenolics varies greatly depending on cultivar. Environmental conditions, such as altitude and soil composition, can boost anthocyanin production while leaving carotenoids unaffected. Drought stress has varying effects on phytochemical levels among cultivars, with organic and biodynamic approaches exhibiting differences in anthocyanins and carotenoids when compared to conventional methods. Tuber maturity coincides with a decrease in certain chemicals. Despite multiple studies, there is still a large knowledge gap regarding breeding and yield data for pigmented cultivars, indicating the need for additional collaborative research efforts (Bvenura et al., 2022).

Rising consumer expectations in Russia regarding the culinary and nutritional quality of potatoes have led to the emergence of a new breeding focus: the development of cultivars aimed at balanced and health-promoting (functional or therapeutic) diets (Simakov et al., 2020). In order to enhance the quality of food products, specific criteria have been defined for key agronomic and nutritional traits of table potato varieties. Varieties intended for dietary (therapeutic) use should have low starch content (8–10%), elevated levels of vitamin C (25–30 mg%) and increased concentrations of carotenoids (>20 mg/100 g) or anthocyanins (>500 mg/100 g) (Simakov et al., 2020). The State Register of Breeding Achievements of the Russian Federation includes three potato varieties with pigmented tuber flesh: Severnoe Siyaniye, Syurpriz, and Fioletovyi (State Variety Commission, 2025). In order to expand the genetic diversity of potato varieties for emerging breeding objectives, the Federal Research Center “N.I. Vavilov All-Russian Institute of Plant Genetic Resources” (VIR) is conducting systematic introduction of potato varieties and breeding clones. In 2021–2022, VIR acquired a number of promising pigmented-flesh potato varieties developed by the leading breeder of Kazakhstan Andrey S. Udovitsky.

However, Kazakh–Russian colored-flesh breeding materials remain insufficiently characterized in terms of the combined assessment of yield, nutritional quality, bioactive compound accumulation, and response to contrasting environments. The Kostanay Region and the Leningrad Region were selected because they represent two markedly different agro-ecological backgrounds: a sharply continental, relatively dry environment with southern black soil in northern Kazakhstan and a humid temperate environment with sod-podzolic acidic loamy soils in northwestern Russia. Such contrast is suitable for revealing genotype-dependent responses in yield formation and tuber biochemical composition. The present study focused on four colored-flesh genotypes from the introduced Kazakh breeding material because they represented the core pigmented set available for comparative field and biochemical evaluation and differed in pigmentation, pedigree, and maturity: Kiru has purple skin and flesh, Travnik and Tanyusha have red skin and flesh, and Olyushka has red skin and deep-pink flesh; Kiru and Travnik are seedlings of the Stepan variety, whereas Tanyusha and Olyushka originated from spontaneous mutagenesis.

Accordingly, the objective of this study was to compare the yield performance and tuber nutritional and biochemical quality of selected Kazakh–Russian colored-flesh potato genotypes under the contrasting environmental conditions of the Kostanay Region, Republic of Kazakhstan, and the Leningrad Region, Russian Federation, and to identify promising materials for regional breeding and functional food development.

2. MATERIALS AND METHODS

In the Leningrad Region, field trials were conducted during 2022–2024 at the VIR experimental facilities in Pushkin (near St. Petersburg) to evaluate four pigmented-flesh potato varieties and breeding samples: Kiru, Olyushka, Tanyusha, and Travnik — along with a white-fleshed variety, Udovitsky, all developed in the Republic of Kazakhstan (Fig. 1). The pigmented-flesh variety Fioletovyi, developed at the A.G. Lorkh Federal Research Center for Potato and approved for cultivation in the Leningrad Region, was included as the reference cultivar (Table 1).

In 2024, the potato breeding samples Tanyusha, Travnik, Olyushka, and the cultivar Kiru (used as a control) were evaluated under the field conditions of the Kostanay District, Kostanay Region, at the Terra private farm. At each trial site, yield performance was assessed for the breeding material, including total and marketable yield, the number of tubers per plant, average tuber weight, and the percentage of marketable tubers by weight.

Between 2021 and 2024, the chemical composition of potato tubers was assessed at the Biochemistry Department of the N.I. Vavilov Institute of Plant Genetic Resources (VIR). Analyses were conducted on tuber samples obtained from harvests in the Kostanay Region (2021-2024) and the Leningrad Region (2022–2024).

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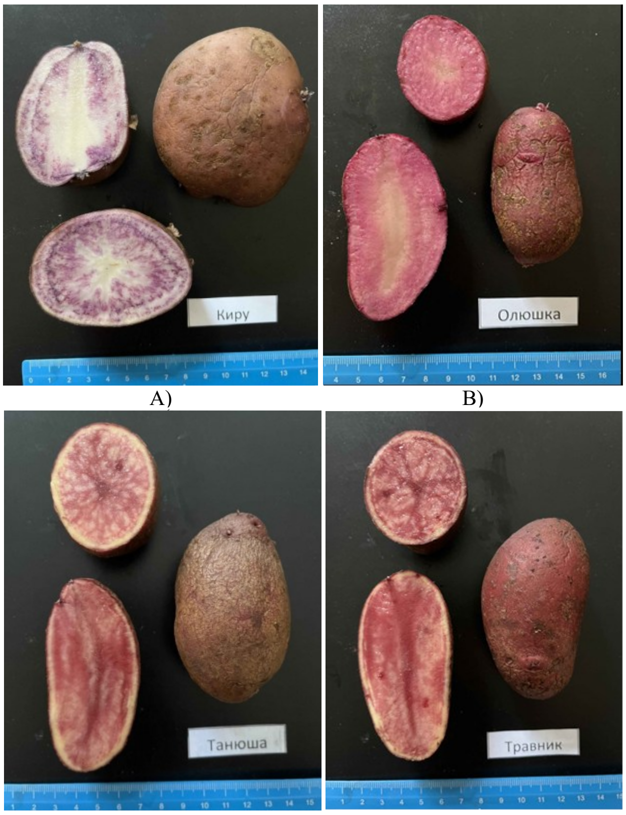
Table 1: Research material

No	Selection sample	Accession Collection number	Pedigree	Maturity	Tuber shape	Skin color	Flesh color
1	Kiru	25255	Seedling of the Stepan variety	Late-maturing	Round	Purple	Purple
2	Tanyusha	25550	Spontaneous mutagenesis of the Travnik breeding sample	Late-maturing	Elongated oval	Red	Red
3	Travnik	25549	Seedling of the Stepan variety	Late-maturing	Elongated oval	Red	Red
4	Olyushka	25644	Spontaneous mutagenesis of the Tanyusha breeding sample	Mid-season	Elongated oval	Red	Deep pink flesh
5	Udovickij	25260	Self-pollination of the Spiridon variety	Late-maturing	Oval	Red	Light yellow
6	Fioletovyj	25220	PRT 703 x 1092-7	Medium-late maturing	Oval	Purple	Purple



C) D)

Fig. 1: Tuber samples of pigmented-flesh potato varieties and breeding lines from the 2024 harvest grown at VIR Pushkin Laboratories, Leningrad Region: a) Kiru, b) Olyushka, c) Tanyusha, and d) Travnik.

