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Agrobiological assessment of productivity and nitrogen fixation of vegetable soybean (edamame) in the conditions of Forest-Steppe of Ukraine

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Abstract Agrobiological evaluation of vegetable soybean cultivars (*Glycine max* var. *Shirofumi*) according to a complex of economically valuable traits for introduction in the conditions of the Forest-Steppe of Ukraine it was carried out with the aim of selecting the source material and selecting promising breeding forms according to morpho-biological and physiological-biochemical characteristics. The research was conducted in the conditions of the educational and production department of Uman National University of Horticulture during 2020–2022, collection cultivars of different ecological and geographical origins were used. The cultivars 'Sac' (166.00 g plant^{-1}), 'Vesta' (139.33 g plant^{-1}), 'Fiskeby V' (133.33 g plant^{-1}), and 'Fiskeby V-E5' (146.67 g plant^{-1}) possessed a large mass of edamame beans. The maximum yield of edamame beans was formed by plants of the 'L 380-2-13' (12.67 t ha^{-1}), 'Vesta' (12.33 t ha^{-1}), 'Sac' (13.20 t ha^{-1}), 'Fiskeby V' (13.97 t ha^{-1}), and 'Fiskeby V-E5' (14.53 t ha^{-1}). Weather conditions during the period of research significantly influenced the yield and biochemical composition of edamame varieties. The yield of edamame beans ranged from 5.40 t ha^{-1}in 2020 (min) to 22.40 t ha^{-1} in 2021 (max), and the coefficient of variation by varieties was at the level of 19–41%. This phenomenon is explained by the minimum amount of precipitation in 2020 and the high amount in 2021, which is confirmed by the hydrothermal coefficient during the period of intensive pod growth (VII–VIII) - 2020 - 0.3; 2021 - 1.3 and 1.1 respectively for the month. The protein concentration in Edamame beans was in the range of 27.94–36.29%. A higher protein content relative to the standard was noted in one sample - 'Karikachi' - 36.29%. Minimal accumulation of oligosaccharides was noted in 'Sac' and 'Astra' cultivars, which indicates their suitability for consumption. Promising cultivars were identified by the amount of fixed nitrogen - 'Sac' (168.00 ± 4.32 kg ha^{-1}), 'Astra' (161.67 ± 2.36 kg ha^{-1}) and SybNYYSOH 6 (158.19 ± 4.56 kg ha^{-1}). The conducted regression analysis showed close relationships (from moderate to functional) between various indicators of the development and productivity of the nodulation apparatus of edamame cultivars. The evaluation of the collection cultivars of vegetable soybeans, their use according to the variability of morphological features and productivity made it possible to single out the 'Sac' among the introduced collection cultivars based on a set of valuable traits for use in the selection process to create new cultivars of vegetable soybeans.

Key words: nitrogen fixation, nutritional value, oligosaccharides, yield, protein, soluble sugars.

INTRODUCTION

Vegetable soybean (*Glycine max*), known as edamame, has a high nutritional and market value. It is a relatively new crop (Jiang et al., 2023). In the world, edamame is known by the name vegetable soybean, also common names are 'edible soybean', 'fresh green soybean', 'garden soybean', 'green soybean', 'green ripe soybean', 'green vegetable soybean', 'immature soybeans', 'large-seeded soybeans', 'beer beans', and 'vegetable soybeans' (Carneiro et al., 2021).

Vegetable soybean or edamame, which is popular in Asian nations (Zeipiņa et al., 2017), may be eaten in a variety of ways, including stews, chips (Santana et al., 2012), snacks, soups, and salads (Battistini et al., 2018). The pods are big in the consumed part (Zhang et al., 2010), and the grains are bright green with a yellow or grey hilum (Czaikoski et al., 2012), with organoleptic properties that stimulate ingestion, such as sweet seeds (Williams, 2015) and less beany taste (Islam et al., 2019); these vary throughout the development of the plant (Yu et al., 2022).

In terms of how it is grown, sowing time, fertilizer recommendations, and the need to manage pests and diseases, vegetable soybeans are comparable to conventional soybeans (Carrão-Panizzi, 2006). Nevertheless, the harvest period varies by crop; for vegetable soybeans, it occurs when the pods are 80% mature and the humidity is approximately 65% (Moseley et al., 2021). Furthermore, the appearance, food quality, and nutritional content of the vegetable soybean are used to evaluate overall quality (Li et al., 2022), characteristics that are different from those evaluated in type soybean cultivar grain soybeans.

In terms of nutritional properties, the soybean crop has high water (Ntatsi et al., 2018) and protein contents and is healthy and accessible to the population (Hendrawat et al., 2021).

As essential as the cultivars' genetic characteristics, crop management must be done in a natural way, supporting the development of healthy and rustic plants with a high production rate without using excessive agrochemicals (Penteado, 2010). Low-impact agricultural practices are an example of natural management that is used by most vegetable growers (Smiderle et al., 2009) to create high-value, well-accepted goods from alternative resources. Producing the crop in a low-impact organic production agricultural practice and as a horticulture plant benefits the producer by increasing production and grain size (Espolador et al., 2017), as well as supplying consumers with goods that meet their needs.

Whether for cultural or traditional reasons, vegetable soybeans are being slowly introduced to the menu of Europeans. The misinformation about the potential of soybean vegetables, in association with a lack of knowledge, constitutes one of the greatest difficulties of popularizing this crop, justifying the lack of information on commercial production and consumption of edamame (Anghinoni, et al., 2021). The growing demand for organic food of plant origin by the population can boost the consumption of edamame since the introduction of certain eating habits, such as vegetarianism, to the Europeans population (Polli et al., 2021), following the global trend toward healthier habits.

In soybean plants, the type of nitrogen nutrition varies depending on the growing conditions. From the point of view of biologicalization of agriculture, symbiotrophic nutrition is more profitable than autotrophic, because it improves the ecological conditions in the agrocenosis and reduces the man-made load on the soil, as well as saving production costs. For this, it is necessary to provide optimal conditions for legume-rhizobial symbiosis. Atmospheric nitrogen fixation by nodule bacteria begins approximately on the 15th–20th day after the appearance of seedlings, but at the beginning of the growing season, nitrogen fixation is slow. This process continues until the plants age, and its noticeable activity is observed in the flowering phase - the formation of beans (Yatsenko, 2021).