Meteorological data for the Kostanay site were retrieved from the Kostanay meteorological station (53.2367° N, 63.7408° E; 151 m a.s.l.). For the Leningrad site, the complete monthly archive of the St. Petersburg meteorological station (59.9691° N, 30.2839° E; 3 m a.s.l.) was used as a regional proxy for the VIR Pushkin Laboratories site. Daily or monthly data were summarized for the active potato growth period from May to August. The soil and climatic conditions of the two regions where pigmented potato varieties were cultivated are highly contrasting. The climate of the Kostanay Region is sharply continental, characterized by cold, low-snow winters and hot, dry summers. Prolonged cold spells in spring, early autumn frosts, and late summer precipitation are typical features of the region and distinguish it from other arid zones. All climatic factors exhibit considerable interannual variability in both intensity and timing. In 2021, air temperatures exceeded the long-term average in June and August. Precipitation was below normal in May, June, and August, while in July it was nearly twice the average. In 2024, temperatures were above the long-term average in May, June, and August. Precipitation was again below normal in May and August, but exceeded the norm in June.

The climate of the Leningrad Region is temperate, transitional from oceanic to continental, characterized by relatively mild winters with frequent thaws and moderately warm summers. Precipitation is most abundant during summer and autumn. Agro-meteorological conditions during the growing seasons of 2022–2024 were highly unstable and not always favorable for obtaining high potato yields with good consumer qualities. The summer of 2022 was warm, though not particularly sunny; average July temperatures were below the long-term average. Precipitation in June and July was below normal, while August saw 185% of the monthly average. The summer of 2023 was rather variable, with alternating warm and sunny periods. July temperatures were below the multi-year average, and rainfall was twice below normal; in August, only 38% of the average precipitation was recorded. The summer of 2024 was warm, with temperatures above the long-term average in June and July. A deficit of precipitation was observed in July (62% of normal), while in August precipitation reached 144% of the monthly norm.

In the field trial conducted at VIR's Pushkin Laboratories (Leningrad region), each potato variety was represented annually by 10 plants in three replicates. The soil at the VIR experimental site is sod-podzolic, sandy loam with light loam inclusions, containing 3.0–3.5% humus, with pH ranging from 4.8 to 5.1. Crop management followed standard practices for the Northwestern region. In the irrigated field trial at the Terra private farm (Kostanay Region), each variety was represented by 10 plants in four replicates. The soil of the experimental site is southern black soil with light to medium loam texture, humus content ranging from 3.17% to 3.71%, and a pH of 7.53. Crop management followed conventional practices for the Kostanay Region.

For biochemical evaluation, one tuber (weighing 50–90 g) was taken from 10 morphologically typical plants of

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each cultivar at each trial site during harvest. The selected tubers were combined into a composite sample. In the laboratory, each tuber was longitudinally cut in half, and one half from each was homogenized for analysis. The samples were processed and analyzed as described previously (Ermakov et al., 1987):

2.1. Determination of Dry Matter Content

Dry matter content (%) was determined gravimetrically. A 50 g fresh tissue sample was dried in a thermostat at 80°C for 12 hours, followed by drying at 105°C for 1 hour until constant weight. Results were expressed as a percentage.

2.2. Determination of Ascorbic Acid

Ascorbic acid was extracted directly from 10 g of tissue using a 1% HCl solution (according to I.K. Murry) and titrated with 2.6-dichlorophenolindophenol (Tillmans reagent). Results were expressed in mg per 100 g of fresh weight.

2.3. Sugar Analysis

Total sugar content was determined by Bertrand's method. A 25 g sample was used for analysis. Oligosaccharides were pre-hydrolyzed with 10% HCl. The amount of cuprous oxide precipitated corresponded to the sugar concentration. The precipitate was dissolved in ferric sulfate in the presence of sulfuric acid, where cuprous oxide was oxidized and ferric ions were reduced to ferrous ions. These were titrated with a standardized potassium permanganate solution. Results were expressed as a percentage.

2.4. Determination of Total Acidity

To determine total acidity, a 25 g sample of fresh tissue was homogenized in 250 ml of hot distilled water and filtered. A 10 ml aliquot was titrated with 0.1 N alkali in the presence of a phenolphthalein indicator. Results were expressed as a percentage and recalculated as citric acid equivalents.

2.5. Determination of Protein Content

Protein content was measured using the Kjeldahl method (Kjeldahl, 1883). A sample of dried and ground material was digested with concentrated sulfuric acid at 420°C for 1.5 hours. Nitrogen content was determined using a VELP Scientifica UDK 159 automatic analyzer (Italy). Total protein was calculated using a nitrogen-to-protein conversion factor of 6.25 (specific for vegetables) and expressed as a percentage.

2.6. Determination of Starch

Starch content was determined using the Evers polarimetric method with an automatic polarimeter/saccharimeter SAC-I (Japan). Results were expressed as a percentage.

2.7. Determination of Pigment Content

Carotenoid pigments were extracted using 100% acetone, and their absorbance was measured with an Ultrospec II spectrophotometer at the following wavelengths (nm): 663 for chlorophyll a, 645 for chlorophyll b, 440 for total carotenoids, and 454 for β-carotene. Anthocyanins were extracted with a 1% hydrochloric acid solution, followed by spectrophotometric analysis at 510 nm, with results calculated as cyanidin-3.5-diglucoside equivalents. To correct for the presence of green pigments, optical density was also measured at 657 nm in the same extracts (Wu et al., 2006). Data are presented in mg/100 g.

2.8. Determination of Total Phenolic Content

Phenolic compounds were extracted and antioxidant activity was assessed using 80% ethanol. The total phenolic content was determined by the Folin–Ciocalteu method, as modified by Singleton and Rossi (Ainsworth & Gillespie, 2007). This method is based on the reduction of Mo^{6+} to Mo^{5+}, resulting in a blue coloration of the sample solution, which is measured spectrophotometrically at 765 nm. Results were expressed as Gallic acid equivalents (GAE) in mg GAE/g.

2.9. Determination of Total Antioxidant and Antiradical Activity

The antioxidant activity was evaluated using the free radical spectrophotometric method based on the DPPH (2.2-diphenyl-1-picrylhydrazyl; $C_{18}H_{12}N_5O_6$, M = 394.33) assay. This method involves the reaction of DPPH dissolved in ethanol with the antioxidant sample, measured at a wavelength of 515 nm. Following the neutralization phase of free radicals under standard conditions, the rate of DPPH radical oxidation was measured. Results were expressed as ascorbic acid equivalents (AAE) and as the percentage of radical scavenging activity (Pozdnyakov & Vasilenko, 2017).

2.10. Statistical Analysis

Statistical analysis of yield and biochemical data was conducted using Statistica 13 software. Data are presented as mean ± SE. The distribution type of each variable was evaluated before statistical comparison. Depending on the variable's distribution, either parametric or non-parametric statistical procedures available in Statistica 13 were applied. For selected comparisons where F-values are reported in the Results, Fisher's criterion was used. Differences were considered statistically significant at $P<0.05$. Since the statistical workflow was based on the applied parametric or non-parametric comparisons rather than on ANOVA followed by post-hoc testing, additional post-hoc tests such as Tukey's HSD or Duncan's test were not applied. Superscript letter indices in the tables indicate statistically significant differences identified by the applied statistical procedure for each trait.

3. RESULTS

Overall, the evaluated potato genotypes showed three major agronomic and biochemical trends. First, yield performance was strongly genotype- and location-dependent, with Kiru producing the highest mean yield at both trial sites. Second, Tanyusha and Travnik generally formed more tubers per plant, whereas Kiru and Olyushka were characterized by fewer but larger tubers. Third, the biochemical profile of tubers differed between the two growing regions: the Kostanay Region was generally associated with higher dry matter, starch, and protein content, while the Leningrad Region was associated with higher monosaccharide and carotenoid accumulation. Unless otherwise stated, statistically significant differences in this section are reported at $P<0.05$.

The studied potato varieties and breeding samples differed significantly in yield depending on the growing location ($P<0.05$; Table 2, Fig. 2). The highest-yielding variety at both testing sites was Kiru, producing 603–981 g of tubers per plant. In the conditions of the Kostanay Region, the breeding samples Tanyusha, Travnik, and Olyushka had yields ranging from 548 to 882 g/plant and did not differ significantly from Kiru ($P\geq0.05$). Under the conditions of the Leningrad Region, Kiru, Travnik, and Tanyusha significantly exceeded the standard variety Fioletovyi, as well as Olyushka and Udovitsky, in terms of yield ($P<0.05$; Table 2, Fig. 2). The study's findings are consistent with current research trends, which support the concept that potato yields vary substantially depending on location. This is because location influences crucial environmental factors such as temperature, water availability, and day length, as well as soil characteristics such as drainage, pH, and nutrient availability. The location also influences optimal planting dates and potato quality, but it cannot be used alone to anticipate production (Muthoni & Shimelis, 2020; Tunio et al., 2020; Piekutowska et al., 2021).

Table 2: Meteorological conditions during the active potato growth period (May–August) in the experimental regions

Region/site	Year	Mean air temperature, °C	Total precipitation, mm	Mean relative humidity, %	Main weather feature during May-August
Kostanay Region, private farm	Terra 2021	21.1	127	47.8	Hot and relatively dry season; most precipitation was concentrated in July, while May, June and August were dry
Kostanay Region, private farm	Terra 2022	18.5	173	58.7	Moderately warm and relatively humid season; precipitation was mainly concentrated in May and July
Kostanay Region, private farm	Terra 2023	19.7	214	54.2	Warm season with a hot July and high precipitation in August
Kostanay Region, private farm	Terra 2024	17.9	210	67.8	Cooler May, warm June-July, and relatively humid conditions during July-August
Leningrad Region, Pushkin Laboratories	VIR 2022	17.0	262	71.8	Warm and humid season; August had the highest precipitation
Leningrad Region, Pushkin Laboratories	VIR 2023	16.9	209	67.4	Moderately warm season with high precipitation in July
Leningrad Region, Pushkin Laboratories	VIR 2024	17.9	334	74.6	Warm and very humid season; precipitation was particularly high in July and August

Note: Mean air temperature and mean relative humidity were calculated as day-weighted means for May–August. Total precipitation was calculated as the cumulative precipitation for the same period.

The highest marketability in both trial locations was also observed in the Kiru variety, reaching 90–100%. Under the conditions of the Kostanay Region, the breeding samples Tanyusha and Olyushka also demonstrated high marketable yields (93–99%), whereas the marketability of Travnik varied considerably (Table 2). In the Leningrad Region, the marketability of all tested potato genotypes - except Kiru - was relatively low, ranging from 44.9 to 87.7%.

In the Kostanay Region, the Kiru and Olyushka breeding samples produced relatively few tubers—on average 5–8 per plant—with an average weight ranging from 66 to 154 g. In contrast, Travnik and Tanyusha formed 12–18 tubers per plant, but these were smaller, with an average weight of 44 to 59 g (Table 2, Fig. 3 and 4).

Under the growing conditions of the Leningrad Region, a similar trend was observed: the breeding samples Kiru and Olyushka produced a relatively small number of tubers per plant (6 to 12), while the genotypes Tanyusha and Travnik formed a greater number of tubers, ranging from 12 to 28 (Table 2, Fig. 3). However, the average tuber weight of Kiru and Olyushka in the Leningrad Region was 1.5–2 times lower than that observed under the conditions of the

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Kostanay Region. In the Leningrad Region, the tubers of Travnik and Tanyusha were just as small as in the Kostanay Region, with an average weight of 28–47 g. For the Udovitsky and Fioletovyi varieties, the number of tubers ranged from 5 to 15 per plant, with an average weight of 29–60 g (Table 2, Fig. 3, 4). The results align with the fact that for the majority of commercial agricultural markets, crop marketability is largely determined by quality rather than quantity.

Table 3: Yield and yield structure of potato varieties under the conditions of the Kostanay Region (KR) and Leningrad Region (LR)

Selection sample	Yield, g/plant	Number of tubers per plant, pcs.	Average tuber weight, g	Marketable yield, %
Kiru (KR)	777.25 ± 75.60	5.7 ± 0.30	135.97 ± 9.52	100.00
Tanyusha (KR)	687.00 ± 9.63	13.3 ± 0.80	52.2 ± 3.25	94.58 ± 1.27
Travnik (KR)	734.75 ± 54.37	14.85 ± 0.58	49.4 ± 2.69	72.42 ± 21.81
Olyushka (KR)	728.50 ± 76.90	8.77 ± 0.49	83.15 ± 8.00	97.12 ± 1.36
Kiru (LR)	884.95 ± 96.55	9.8 ± 0.20	90.52 ± 11.68	92.45 ± 1.45
Tanyusha (LR)	678.53 ± 72.96	17.98 ± 2.07	38.12 ± 2.19	68.26 ± 3.68
Travnik (LR)	660.37 ± 63.29	16.61 ± 0.98	39.30 ± 1.72	71.01 ± 3.32
Olyushka (LR)	428.03 ± 73.29	9.57 ± 1.48	44.49 ± 1.67	74.06 ± 2.72
Fioletovyi (LR)	368.90 ± 39.34	9.61 ± 1.16	39.49 ± 3.33	63.36 ± 5.39
Udovitsky (LR)	285.7 ± 58.1	6.06 ± 0.97	46.51 ± 2.30	79.43 ± 1.62

Values (mean ± SE) bearing superscript letter indices indicate statistically significant differences within the same trait according to the applied parametric or non-parametric statistical procedure at P<0.05.

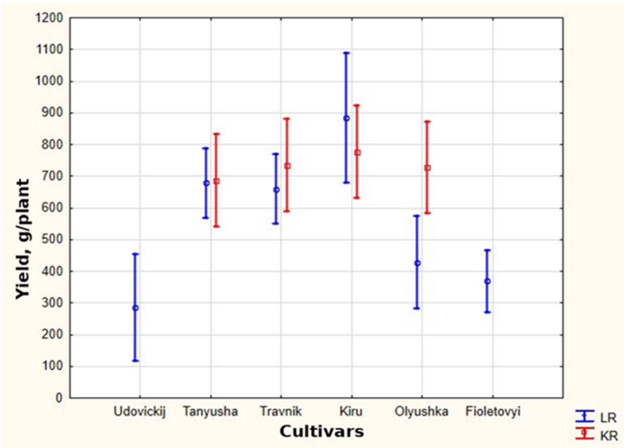

Fig. 2: Yield of pigmented-flesh potato varieties and breeding samples grown in the Kostanay Region (KR) and Leningrad Region (LR). Values are presented as means ± SE; vertical bars indicate SE.