The purpose of the study was to conduct an agrobiological evaluation of vegetable soybean cultivars in the Forest Steppe of Ukraine (in the zone of unstable moisture) according to growth and development parameters, edamame bean and seed yield, and natural symbiotic nitrogen fixation (without additional inoculation).

MATERIAL AND METHODS

The research of varietal characteristics of vegetable soybean productivity formation was carried out in 2020–2022 in the conditions of the Right-Bank Forest Steppe of Ukraine on the experimental field of the Department of Vegetable Growing of Uman National University of Horticulture geographic coordinates according to Greenwich 48° 46′ north latitude, 30° 14′ east longitude and height above sea level 245 m in accordance with generally accepted methods (Bondarenko & Yakovenko, 2001, Ulianych et al., 2019; 2020a, 2020b, Havrilyuk et al., 2021).

The experimental design was a randomized complete block design with four replicates. The area for the sampling - 100 m². Planting was carried out by the scheme of 45×5 cm (444,000 plants ha^{-1}) of the May 5, 2020, May 22, 2021, and May 12, 2022. Early-maturing cultivars of soybean *(Glycine max)* were used for research. Harvesting took place at the technical ripeness of the beans (BBCH 81).

Biometric measurements (number of shoots, pcs per plant; number of pods per plant and number of seeds, pcs per pod) and indicators of individual productivity (weight of pods, g plant^{-1}) were carried on 100 typical plants. All measurements and records were carried out in the phase of technical ripeness of beans (BBCH 81), seed yield was determined in the BBCH 99 phase.

Basil was the predecessor. Pre-sowing treatment of seeds with inoculants was not carried out for objective assessment of natural nitrogen fixation. Fertilization was carried out according to the generally accepted technology for soybeans in the Forest Steppe of Ukraine - applied $N_{60}P_{60}K_{60}$: urea (46% nitrogen content), double superphosphate (50% phosphorus content) and potassium sulfate (50% potassium content).

The scheme of the experiment included eight collection cultivars of vegetable soybeans (Table 1).

The soil was black, puddle, heavy loam with a well-developed humus horizon (about 2.9% of humus) (Krupskiy & Polupan, 2018) (Table 2), in the deep of 40–45 cm. Soil pH was determined in water (soil to water ratio 1:1). The electrical conductivity (EC) of the soil suspension was measured using the conductivity meter. The P and K were determined by the ammonium bicarbonate-diethylenetriaminepentaacetic acid (ABDTPA) method (Ryan et al., 2001).

Air-dry soil was used for analysis. 16 samples were taken from each site, mixed to a homogeneous mass and 4 samples weighing 200 g were taken, which were then analyzed in four repetitions.

The analysis of the given data on air temperature and the amount of atmospheric precipitation during the research period was generally characterized as favourable for the growth and development of soybeans. A characteristic feature of the 2019–2020 agricultural year was the elevated temperature background, insufficient precipitation in the summer and autumn periods. The average air temperature of the agricultural year was 10.8 °C, so it was 3.4 °C higher than the long-term average. The long summer rainfall deficit was a limiting factor for the growth and development of agricultural crops (Novak & Novak, 2021). A characteristic feature of the 2020–2021 agricultural year was a favourable temperature background and a sufficient amount of precipitation. The average air temperature of the agricultural year was 9.2 °C, so it was only 0.4 °C higher than the long-term average. At the same time, in the cold period (December–March), the total increase in temperature was 1.4 °C, and in the warm period (April–September), the total decrease was 1.9°C. The total amount of precipitation for the year was 655.7 mm, which was 69 mm higher than the long-term average (data not shown) (Novak & Novak, 2022). The weather conditions of the 2021–2022 agricultural year were characterized by a significantly lower level of precipitation compared to previous years and multi-year average data, and the temperature regime was close to the multi-year average data Table 3).

Table 1. Origin of cultivars of vegetable soybeans

Number in the National Catalogue*	Cultivar	Origin
	Romantyka (standard)	Ukraine
UD0200177	Fiskeby V	Sweden
UD02200640	Karikachi	Japan
UD0201068	Astra	Russia
UD0201080	Vesta	Russia
UD0201152	SybNYYSOH 6	Russia
UD0202500	Sac	Japan
UD0202625	Fiskeby V-E5	Belarus
UKR001:02894	L 380-2-13	Ukraine

* – National Catalogue of samples of leguminous crops of the National Center of Plant Genetic Resources of Ukraine, Plant Breeding Institute named after V. Ya. Yuryev of the National Academy of Agrarian Sciences of Ukraine.

Table 2. Chemical properties of soil

Parameter	Value		
	2020	2021	2022
Organic carbon, %	2.07	2.09	1.90
Acidity (pH)	6.28	5.91	6.10
Electrical conductivity (EC) µS cm^{-1}	23.96	23.52	24.52
Extractable P (ABDTPA) mg kg^{-1}	107.07	98.24	100.69
Extractable K (ABDTPA) mg kg^{-1}	128.90	116.94	123.15
NO_3N mg kg^{-1}	61.74	61.55	68.71

Table 3. Climate chart for the study period (2020–2022), (data of the Meteorological Station 'Uman')

Moon / Year	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
	precipitation, mm											
Average (1970–2022)	38.0	34.0	36.0	41.0	52.0	81.0	68.0	49.0	61.0	43.0	43.0	40.0
2020	12.7	50.5	23.9	21.0	101.0	70.4	21.4	17.1	27.4	81.5	19.4	32.6
2021	59.7	43.2	32.4	49.9	56.4	104.7	89.8	69.9	16.2	7.0	21.2	91.2
2022	23.9	7.2	13.4	57.7	22.4	36.3	28.1	44.4	99.2	10.0	71.8	53.1
	air temperature, °C											
Average (1970–2022)	-3.4	-2.3	2.5	9.7	15.4	19.0	20.9	21.1	14.5	8.3	2.8	-1.8
2020	0.4	2.2	6.3	9.2	12.5	20.9	2.6	21.2	17.8	12.7	3.7	0.0
2021	-2.3	-3.8	2.0	7.4	14.0	19.8	23.0	20.3	13.0	7.2	4.7	-1.0
2022	-1.3	1.8	2.0	8.6	14.5	20.5	21.0	21.7	13.1	10.0	3.7	-0.4
	hydrothermal coefficient (HTC), norm - 1.0											
2020	–	–	–	–	2.6	1.1	0.3	0.3	0.5	2.1	–	–
2021	–	–	–	–	1.3	1.8	1.3	1.1	0.4	–	–	–
2022	–	–	–	–	0.5	0.6	0.4	0.7	2.5	0.3	–	–

For description of growing conditions of trees hydrothermal coefficient (HTC) has been used, it is correlation between amount of precipitation in the time period, when average day temperature exceeds +10 °C, and sum of temperature in degrees in the very same period. Hydrothermal coefficient has been calculated by applying formula of G. Selyaninov (Selyaninov, 1928):

$$HTC = \Sigma x / \Sigma t \times 10, \quad (1)$$

where Σ x and Σ t – accordingly sum of precipitations and temperatures in the period, when the temperature has not been lower than 10 °C. (HTC from 1.0 till 2.0 – humidity is sufficient; HTC > 2.0 – immoderately humid; HTC < 1.0 – insufficient humidity; HTC from 1.0 till 0.7 – dry; HTC from 0.7 till 0.4 – very dry (Čirkovs 1978).

Dry matter (DM) of green beans (%). The average DM weight (g) of the green bean after curing were measured by drying 10 randomly sampled beans in an oven with a forced hot air circulation at 70 °C until a constant weight was obtained. The percent of bean DM was calculated by taking the ratio of the dry weight to the fresh weight (FW) of the sampled beans and multiplying it by 100.

The crude proteins content (N × 6.25) of the seeds was determined by Kjeldahl nitrogen, according to the AOAC method 955.04 (Horwitz & Latimer, 2016).

Free sugar was determined using HPLC, coupled with a refractive index detector using the internal standard methodology (IS, mesostiosis) (Guimarães et al., 2013). For the food and chemical composition, three samples were analysed for each cultivar, and all analyses were performed in three replicates. All results are expressed as g 100^{-1} g FW.

The extraction of free sugars (sucrose, fructose, glucose, raffinose, and stachyose) in edamame was conducted based on the method reported by Yu et al. (2016) and Machado et al. (2020), with some adjustments. Briefly, 1.5 mL of deionized water and 0.15 g of dry powdered edamame were mixed in a 2 mL centrifuge tube. The tube was placed on a tube revolver (Shimadzu, Model Prominence 20A, Japan) and shaken for 2 hat room temperature, followed by centrifugation at 13,500 ×g for 10 min. Afterward, 750 µL acetonitrile was added to 750 µL of the supernatant for purification. The mixture was shaken atroom temperature for 10 min, and then centrifugated at 13,500 × g for 10 min. After centrifugation, 750 µL of the supernatant was filtered through a 0.2-µm membrane disc filter into a 1.5-mL HPLC vial and sugar content was determined using high-performance liquid chromatography (HPLC, 1260 Infinity II, Agilent Technologies, Santa Clara, CA, USA) equipped with are fractive index detector (RID). The Luna Omega 3 µm SUGAR column (150×4.6 mm, Phenomenex, Torrance, CA, USA) wasused to separate different sugars. The column temperature wasset at 40 °C with a flow rate of 1.0 mL min^{-1}.

The nutritional value. Proteins, fats, carbohydrates, and ash content were determined by using standard methods described in the procedures of the American Organization of Analytical Chemists (International Organization of International, AOAC International) (Horwitz & Latimer, 2016). The crude fat was determined using a Soxhlet apparatus (Behr R 106 S, Germany) with petroleum ether, according to the AOAC 920.85 methodology (Horwitz & Latimer, 2016). The content of ash was determined by burning at 600 °C to constant mass following procedures AOAS 923.03 (Horwitz & Latimer, 2016). The energy was calculated by the formula:

$$Energy, kcal = 4 \times (protein) + 4 \times (carbohydrate) + 9 \times (fat). \qquad (2)$$

Accounting for the development of the nodulation apparatus of leguminous crops was carried out in the phase of technical (harvesting) maturity of the beans: the number and mass of active nodules was determined by the method of taking a monolith (size 55×45×15 cm), then the nodules were washed; the content of legoglobin was found using the method: 1. Preparation of 0.1 M (CFB), pH = 7.2; 2. The bulbs were separated from the roots immediately before the analysis; 2 g of nodules were taken and ground with a porcelain mortar in potassium phosphate buffer (2 mL); 3. The resulting mass was transferred to cooled centrifuge tubes. Centrifugation - 20 min., number of revolutions - 7–8 thousand per minute; 4. The resulting supernatant was transferred to test tubes (10 mL); 5. Then 2.43 g of ammonium sulphate was added to the test tubes so that the degree of saturation was 40%, and the resulting mixture was mixed with a glass rod. The supernatant was placed in the refrigerator to obtain a precipitate for 3 hours; 6. The obtained sediment was separated by centrifugation for 20 minutes, the number of revolutions: 7–8 thousand per minute; the centrifuge was transferred to graduated tubes and the resulting volume was determined, then photocolorimetry was performed (wavelength - 525 nm, light filter green, cuvette thickness should be 1 cm).

The fixed-N (kg ha^{-1}) was estimated as the aboveground N (kg ha^{-1}) multiplied by Ndfa (%) at each sampling stage. Aboveground N (kg ha^{-1}) was calculated as the product of plant biomass (g), N tissue concentration (g g^{-1}), and plant density (plants ha^{-1}).

Used the natural $d^{15}N$ isotopic differences between nodulating and non-nodulating isolines, as well as the ^{15}N dilution method, for determining Ndfa. Briefly, a month before sowing, an equivalent dose of 8.7 kg N ha^{-1} of ammoniumnitrate with 99 atoms % ^{15}N ($^{15}NH^{15}{}_4$ NO_3) was applied to the soil. The Ndfa was determined as follows (Unkovich et al., 2008), herein termed as N dilution method:

$$\text{Ndfa} = \frac{\delta^{15}\text{N of soybean} - \delta^{15}\text{N of atmosphere}}{\delta^{15}\text{N soil inorganic pool} - \delta^{15}\text{N of atmosphere}} \times 100, \qquad (3)$$

where atom % ^{15}N of atmosphere is assumed as 0.3663, and the atom % ^{15}N of soil inorganic pool is a 3-parameter decay function of soil mineral N content at 30 cm depth. In all datasets, plant tissue total N and atom % ^{15}N were measured by nitrogen and carbon elemental analyser interfaced with an isotope ratio mass spectrometer.