The value of a crop and a farmer's profitability are essentially determined by whether the produce satisfies certain quality standards demanded by buyers and consumers, even though high yields are crucial for overall production volume (Kubiak et al., 2022; Gazzea et al., 2023). According to the results and in alignment with other studies, it can be stated that the weight of potato crops is a crucial component in determining the marketability of potato crops (Tessema et al., 2020; Larkin et al., 2021; Asnake et al. 2023). Certain genotypes performed consistently even in the variable conditions, while others performed more variably. Olyushka in Kazakhstan had comparatively high yield, low starch, and vitamin C in both years, while purple clones consistently had low yield. This result is similar to the study conducted in Kazakhstan, where Kura and Olyushka produced a high marketable yield in Kostanay conditions. Broader surveys show similar trends; in Russia, Solovyeva et al. (2024) found that the tuber composition of cultivar "Sokur" was among the most stable across regions and that it consistently had very high dry matter and protein content everywhere.

When combined, these findings imply that some varieties with colored flesh are trait-robust in various settings. Similar to how Sokur was stable in Russia, Olyushka's combination of a respectable yield and high vitamin C was stable in our trials. Such stability is important, as Sokur was a promising candidate for widespread cultivation due to its consistently high dry matter in both central and northwest Russia. In Kazakh and Russian trials, varieties such as Olyushka, Kura, and Travnik consistently demonstrated genotype-specific strengths (yield, antioxidants, or starch content) under different conditions, indicating their suitability for those particular agroclimatic zones.

Table 3: Nutrient content in the tubers of colored-flesh potato varieties grown under the conditions of the Kostanay Region (KR) and the Leningrad Region (LR)

Selection sample	Dry matter, %	Starch, %	Protein, %	Total sugars, %	Monosaccharides, %	Total acidity, %
Kiru KR	21.46 ± 0.14^b	15.49 ± 0.31	1.92 ± 0.09	0.52 ± 0.33	0.24 ± 0.15	0.30 ± 0.01^b
Kiru LR	20.48 ± 1.08^b	14.17 ± 0.60	1.60 ± 0.23	1.03 ± 0.04	0.65 ± 0.24	0.25 ± 0.01^b
Tanyusha KR	26.24 ± 0.48	17.56 ± 0.10	2.82 ± 0.59	0.78 ± 0.51	0.31 ± 0.18	0.28 ± 0.01^b
Tanyusha LR	21.11 ± 0.66	13.91 ± 0.91	1.82 ± 0.04	1.19 ± 0.18	0.98 ± 0.05	0.27 ± 0.01^b
Travnik KR	26.44 ± 0.52^a	18.45 ± 0.74	2.71 ± 0.35	0.76 ± 0.22	0.29 ± 0.14	0.29 ± 0.01^b
Travnik LR	23.20 ± 0.27^a	14.85 ± 0.64	1.97 ± 0.07	1.16 ± 0.21	0.80 ± 0.04	0.28 ± 0.01^b
Olyushka KR	23.02 ± 1.62	15.63 ± 0.78	2.26 ± 0.22	0.76 ± 0.39	0.30 ± 0.18	0.29 ± 0.03^b
Olyushka LR	20.43 ± 0.37	14.16 ± 0.16	1.63 ± 0.14	1.07 ± 0.07	0.68 ± 0.06	0.23 ± 0.01^b
Udovitsky KR	19.88 ± 0.00^b	12.07 ± 0.00	2.51 ± 0.00	0.23 ± 0.00	0.09 ± 0.00	0.41 ± 0.00^a
Udovitsky LR	19.97 ± 1.34^b	13.36 ± 0.99	1.49 ± 0.01	0.99 ± 0.05	0.88 ± 0.07	0.33 ± 0.01^a

Values (mean ± SE) bearing superscript letter indices indicate statistically significant differences within the same trait according to the applied parametric or non-parametric statistical procedure at P<0.05.

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Table 4: Content of Biologically Active Compounds in Colored Potato Tubers Grown under the Conditions of the Kostanay Region (KR) and the Leningrad Region (LR)

Selection sample	Ascorbic acid, mg/100 g	Carotenoids, mg/100 g	Beta-carotene, mg/100 g	Anthocyanins, mg/100 g	Chlorophyll A, mg/100 g	Chlorophyll B, mg/100 g	Phenolic compounds, mg GAE/100 g	AOC, mg AAE/100 g	DPPH, %
Kiru KR	20.14 ± 0.34	0.15 ± 0.01^{a}	0.02 ± 0.00^{b}	15.20 ± 12.61^{b}	0.06 ± 0.03	0.03 ± 0.03	32.38 ± 13.02	26.23 ± 6.98^{b}	14.22 ± 1.11^{b}
Kiru LR	15.63 ± 3.90	0.32 ± 0.04^{a}	0.04 ± 0.01^{b}	39.57 ± 8.84^{b}	0.09 ± 0.01	0.15 ± 0.03	46.58 ± 18.39	31.02 ± 10.22^{b}	14.24 ± 1.28^{b}
Tanyusha KR	25.24 ± 7.76	0.36 ± 0.01^{b}	0.05 ± 0.01^{b}	43.44 ± 30.46	0.16 ± 0.16	0.06 ± 0.02	43.68 ± 10.40	23.80 ± 9.26^{b}	12.25 ± 3.0^{b}
Tanyusha LR	28.29 ± 5.93	0.64 ± 0.04^{b}	0.08 ± 0.01^{b}	44.72 ± 14.20	0.15 ± 0.05	0.18 ± 0.01	48.61 ± 9.34	30.82 ± 6.46^{b}	14.30 ± 0.92^{b}
Travnik KR	22.52 ± 3.89	0.58 ± 0.12^{b}	0.07 ± 0.03^{b}	55.17 ± 31.75	0.43 ± 0.39	0.11 ± 0.10	41.16 ± 13.58	25.34 ± 7.63^{b}	13.53 ± 1.68^{b}
Travnik LR	23.77 ± 5.37	0.51 ± 0.04^{b}	0.06 ± 0.00^{b}	57.21 ± 17.24	0.08 ± 0.02	0.13 ± 0.02	49.17 ± 7.59	31.37 ± 6.32^{b}	14.69 ± 0.80^{b}
Olyushka KR	26.16 ± 6.84	0.49 ± 0.08^{b}	0.07 ± 0.02^{a}	76.86 ± 37.72^{a}	0.58 ± 0.56	0.18 ± 0.10	47.84 ± 10.65^{a}	25.48 ± 6.59^{b}	13.75 ± 0.94^{b}
Olyushka LR	23.99 ± 7.00	0.74 ± 0.13^{b}	0.10 ± 0.02^{a}	101.43 ± 11.21^{a}	0.13 ± 0.05	0.34 ± 0.12	59.34 ± 12.51^{a}	33.09 ± 6.59^{b}	13.98 ± 0.85^{b}
Udovitsky KR	26.40 ± 0.00	0.32 ± 0.00	0.06 ± 0.00^{b}	2.91 ± 0.00^{b}	0.36 ± 0.00	0.01 ± 0.00	13.97 ± 0.00^{b}	2.82 ± 0.00^{a}	0.00 ± 0.00^{a}
Udovitsky LR	23.61 ± 1.24	0.48 ± 0.05	0.06 ± 0.01^{b}	6.94 ± 2.40^{b}	0.07 ± 0.01	0.12 ± 0.03	21.21 ± 3.56^{b}	11.59 ± 1.29^{a}	3.58 ± 0.95^{a}

Values (mean ± SE) bearing superscript letter indices indicate statistically significant differences within the same trait according to the applied parametric or non-parametric statistical procedure at P<0.05.

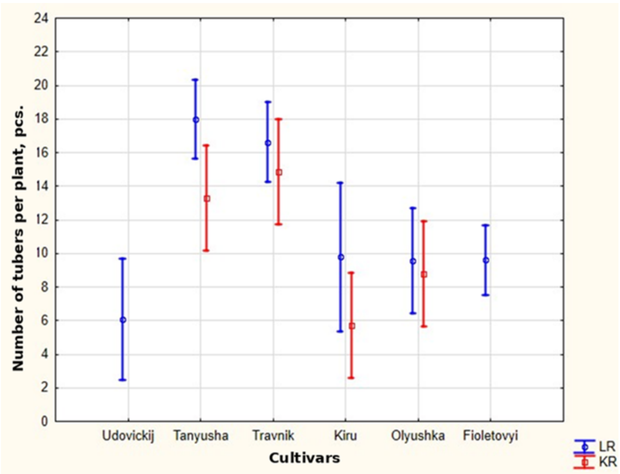

Fig. 3: Number of tubers per plant in pigmented-flesh potato varieties and breeding samples grown in the Kostanay Region (KR) and Leningrad Region (LR). Values are presented as means ± SE; vertical bars indicate SE.

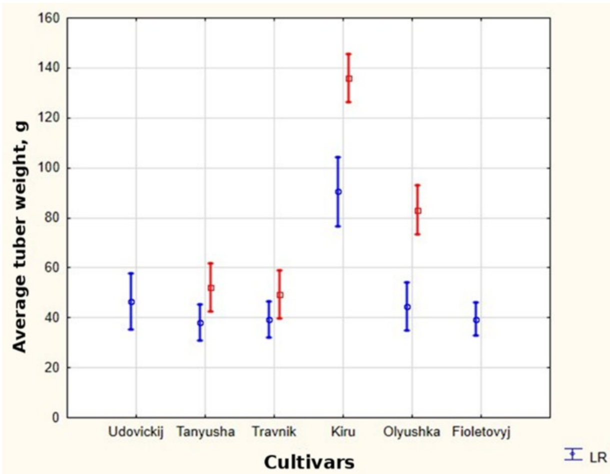

Fig. 4: Average tuber weight of pigmented-flesh potato varieties and breeding samples grown in the Kostanay Region (KR) and Leningrad Region (LR). Values are presented as means ± SE; vertical bars indicate SE.

The main biochemical pattern was the separation of nutrient-related traits and bioactive-compound traits among the studied genotypes. Travnik was distinguished by high dry matter and starch content, Udovitsky by higher total acidity, and Olyushka by the highest accumulation of anthocyanins, phenolic compounds, and antioxidant activity. In general, the pigmented-flesh Kazakh breeding materials accumulated more bioactive compounds than the light-fleshed Udovitsky cultivar (Table 3). Tables 3 and 4 present data for 15 of these parameters; the content of disaccharides (%) is not shown but was calculated as the difference between total sugars and monosaccharides. Total chlorophyll content was determined as the sum of chlorophyll A and chlorophyll B.

Thus, the previously known dependence of the biochemical parameters of potato tubers on genotype (variety) and environment (growing season conditions) has been confirmed. In our experiments, statistically significant differences among the potato accessions were observed in dry matter content, total acidity, and the content of biologically active compounds such as carotenoids, β-carotene, phenolic compounds, and anthocyanins (Table 3, 4). This is consistent with the findings of Samaniego et al. (2020), Scavo et al. (2022), and Solovyeva et al. (2024), who emphasized the significance of the genotype-environment interaction. Solovyeva et al. (2024) discovered that while the year of cultivation had a greater impact on vitamin C, carotenoids, and anthocyanins, genotype accounted for 38 – 49% of the variation in dry matter, starch, and sugars. Similar genotype differences in dry matter and starch were observed in our study; for example, Travnik consistently displayed high starch while Olyushka consistently showed lower starch, indicating strong genetic control. This aligns with Solovyeva et al. (2024), who reported that antioxidant vitamins varied with seasonal conditions, vitamin C and carotenoids exhibited greater year-to-year fluctuation. Samaniego et al. (2020) discovered that variations in potato production were caused by both growth environment and genetics. The genotype is related to more diversity in phytochemical components. They also proposed that using genetic improvement, genotypes with the highest biocompound content may be used as progenitors. Scavo et al. (2022) also stated that, for optimal farming and genetic development, once a novel genotype is offered for cultivation, the genotype x environment interaction (GEI) with the specific cultivated area should be evaluated. Anthocyanins and phenolics, on the other hand, showed notable G×E effects. It has been demonstrated that environmental elements

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like climate and altitude have a significant impact on tuber pigment levels. According to reports, pigmented potato anthocyanins rise in high-altitude locations and drastically decrease during drought stress (Liu et al., 2023; Wu and Xiao, 2024). Only in the more favorable environment did colored varieties, such as purple-fleshed clones, accumulate particularly high anthocyanin and phenolic content in this study, suggesting genotype-specific site sensitivity. These results are consistent with reports by Mattoo et al. (2022) that purple potatoes' anthocyanin levels can be significantly lowered by heat or drought. Similar to other multi-environment trials, this study's polysaccharide/phenolic antioxidant activity was genotype-dependent, with pigmented cultivars continuously having higher levels of DPPH and FRAP than white tubers.

3.1. Dry Matter

The primary indicator of potato quality and nutritional value is its chemical composition, particularly the content of key nutrients. The cumulative concentration of these elements is reflected in the "dry matter" parameter. Dry matter content is a varietal trait that can vary significantly depending on the growing conditions, with a reported range of 13–37%. In our study, the breeding samples Travnik, Tanyusha, and Olyushka showed higher dry matter accumulation compared to Kiru and Udovitsky. The sample Travnik had a significantly higher dry matter content (23.2–26.4%) than Kiru and Udovitsky (Table 3).

3.2. Starch

The value of potatoes as a food product is primarily determined by their starch content, which typically constitutes about 70–80% of the dry matter. The relationship between dry matter and starch is relatively constant in potatoes and follows a general rule: the higher the dry matter content, the higher the starch content. On average, edible potato varieties contain 16–20% starch (Burgos et al., 2020). In our study, starch content in the tested varieties ranged from 12.07% to 18.45%. Low starch content (12.07–13.36%) was recorded in the Udovitsky variety. In the colored potato varieties, depending on the cultivation site, starch levels were average to above average (Table 3). While the correlation between high dry matter content and high starch content was observed, no statistically significant differences among the accessions were found for this trait (Table 3).