Statistical analysis. Statistical processing of the obtained results was performed with the calculation of the arithmetic mean (X) standard deviation (SD), calculated using Microsoft Excel 2019 and Statistica, version 10. The obtained data were compared using an analysis of variance. The validity of the research and the significance of the differences between the mean values of the variables examined were evaluated by the dispersion and correlation analysis.

RESULTS

The vegetation period from germination to the onset of technical maturity varied within 73–109 days (CV = 15%), from germination to biological maturity - 92–135 days (CV = 12%). By the onset of the phase of technical ripeness, the researched varieties of vegetable soybeans were grouped as follows: 1) early-ripening varieties with a growing season of 73–80 days ('Fiskeby V', 'SybNIYSOH 6', 'Romantyka', 'Fiskeby V-E5'); 2') medium-ripe varieties with a growing season of 95–97 days ('Karikachi', 'L 380-2-13', 'Sac'); 3) late-ripening varieties with a growing season of 106–109 days ('Astra' and 'Vesta').

According to the onset of the phase of biological maturity, the researched vegetable soybean varieties were grouped as follows: 1) early-ripening varieties with a growing season of 92–95 days ('Fiskeby V', 'SybNYYSOH 6'; 2) medium-ripe varieties with a growing season of 95–97 days ('Romantyka', 'Fiskeby V-E5', 'Karikachi'); 3) late-ripening varieties with a growing season of 120–135 days ('L 380-2-13', 'Sac', 'Astra' and 'Vesta'). As a result of the research, it was found that the growth and development processes of vegetable soybean during the vegetation period differed significantly depending on the variety. Analyzing the obtained data and comparing the researched collection varieties with the standard, it can be seen that the shortest period from germination to the onset of technical ripeness of the beans was observed in the varieties 'Fiskeby V', 'SybNIYSOH 6' - 73 days, which is four days less than the standard. All other researched collection varieties of vegetable soybeans were characterized by a longer duration of this period compared to the standard by 15–29 days. The results of studies of the onset of the phase of biological maturity showed similar dynamics. Relative to the standard, 'Fiskeby V', 'SybNIYSOH 6' were earlier ripening (by 13 and 16 days), and all other varieties were later ripening by 1–27 days. During the growing season of the plants, their significant differentiation was noted, which indicates the possibility of creating a conveyor belt cultivation of green edamame beans by using varieties of different maturity groups (Fig. 1).

According to the research results, it was established that the standard cultivar 'Romantyka' and the cultivars 'Karikachi' and 'Astra' belong to the semi-determinant type of growth. Plants of 'Karikachi' and 'Astra' in the phase of technical ripeness had a larger size. Compared to the standard, their height differed by 10.7% and 11.1%. Collection cultivars 'Fiskeby V', 'L 380-2-13', 'Fiskeby V-E5', 'SybNYYSOH 6', 'Sac', and 'Vesta' belongs to the determinant type of growth, the height of which was in the range of 53.00–67.33 cm, which is less than the standard by 10.16–29.6% (Fig. 2).

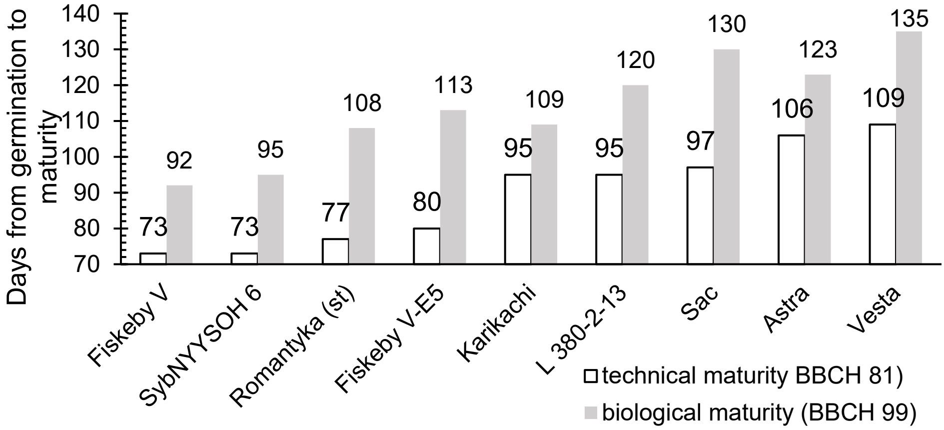

Figure 1. The duration of the periods from the emergence of seedlings to the onset of technical/biological maturity of vegetable soybean collection varieties (2020–2022).

It is known that 90–95% of the dry crop residue of cultivated plants is created due to photosynthesis, which takes place in the leaves. Considering this, the productivity of agricultural crops depends to a large extent on the dynamics of the growth of the area of plant leaves and the intensity of their work during the growing season. The area of the leaf surface and, accordingly, its index is a rather variable value, the formation of which is significantly influenced by varietal features, conditions of moisture supply, nutrition, and other technological methods of cultivation. According to the leaf area index, vegetable soybean cultivars were moderately variable - CV = 12%. The highest indicator of leaf index was formed by plants of ‘Sac’, ‘Fiskeby V-E5’, and ‘Vesta’ - 2.86–3.26, which is 16.0–32.3% higher than the standard. Plants of ‘Astra’, ‘L 380-2-13’, ‘SybNYYSOH 6’ - 2.38 formed a lower leaf index compared to the standard. 2.30 and 2.42, which is less than the standard by 1.9–6.5% (Fig. 2).

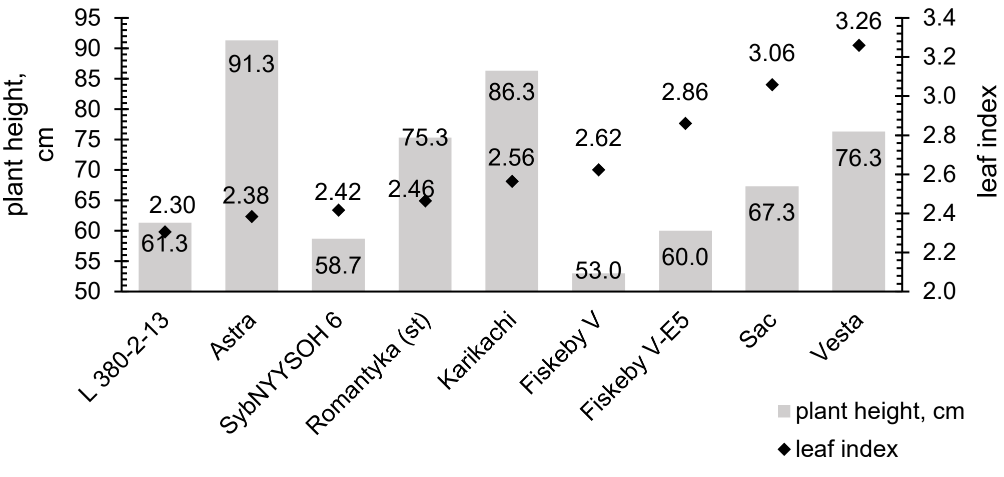

Figure 2. Plant height and leaf area index of different cultivars of vegetable soybeans, BBCH 81, (2020–2022).

According to the indicator of the number of shoots, plants of most cultivars varied significantly (CV = 25%). The maximum number of shoots was formed by plants of 'Astra' % - 2.67 and 'Vesta' - 3.23 pcs per plant, which is more than the standard by 45.5% and 76.4%, or 0.83 and 1.40 pcs per plant. According to the indicator of the number of beans per plant, 'Romantyka' significantly prevailed over the 'Fiskeby V-E5' - 53.00 pcs per plant and 'Astra' - 44.33 pcs per plant, which is 70.1% and 42.2% more. The variation of this characteristic was strong - CV = 31%. According to the indicator of the number of seeds in one pod, the cultivars were moderately variable, the coefficient of variation was 13%, but there was no clear distinction between two-seeded and three-seeded pods (Table 4).

Table 4. Formation of the number of shoots, pods, seeds in a pod and mass of pods of different vegetable soybean cultivars, BBCH 81 (2020–2022) (X ± SD)

Cultivar		Number of shoots, pcs per plant	Number of pods, pcs per plant	Number of seeds, pcs per bean	Weight of pods g plant^{-1}
Romantyka (st)		1.83 ± 0.62	31.17 ± 12.26	2.33 ± 0.47	74.33 ± 11.15
Fiskeby V		1.67 ± 0.47	23.33 ± 7.59	**3.00 ± 0.00**	**133.33 ± 27.01**
Karikachi		**2.33 ± 0.47**	22.27 ± 6.85	2.00 ± 0.00	67.67 ± 10.62
Astra		**2.67 ± 0.47**	**53.00 ± 16.31**	**3.00 ± 0.00**	71.67 ± 13.27
Vesta		**3.23 ± 0.21**	30.00 ± 13.59	2.67 ± 0.47	**139.33 ± 16.86**
SybNYYSOH 6		1.93 ± 0.74	22.00 ± 6.68	2.67 ± 0.47	75.13 ± 14.54
Sac		1.83 ± 0.62	32.00 ± 18.46	**3.00 ± 0.00**	**166.00 ± 27.86**
Fiskeby V-E5		**2.33 ± 1.25**	**44.33 ± 22.05**	2.33 ± 0.47	**146.67 ± 20.81**
L 380-2-13		**2.33 ± 1.25**	28.67 ± 6.80	2.33 ± 0.47	**118.20 ± 14.52**
Xmed.		2.24	31.86	2.59	110.26
SD		0.47	9.88	0.34	36.06
CV%		21	31	13	33
$LSD_{0.05}$		0.15	6.21	0.59	35.97
Year	2020	2.33 ± 0.82	24.78 ± 9.89	2.56 ± 0.50	94.78 ± 31.04
	2021	2.72 ± 0.67	48.59 ± 15.84	2.78 ± 0.42	129.07 ± 37.20
	2022	1.67 ± 0.82	22.22 ± 7.90	2.44 ± 0.50	99.11 ± 29.86
$LSD_{0.05}$		0.12	2.75	0.24	5.92

st – standard; * text in bold show significance at the $P \leq 0.05$ probability levels.

The commercial yield for vegetable purposes and the efficiency of growing technology in general depend on the mass of beans. The variation of this characteristic was significant, the coefficient of variation was 30%. The cultivars 'Sac', 'Vesta', 'Fiskeby V' and 'Fiskeby V-E5' were characterized by a significantly higher mass of beans - 133.33–166.00 g plant^{-1}, which is 79.4–123.3% more than the standard cultivar.

In terms of yield, the most of cultivars significantly outperformed the standard cultivar 'Romantyka', their yield ranged from 7.37 to 14.53 t ha^{-1}. The maximum yield was characterized by cultivars 'L 380-2-13' (12.67 t ha^{-1}), 'Vesta' (12.33 t ha^{-1}), 'Sac' (13.20 t ha^{-1}), 'Fiskeby V' (13.97 t ha^{-1}), and 'Fiskeby V - E5' (14.53 t ha^{-1}), which is more than the standard by 6.2–98.2%. Edamame yield variation was also strong - CV = 27%. Therefore, the yield of vegetable soybeans largely depends on varietal characteristics, which differ significantly among themselves in all indicators (Table 5).

The productivity of cultivars should be evaluated not only by the yield of marketable products, but also by the possibility of obtaining high-quality seed material. A high yield of seeds, higher than the standard, was obtained in samples ‘L 380-2-13’ (1.75 t ha^{-1}), ‘Sac’ (1.95 t ha^{-1}), ‘Vesta’ (1.79 t ha^{-1}), ‘Fiskeby V’ (2.22 t ha^{-1}) and ‘Fiskeby V-E5’ (2.46 t ha^{-1}), which exceeded the standard by 8.0–64.8%.

Our research revealed that the leaf area index is quite strongly relationships on the hydrothermal coefficient (HTC) - $r = 0.7911$ (Fig. 3, e), and the yield level of vegetable soybeans significantly depends on these two indicators. Statistical analysis of the data indicated a strong relationships of the yield level of edamame beans and seeds on the leaf index: $r = 0.8036$ and $r = 0.8105$ (Fig. 3, a and b). The analysis of the yield indicators of edamame beans and seeds indicates a strong relationships on hydrothermal conditions, where the correlation coefficient is $r = 0.7619$ and $r = 0.8625$, respectively. A significantly weaker relationship was found between the yield of edamame beans and HTC, which is explained by a rather significant variation in the accumulation of dry matter (Fig. 3, c and d). The closeness of the relationship between the productivity of vegetable soybeans and the leaf index (which in turn depends on the area of the leaves) is quite variable and significantly relationships on hydrothermal indicators. The developed statistical models make it possible to predict the yield level of edamame beans and seeds based on the index of leaf area and HTC.