3.3. Sugars

Sugars in potatoes are mainly represented by glucose (approximately 65% of total sugars), fructose (5%), and sucrose (30%). Maltose is present in minor quantities, typically during sprouting. In addition to free sugars, potatoes also contain sugar phosphates such as glucose-1-phosphate and fructose-6-phosphate. Mature potato tubers generally contain low levels of sugars (0.5–1.5%). In our study, the total sugar content ranged from 0.23% to 1.19%, and the monosaccharide content from 0.09% to 0.98% (Table 3).

3.4. Crude Protein

Nitrogen-containing compounds in potatoes account for 1.5–2.5% of tuber mass, with a substantial portion being proteins. The amount of protein nitrogen in tubers is 1.5 to 2 times higher than non-protein nitrogen. The crude protein content in cultivated potato varieties averages 1.76–2.95% on a fresh weight basis (Burgos et al. 2020). In our study, the protein content among the tested varieties ranged from 1.63% to 2.82%, with no statistically significant differences between samples (Table 3).

3.5. Ascorbic Acid

Potato tubers contain several vitamins, including B1 (thiamine), B2 (riboflavin), B3 (pantothenic acid), B6 (pyridoxine), B9 (folic acid), PP (niacin), and, predominantly, vitamin C (ascorbic acid – AA), which plays a key role in the nutritional value of the crop. AA is known for its moderate reducing potential and the low reactivity of its radical form, making it an effective primary antioxidant. The highest vitamin C levels in tubers are typically observed shortly after tuber initiation, during the period of rapid growth, and decline as the tubers reach physiological maturity. In our study, AA content in tubers ranged from 15.63 to 28.29 mg/100 g. However, differences among the varieties were not statistically significant (Table 4). The breeding sample Tanyusha demonstrated the highest AA levels, ranging from 25.24 to 28.29 mg/100 g.

3.6. Total (Titratable) Acidity

Organic acids in plants are present in free form or as acidic and neutral salts. The accumulation of particular acids is closely linked to the overall transformation of organic acids during plant development, to the type of metabolism, and its dependence on environmental conditions. Organic acids determine the acidity of potato cell sap. The pH (active acidity) of potatoes typically ranges from 5.6 to 6.2. Potato tubers contain citric, malic, oxalic, isocitric, lactic, pyruvic, tartaric, chlorogenic, quinic, and other acids. Potatoes are especially rich in citric and malic acids. The total

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titratable acidity of potatoes is also influenced by the presence of acidic phosphates.

In our study, we measured titratable acidity, which reflects the total amount of free acids and acid salts. In the tested potato varieties, titratable acidity ranged from 0.23% to 0.41% (expressed as citric acid equivalents). The variety Udovitsky demonstrated significantly higher total acidity (0.33–0.41%) compared to the pigmented-flesh varieties (Table 3).

3.7. Pigments

The plant pigment complex is a dynamic system that responds sensitively to environmental changes within the genetically determined framework. Potato tubers generally contain two major classes of pigments: carotenoids and anthocyanins; however, following light exposure, a third class: chlorophylls - can also accumulate. Since tuber color is an important varietal trait, these pigment classes are discussed in greater detail.

3.8. Potato Carotenoids

Potato carotenoids are mainly xanthophylls, whose ester forms account for more than 60% of the total carotenoid content (Sturaro, 2025). Beta-carotene, an isomer of carotene and a provitamin A, is nutritionally important but is a minor component in most potato varieties, comprising 2–3%, and in some cases up to 5–12% of total carotenoids (Lachman et al., 2016). Among most cultivated varieties, carotenoid content varies from 0.027 to 0.511 mg/100 g (Sturaro, 2025). In yellow-fleshed varieties, carotenoid content typically ranges from 0.100 to 0.350 mg/100 g and can reach up to 0.700 mg/100 g in intensely yellow varieties (Lachman et al. 2016). In our study, carotenoid levels in the examined cultivars and breeding lines ranged from 0.15 to 0.74 mg/100 g. The breeding lines Tanyusha, Travnik, and Olyushka showed significantly higher carotenoid content than the cultivar Kiru (Table 4). In terms of β-carotene content, the line Olyushka significantly outperformed all other genotypes (Table 4).

Greening of potato tubers, resulting from chlorophyll formation (a class of plastid pigments) due to light exposure, is common and typically accompanied by the synthesis of toxic glycoalkaloids such as solanine and chaconine (Burton, 1989), making green-colored tubers unsuitable for consumption. Nonetheless, small amounts of chlorophylls can be present in both the flesh and skin of tubers. In our study, chlorophyll content ranged from trace amounts to 0.76 mg/100 g, with no statistically significant differences observed among the potato genotypes.

3.9. Anthocyanins

Anthocyanins are the primary group of pigments found in pigmented-flesh potato tubers. These are vacuolar pigments responsible for red, purple, or deep pink flesh coloration in the skin or flesh of the tuber, often masking the colors produced by carotenoids. The total anthocyanin content in purple-fleshed potato tubers ranges from 63 to 588 mg/100 g fresh weight (Burgos et al., 2013). Anthocyanins are present in the cell sap as glycosides, which, upon hydrolysis, break down into glucose, galactose, rhamnose, and the colored aglycones - anthocyanidins. Although anthocyanins belong to the flavonoid class, most other flavonoids are typically colorless or yellow. The color and distribution of anthocyanin pigmentation across different plant parts are key varietal identification traits in potatoes. The skin may be fully or partially pigmented, and the flesh may be entirely colored or show varying pigment distribution. The color of sprouts developing under natural diffused light also varies by cultivar (Burton, 1989). In our study, we examined varieties and samples with purple or red skin and various flesh pigmentation (Table 1). Anthocyanin content in the studied tubers ranged from 2.91–6.94 mg/100 g in the Udovitsky variety to 76.86–101.43 mg/100 g in the Olyushka breeding sample. The latter showed significantly higher anthocyanin content than the Kiru variety and did not differ significantly from the breeding samples Tanyusha and Travnik (Table 4). Quantitatively, our anthocyanin levels are in line with recent reports. Colored potatoes have been found to reach up to 1200 mg/kg in tubers, and indeed we observed very high anthocyanin content in our darkest-fleshed genotypes. These values far exceed those of yellow or light colored varieties, which typically show only ~1–2 mg/kg. Our results that dark colored clones accumulated a large quantity of anthocyanins are thus consistent with Kim et al. (2025) findings.

3.10. Phenolic Compounds

Phenolic compounds are a diverse group of molecules containing one or more aromatic (benzene) rings bearing one or more hydroxyl groups. Their synthesis is characteristic of plant cells, which are capable of producing tens of thousands of such compounds. The variation in their chemical structure arises from biosynthetic modifications and chemical reactions such as hydroxylation, glycosylation, and the formation of esters and glycosides. The antioxidant activity of phenolics is based on their ability to donate an electron and a proton, forming relatively stable phenoxyl radicals capable of delocalizing the unpaired electron. Phenolic compounds are secondary plant metabolites, with phenolic acids - primarily chlorogenic acid - accounting for up to 90% of the total phenolic content in potatoes (Kim et al., 2019). Overall, potato tubers contain 22.53–85.85 mg GAE/100 g of polyphenols, with significantly higher concentrations found in the peel than in the flesh; in purple-colored varieties, levels can reach up to 209 mg GAE/100

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g (Rasheed et al., 2022). In our study, the total soluble phenolic content ranged from 13.97 to 59.34 mg GAE/100 g fresh weight. The highest accumulation was observed in the Olyushka breeding sample, which significantly exceeded the Udovitsky variety in phenolic content (Table 4).

3.11. Antioxidant Activity (AOA)

In recent years, there has been growing interest in the antioxidant activity (AOA) of potatoes, with particularly high values observed in cultivars with pigmented tuber flesh. The main groups of antioxidant compounds present in potato tubers include carotenoids, vitamin E, vitamin C, and phenolic compounds such as phenolic acids and anthocyanins (Polivanova & Gins, 2019). These compounds help prevent oxidative stress by interrupting the chain reactions of free radical formation, the accumulation of which exacerbates the progression of many diseases and accelerates aging. The AOA of potatoes is comparable to that of tomatoes, carrots, and some leafy vegetables, although lower than that of berries. However, unlike berries, potatoes are available year-round and are consumed globally in much larger quantities, making them a potentially consistent dietary source of antioxidants (Zhevora et al., 2021). Many studies have shown that the antioxidant activity of potato peel is 2–3 times higher than that of the flesh (Zhevora et al., 2021). Additionally, environmental stress during cultivation can increase the antioxidant content in tubers.

In our study, significant differences in AOA levels were observed among the examined potato samples, ranging from 2.82 mg AAE per 100 g in the Udovitsky variety (red skin, yellow flesh) to 33.09 mg AAE/100 g in the Olyushka breeding sample (red skin, deep pink flesh). The DPPH assay revealed that antioxidant levels in potatoes with red or purple flesh were several times higher than those in yellow-fleshed varieties. These findings correlate with the high content of phenolic compounds in pigmented-flesh genotypes and the low content observed in Udovitsky, thereby indirectly confirming the contribution of phenolics to overall AOA. It is worth noting that the average AOA ratio between red- and purple-fleshed groups depends on the specific varieties represented in each group (Hamouz et al., 2011). The percentage of DPPH radical scavenging ranged from 3.58% in yellow-fleshed varieties to 12–14% in pigmented potato samples (Table 4).

Our experiments confirmed the influence of environmental conditions (i.e., growing location) on the biochemical composition of the tubers. Differences between samples cultivated in the Kostanay region and the Leningrad region were observed in terms of nutritional value - including dry matter, sugars, starch, and protein content - as well as in levels of biologically active compounds such as pigments (carotenoids, anthocyanins, and chlorophyll B) and phenolics (Table 3 and 4). Colored-flesh tubers grown in the Kostanay region on alkaline black soil contained significantly higher levels of dry matter, starch, and protein, but lower levels of monosaccharides and carotenoids compared to those grown in the Leningrad region on slightly acidic loamy soils. These location-related differences were significant at $p < 0.01$ according to Fisher's criterion: $F = 7.29$, 4.37, 5.38, 7.70, and 5.44 for dry matter, starch, protein, monosaccharides, and carotenoids, respectively.

4. DISCUSSION

The results demonstrate that the Kazakh–Russian colored-flesh potato materials differed in their agronomic performance, nutritional value, and accumulation of bioactive compounds under the contrasting environments of the Kostanay and Leningrad regions. This pattern is consistent with recent studies from different potato-growing regions, which show that both yield formation and the accumulation of nutritional and bioactive compounds are strongly affected by genotype, environment, and seasonal conditions. In Ecuador, Samaniego et al. (2020) reported that environmental conditions significantly influenced the phytochemical composition of potato cultivars. In Russia, Solovyeva et al. (2024) showed that genotype had a strong effect on dry matter, starch, and sugar accumulation, whereas year and region more strongly affected vitamin C, carotenoids, and anthocyanins. Multi-environment potato studies also emphasize that genotype × environment effects should be considered when recommending new genotypes for specific cultivation regions (Scavo et al., 2022; Kwambai et al., 2023). Therefore, the contrast observed between the sharply continental conditions of Kostanay and the humid temperate conditions of the Leningrad Region agrees with recent evidence that colored-flesh potato materials require region-specific evaluation before breeding or commercial recommendation.

When grown in the Leningrad Region, the Kazakh breeding materials Kiru, Olyushka, Travnik, and Tanyusha exceeded the regional variety Fioletovyi in several indicators of nutritional value and bioactive compound accumulation. The focus on four colored-flesh genotypes was intentional and reflected the available core set of Kazakh pigmented breeding materials introduced for comparative evaluation at VIR. These genotypes also represented contrasting and breeding-relevant features: Kiru has purple skin and flesh, Travnik and Tanyusha have red skin and flesh, and Olyushka has red skin and deep-pink flesh. In addition, they differed in pedigree and maturity, with Kiru and Travnik originating as seedlings of the Stepan variety, whereas Tanyusha and Olyushka originated from spontaneous mutagenesis. Thus, although the number of colored genotypes was limited, the selected set was

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suitable for an initial comparative assessment of agronomic performance, biochemical composition, and regional adaptation.

Based on multi-year studies, the tubers of the Fioletovy variety grown at the experimental site of the Pushkin Laboratories of the N.I. Vavilov Institute (VIR) contained 19.7% dry matter, 12.7% starch, 1.99% protein, 0.49% sugars, 16.3 mg/100 g vitamin C, 0.47 mg/100 g carotenoids, and 102 mg/100 g anthocyanins (Solovyeva et al., 2024). Compared to Fioletovy, all tested Kazakh breeding samples with pigmented flesh had higher contents of dry matter, starch, and sugars; the samples Olyushka, Travnik, and Tanyusha contained 1.5 times more vitamin C and elevated carotenoid levels. The anthocyanin content in Olyushka was comparable to that of Fioletovy. Fioletovy is a mid-late maturity variety recommended for cultivation in the Northwestern and Central regions of Russia. When grown in the Moscow region (Central Federal District), tubers of Fioletovy also exhibited relatively low dry matter content (13.9–15.9%), although protein and vitamin C levels increased to 3.2–3.9% and 24.2–25.8 mg/100 g, respectively (Simakov et al., 2020). In the Leningrad region, this variety may not have had sufficient time to form a high-quality tuber yield due to its longer vegetation period. The breeding samples Travnik and Tanyusha significantly outperformed the regional variety Fioletovy in yield and were characterized by high nutritional value and a complex of bioactive compounds in tubers, making them recommended for cultivation under the conditions of the Leningrad region.

Soil and climatic conditions during the growing season have a substantial impact on the nutritional quality and content of biologically active compounds in potato tubers (Solovyeva et al., 2024). In our study, colored-flesh varieties and breeding samples showed a wide range of variation in sugar, chlorophyll, phenolic compound, and anthocyanin content: depending on the location and year of harvest, the coefficient of variation ranged from 41.5% to 78.8%. The accumulation of dry matter, monosaccharides, starch, protein, and carotenoids showed genotype-specific responses to the growing environment, indicating that these biochemical traits in colored-flesh potatoes are determined by both the genetic background of the cultivar and local cultivation conditions.