Table 5. Yield of different vegetable soybean cultivars (2020–2022) (X ± SD)

Cultivar		Yield of edamame beans t ha^{-1} (BBCH 81)	Seed yield t ha^{-1} (BBCH 99)
Romantyka (st)		8.93 ± 1.69	1.34 ± 0.61
Fiskeby V		**13.97 ± 5.41**	**2.22 ± 1.00**
Karikachi		7.37 ± 2.22	1.09 ± 0.64
Astra		8.17 ± 3.24	1.44 ± 0.67
Vesta		**12.33 ± 4.91**	1.79 ± 0.78
SybNYYSOH 6		8.27 ± 2.76	1.50 ± 0.63
Sac		**13.20 ± 4.81**	**1.95 ± 0.81**
Fiskeby V-E5		**14.53 ± 5.95**	**2.46 ± 1.11**
L 380-2-13		**12.67 ± 3.68**	1.75 ± 0.80
Xmed.		11.05	1.73
SD		2.66	0.50
CV%		24	24
$LSD_{0.05}$		2.00	0.31
Year	2020	7.60 ± 1.75	1.08 ± 0.26
	2021	16.22 ± 4.36	2.82 ± 0.63
	2022	9.32 ± 2.82	1.28 ± 0.37
$LSD_{0.05}$		0.60	0.095

st – standard; * text in bold show significance at the $P \leq 0.05$ probability levels.

Sucrose was the most abundant soluble sugar in edamame and there was a marked variation in sucrose in edamame seeds presented in Table 4. In plant samples belonging to cultivars ‘Sac’, ‘Fiskeby V’, ‘Fiskeby V-E5’, and ‘Karikachi’, fructose concentration was the highest with 1, 02–1.19 mg 100 g^{-1}, which is more than the standard by 23.8–44.4%. Cultivars ‘SybNYYSOH 6’ and Astra had a slightly lower fructose content but exceeded the standard sample by 7.0–15.8%.

The concentration of glucose in all studied samples of soybean vegetable varied significantly within the range of 0.16–0.25 mg 100 g^{-1} (CV = 15%). ‘Karikachi’ and ‘Astra’ were characterised by a lower concentration than the standard by 20.0%. According to the indicators of sucrose concentration, the cultivars varied significantly by CV = 12%. Cultivars ‘Sac’ and ‘Fiskeby V-E5’ were noted for their high sucrose content – 12.77 and 12.31 mg 100 g^{-1}.

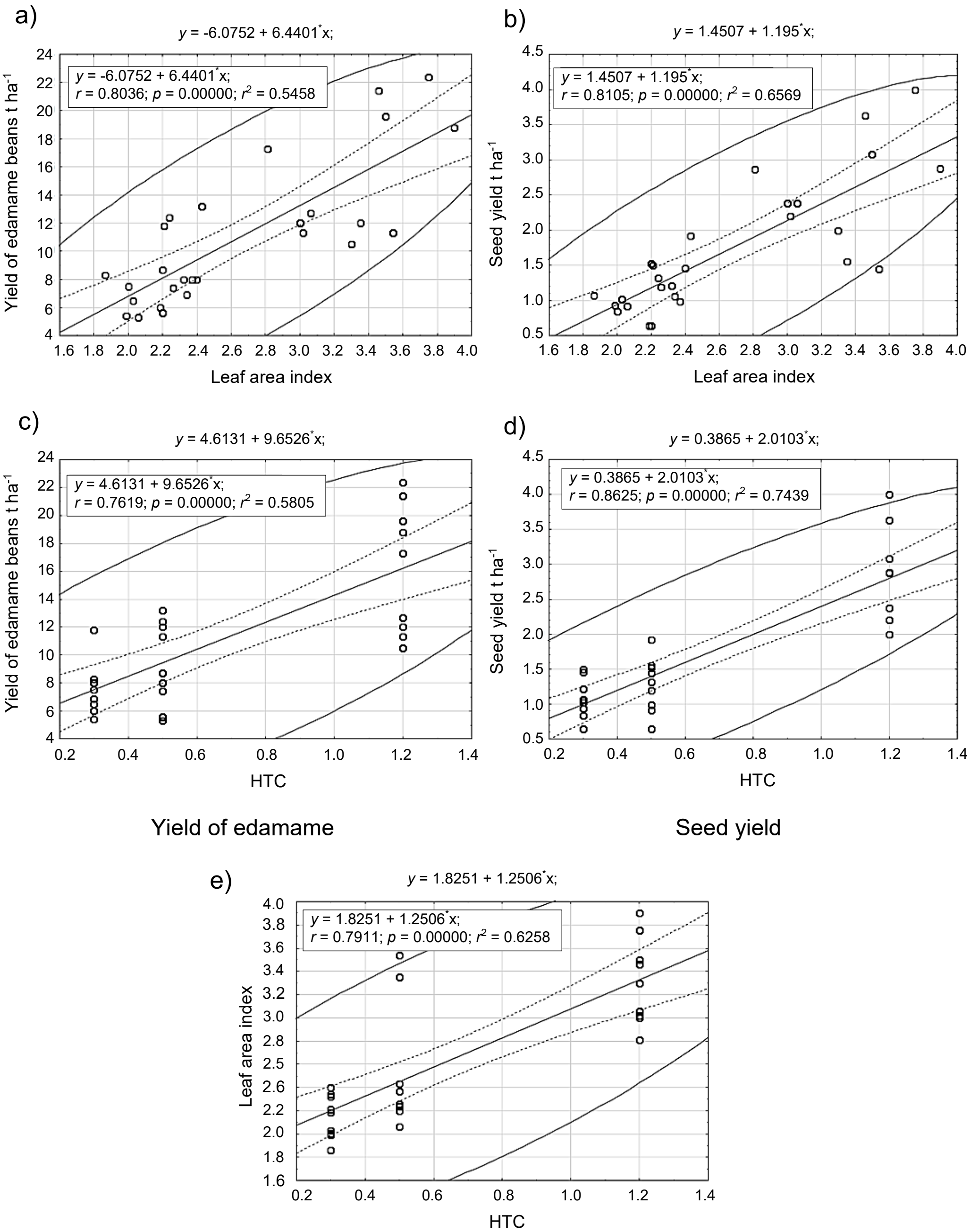

Figure 3. Dot plots and the theoretical line of regression of the relationships according to the linear correlation between the yield indicators of edamame beans (a) and vegetable soybean seeds (b) with the leaf area index and the yield of edamame beans (c) and vegetable soybean seeds (d) with the hydrothermal coefficient (HTC), and the dependence of the index of leaf area on HTC (e).