A more detailed interpretation of these results shows that the genotype × environment response was trait-specific rather than uniform across all parameters. Nutrient-related traits, especially dry matter and starch, showed a relatively stable genotype ranking: Travnik maintained high dry matter and starch content, whereas Kiru showed lower values for these traits under the same growing conditions. In contrast, bioactive compounds and sugar-related traits were more responsive to the growing region. Tubers grown in the Kostanay Region generally accumulated more dry matter, starch, and protein, whereas those grown in the Leningrad Region showed higher monosaccharide and carotenoid contents. This indicates that the same genotype may express different quality advantages depending on the target environment. The comparison of the closely related Tanyusha and Olyushka materials is especially informative, because these genotypes differed in yield components and β-carotene accumulation under the Leningrad conditions, despite their related origin. Therefore, the observed genotype × environment pattern is relevant for breeding not only as evidence of environmental variability, but also as a practical basis for regional recommendations: Travnik is valuable for stable dry matter and starch accumulation, Olyushka for bioactive compound enrichment, and Kiru for yield performance across contrasting environments.

The effect of genotype was particularly evident in the two closely related samples, Tanyusha and Olyushka (Table 1). When grown in the Leningrad region, these lines showed significant differences in yield, number of tubers, and β-carotene content (Table 2, 4; Fig. 2, 3). Varieties with a stable biochemical composition across different environments are of particular interest to consumers. In our experiments, the nutritional value of Kiru tubers (dry matter and starch content) and the levels of carotenoids and phenolic compounds in the Travnik sample remained relatively stable under contrasting soil and climatic conditions.

Between 2021 and 2024, the varietal specificity of tuber chemical composition as a response to growing conditions was observed in colored potato genotypes grown in the Kostanay region. In both years, high air temperatures and a lack of precipitation were recorded in August during the tuber bulking period. Under these conditions, the ranking order of the three genotypes: Tanyusha, Travnik, and Kiru — in terms of dry matter and starch content remained consistent. The highest dry matter content (26.9 and 24.5%) and starch content (19.2–15.9%) were recorded in the breeding line Travnik. The lowest dry matter (21.3 and 21.5%) and starch content (15.8–14.9%) among these three samples were found in the variety Kiru.

A distinctive feature of the breeding sample Olyushka is its highest anthocyanin content among all studied potato genotypes. The tubers of Olyushka have pink-colored flesh, similar to the breeding samples Tanyusha and Travnik. However, in terms of anthocyanin concentration, Olyushka significantly exceeded both of them (Fig. 1, Table 4). Further investigation into the anthocyanin composition in colored-flesh potato cultivars is of particular interest. Under the environmental conditions of the Kostanay region, the Olyushka breeding sample showed the highest levels of bioactive compounds, including carotenoids (especially beta-carotene), phenolic compounds, and anthocyanins. No statistically significant differences in yield were observed between Olyushka and the other two newly developed colored potato genotypes compared to the Kiru variety when cultivated in the Kostanay region. Thus, the Olyushka breeding sample appears to be the most promising candidate for cultivation and application in functional and dietary nutrition. The observed accumulation of anthocyanins, carotenoids, and phenolic compounds can also be interpreted in light of recent molecular studies on pigmented potato tubers. Multi-omics analyses have shown that differences between red, purple, yellow, and light-colored potato flesh are associated with the regulation of anthocyanin- and carotenoid-related pathways, including genes involved in flavonoid hydroxylation and carotenoid biosynthesis such as F3′5′H, BCH2, ZEP, NCED1, and CCD1 (Zhang et al., 2023). Recent transcriptomic and metabolomic studies further indicate that environmental factors, including altitude and stress conditions, can modify flavonoid accumulation in potato tubers (Liu et al., 2023; Wu and Xiao, 2024). From a breeding perspective, this suggests that Olyushka may be used as a donor of high anthocyanin, phenolic, and antioxidant potential, while Travnik and Tanyusha may be valuable for combining acceptable yield with stable nutritional quality. From a functional food perspective, these materials are relevant because they combine the dietary role of potato as a staple crop with naturally increased levels of antioxidant compounds and pigments that may be used in fresh consumption, dietary products, and natural colorant-oriented breeding.

The focused evaluation of four Kazakh colored-flesh genotypes made it possible to identify clear genotype-specific strengths under contrasting environments: Kiru for yield performance, Travnik for dry matter and starch accumulation, and Olyushka for anthocyanins, phenolic compounds, carotenoids, and antioxidant activity. These results provide a practical basis for further regional breeding work and for selecting parental material according to the target trait and intended end use.

Furthermore, the genetic basis for observed traits is still unknown due to the lack of molecular analysis; this gap could be filled by combining transcriptomics and genomics to find important regulatory genes. Furthermore, some G×E patterns may be explained by unmeasured variables like soil moisture or nutrient levels, suggesting future factorial experiments to analyze management effects. However, the focus on raw tubers alone raises questions about how processing and storage affect nutritional quality. Longer-term trials are necessary to fully capture climate impacts, even though the three-year dataset may still reflect unique seasonal conditions. Building on these limitations, future directions should include expanded testing across diverse sites and years, coupled with molecular profiling to enable marker-assisted breeding. Research should also evaluate additional quality traits and post-harvest stability, deliberately test cultivars under controlled abiotic stresses to quantify biochemical responses, and use advanced statistical analyses to inform breeding strategies for developing resilient, high-nutrient colored potatoes (Kwambai et al., 2023).

5. CONCLUSION

The evaluation of Kazakh–Russian colored-flesh potato materials under the contrasting conditions of the Kostanay and Leningrad regions revealed clear genotype-specific advantages in yield performance, nutritional quality, and accumulation of bioactive compounds. Kiru was distinguished by high yield potential, Travnik and Tanyusha combined good productivity with valuable nutritional traits under the conditions of the Leningrad Region, and Olyushka showed the strongest potential for bioactive compound accumulation under the conditions of the Kostanay Region. For breeding programs, Olyushka may be considered a promising donor of anthocyanins, phenolic compounds, carotenoids, and antioxidant activity, Travnik may be useful for improving dry matter and starch-related quality traits, and Kiru may serve as a source of high yield performance. For growers, Travnik and Tanyusha are promising materials for further cultivation testing in northwestern Russia, whereas Olyushka is recommended for further evaluation in northern Kazakhstan, especially for the development of colored-flesh potato products with enhanced nutritional value. Future research should include wider multi-location and multi-year testing, detailed profiling of individual anthocyanins, carotenoids, and phenolic compounds, and evaluation of storage and processing effects on the nutritional quality of colored-flesh potato tubers.

Declarations

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Data Availability: Data will be available upon request.

Ethics Statement: This study involved potato plant material only and did not involve human participants, animals, or any endangered or protected species. Therefore, approval by an ethics committee was not required. All field and laboratory work were conducted in accordance with institutional guidelines and national regulations applicable to plant research.

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