The results of the study indicate a very strong differentiation of cultivars according to all economic characteristics. The average sugar content (Table 6) in 2020 with maximum moisture supply contributed to a significant reduction in the concentration of free sugars. Raffinose and stachyose belong to the raffinose oligosaccharide (RFO) family and are also important free sugars in edamame. RFO is not digested by humans. When moving to the lower intestine, their fermentation in the intestine causes flatulence and leads to diarrhea. Hence, edamame genotypes with low RFO levels are usually preferred. A strong variation of CV = 36% was observed for the content of raffinose. The studied cultivars 'Sac', 'Astra', 'Fiskeby V-E5', and 'Fiskeby V' were characterised by the lowest concentration - 0.13–0.25 mg 100 g^{-1}. The concentration of stachyose was remarkably variable - CV = 13%. The cultivars 'Sac', 'Fiskeby V', 'L 380-2-13', 'Vesta' and 'Fiskeby V-E5' had a low content of stachyose - 0.07–0.09 mg 100 g^{-1}. The 'Sac' and 'Fiskeby V' had a high content of monosaccharides and the lowest content of oligosaccharides and 'Fiskeby V-E5', which can later be used as a source of this trait in breeding studies (Table 6).

Table 6. Content of soluble sugars in vegetable soybeans, BBCH 81 (2020–2022) (X ± SD), mg 100 g^{-1}

Cultivar		Fructose	Glucose	Saccharose	Raffinose	Stachyose
Romantyka (st)		0.83 ± 0.05	0.20 ± 0.03	11.25 ± 1.44	0.38 ± 0.05	0.10 ± 0.03
Fiskeby V		**1.10 ± 0.20**	**0.23 ± 0.02**	**12.31 ± 2.25**	0.25 ± 0.10	0.08 ± 0.01
Karikachi		1.02 ± 0.05	0.16 ± 0.01	8.98 ± 0.54	0.30 ± 0.04	0.10 ± 0.01
Astra		0.96 ± 0.05	0.16 ± 0.02	8.67 ± 0.70	**0.19 ± 0.02**	0.12 ± 0.01
Vesta		0.83 ± 0.09	0.21 ± 0.01	10.96 ± 1.17	0.43 ± 0.03	0.09 ± 0.02
SybNYYSOH 6		0.88 ± 0.07	0.20 ± 0.03	10.37 ± 1.23	0.33 ± 0.02	0.10 ± 0.01
Sac		**1.19 ± 0.05**	**0.22 ± 0.06**	**12.77 ± 4.23**	**0.13 ± 0.02**	0.07 ± 0.01
Fiskeby V-E5		1.03 ± 0.10	**0.25 ± 0.06**	11.24 ± 2.00	**0.22 ± 0.07**	0.09 ± 0.01
L 380-2-13		0.78 ± 0.07	**0.25 ± 0.03**	10.93 ± 1.11	0.48 ± 0.03	0.08 ± 0.02
Xmed.		0.96	0.21	10.83	0.30	0.09
SD		0.13	0.03	1.28	0.11	0.01
CV%		14	15	12	36	13
$LSD_{0.05}$		0.260	0.02	0.554	0.136	0.047
Year	2020	1.04 ± 0.13	0.23 ± 0.04	12.17 ± 2.00	0.29 ± 0.11	0.10 ± 0.02
	2021	0.88 ± 0.18	0.18 ± 0.04	8.54 ± 0.81	0.35 ± 0.11	0.08 ± 0.02
	2022	0.95 ± 0.18	0.21 ± 0.05	11.78 ± 1.89	0.27 ± 0.11	0.09 ± 0.01
$LSD_{0.05}$		0.055	0.011	0.59	0.021	0.005

st – standard; * text in bold show significance at the $P \leq 0.05$ probability levels.

Dry matter is the main indicator on which the energy and bioenergy efficiency of the production of any product depends, therefore, the analysis of this indicator was carried out in sufficient detail. In terms of the share of dry residue, the standard prevailed, although not significantly, the 'Karikachi' - 36.43%, the 'Astra' - 34.67% and 'SybNYYSOH 6' - 34.43% were close to the standard, all other cultivars accumulated DM at the level to 32.12%.

The study of crude protein content in immature vegetable soybean grain showed that the protein concentration of edamame beans was within 26.47–36.29%. A higher content of protein and carbohydrates relative to the standard was noted in one cultivar 'Karikachi' – 36.29% and 31.43 g 100 g^{-1} FW in the phase of technical ripeness, which is insignificantly higher than the standard cultivar. The variation of the protein content data was 11%, and the carbohydrate content was 4%, which indicates a high stability of the culture in terms of nutritional value (Table 7).

Table 7. The content indicators of the components of biochemical composition and nutritional value of edamame cultivars, BBCH 81 (X ± SD)

Cultivar	Dry matter %	Ash g 100 g^{-1} FW	Protein content %	Carbohydrates g^{-1} 100 g FW	Fat g 100 g^{-1} FW	Energy kcal 100 g^{-1} FW
Romantyka (st)	35.67 ± 2.82	5.65 ± 0.10	36.19 ± 1.54	30.51 ± 0.37	11.24 ± 0.69	368 ± 14
Fiskeby V	28.43 ± 3.90	5.66 ± 0.07	27.94 ± 0.88	28.03 ± 0.53	**14.93 ± 1.11**	358 ± 15
Karikachi	**36.43 ± 3.14**	5.64 ± 0.07	36.29 ± 1.70	31.43 ± 0.33	11.54 ± 0.69	375 ± 14
Astra	34.67 ± 2.81	5.49 ± 0.03	34.98 ± 1.29	30.63 ± 0.49	12.09 ± 0.79	371 ± 14
Vesta	31.53 ± 3.08	5.45 ± 0.04	28.73 ± 1.76	29.33 ± 0.47	**14.43 ± 1.27**	362 ± 19
SybNYYSOH 6	34.43 ± 3.12	4.67 ± 0.15	33.50 ± 0.64	30.03 ± 0.37	12.82 ± 1.05	369 ± 13
Sac	30.63 ± 3.72	5.20 ± 0.10	31.28 ± 2.33	28.74 ± 0.49	**13.93 ± 0.95**	365 ± 18
Fiskeby V-E5	26.47 ± 2.98	5.00 ± 0.12	26.47 ± 1.51	28.43 ± 0.59	**16.53 ± 1.15**	368 ± 16
L 380-2-13	30.83 ± 3.45	4.54 ± 0.39	33.14 ± 1.60	29.72 ± 0.51	12.56 ± 0.48	364 ± 13
Xmed.	32.12	5.26	32.1	29.65	13.34	367
SD	3.21	0.41	3.4	1.06	1.64	4.67
CV%	10	8	11	4	12	1
$LSD_{0.05}$	0.73	0.242	1.60	1.317	1.642	22.02
Year 2020	35.34 ± 3.03	5.38 ± 0.35	33.37 ± 3.58	30.18 ± 0.98	14.42 ± 1.96	384 ± 5
2021	28.20 ± 3.39	5.19 ± 0.40	30.12 ± 3.56	29.10 ± 1.12	12.41 ± 1.83	349 ± 7
2022	32.82 ± 3.94	5.21 ± 0.51	32.68 ± 3.38	29.68 ± 1.10	13.20 ± 1.23	368 ± 8
$LSD_{0.05}$	1.76	0.289	1.76	1.630	0.733	20.18

st – standard; * text in bold show significance at the $P \leq 0.05$ probability levels.

The highest fat content was noted in 'Fiskeby V-E5', 'Fiskeby V', 'Vesta', and 'Sac' - 13.93–16.53 g 100 g^{-1} FW. The energy value of edamame products was in the range of 358–375 kcal 100 g^{-1}, the variation of this characteristic was minimal in the experiment and amounted to only 1%.

From the results presented in Table 7, it can be seen that 'Romantyka' (standard), 'Fiskeby V' and 'Sac' formed the largest total number of nodules on one plant - 10.00–12.33 pcs per plant, all other cultivars formed from 3.33 to 7.33 pcsper plant, which was significantly less than the above-mentioned cultivars. Intervarietal differentiation of soybean plants for this trait was very large CV = 44%. According to the indicator of the number of active nodules, 'Sac' stood out - 8.00 pc per plant, 'Fiskeby V' - 7.67 pcs per plant and the standard cultivar 'Romantyka' - 6.00 pcs per plant. In other cultivars, this indicator ranged from 3.00 to 5.67 pc per plant active nodules, the variation of this feature was 32%.

According to the indicator of the total mass of nodules on one plant, the cultivars varied greatly (CV = 20%). The research revealed that the collection cultivars of edamame produce nodules that are 9.1–32.7% smaller in mass than the standard cultivar, with the exception of ‘Sac’, where their mass is greater than standard ‘Romantyka’ by 25.5%. The highest mass of active nodules (containing legoglobin) was formed by cultivars ‘Sac’ - 0.19 and ‘Astra’ - 0.15 pcs per plant, other cultivars had a mass of active nodules in the range of 0.10–0.13 g plant^{-1}, which was 58.46–100% of the total mass of nodules.

Therefore, cultivars in which a small number of nodules were formed, all of them (or most of them) were active. One of the qualitative indicators of the symbiotic apparatus is the content of legoglobin in nodules. The activity of nitrogen fixation depends more precisely on the content and concentration of legoglobin in nodules than on their number and mass. Therefore, the study of the influence of varietal features on the accumulation of legoglobin is of great practical interest. A high concentration of legoglobin was noted in nodules with a high mass – these are nodules of cultivars ‘Sac’ - 12.44 mg g^{-1}, ‘Romantyka’ - 9.52 mg g^{-1} and ‘Astra’ - 9.08 mg g^{-1} (Table 8).

Table 8. Development of the nodulation apparatus of vegetable soybean cultivars, BBCH 81 (2020–2022) (X ± SD)

Cultivar		Number of nodules, pcs per plant		Mass of nodules, g per plant	
		total	active	total	active
Romantyka (st)		10.33 ± 1.70	6.00 ± 0.82	0.18 ± 0.04	0.11 ± 0.02
Fiskeby V		**12.33 ± 3.68**	**7.67 ± 1.25**	0.15 ± 0.04	0.10 ± 0.01
Karikachi		3.33 ± 1.25	3.00 ± 0.82	0.12 ± 0.04	0.11 ± 0.02
Astra		5.33 ± 1.89	4.67 ± 0.94	0.17 ± 0.03	**0.15 ± 0.01**
Vesta		5.00 ± 2.16	4.00 ± 0.82	0.15 ± 0.03	0.12 ± 0.01
SybNYYSOH 6		4.00 ± 2.16	3.33 ± 1.25	0.12 ± 0.02	0.10 ± 0.01
Sac		10.00 ± 4.55	**8.00 ± 3.27**	**0.23 ± 0.04**	**0.19 ± 0.03**
Fiskeby V-E5		7.33 ± 0.94	5.67 ± 0.47	0.17 ± 0.02	**0.13 ± 0.02**
L 380-2-13		4.67 ± 0.47	4.00 ± 0.00	0.14 ± 0.02	0.12 ± 0.01
Xmed.		6.93	5.15	0.16	0.13
SD		3.04	1.71	0.03	0.03
CV, %		44	33	20	21
$LSD_{0.05}$		0.34	0,27	0.05	0.02
Years	2020	5.22 ± 2.94	4.22 ± 1.62	0.13 ± 0.03	0.11 ± 0.02
	2021	9.56 ± 4.19	5.56 ± 2.36	0.20 ± 0.04	0.14 ± 0.03
	2022	6.00 ± 2.91	4.78 ± 1.75	0.15 ± 0.04	0.12 ± 0.04
$LSD_{0.05}$		0.38	0.26	0.008	0.007

st – standard; * text in bold show significance at the $P \leq 0.05$ probability levels.

The main reserve for increasing the yield of leguminous crops is the scientifically based use of the nutritional potential of the soil, environmental conditions, and new cultivars. It is known that at least half of the yield increase is achieved due to the use of fertilizers. As a result of research, it was found that Sac had the highest activity of symbiotic potential - 34.38 thousand kg·ha^{-1} day, while the amount of fixed nitrogen was 168.00 kg ha^{-1} ‘Astra’ - 32.17 thousand kg·ha^{-1} day and 161.67 kg ha^{-1} of fixed nitrogen. (Table 9).

There was no statistically significant difference between the years of research in terms of indicators of active symbiotic potential and the amount of fixed nitrogen in the soil.

Table 9. Activity of the symbiotic apparatus of vegetable soybean cultivars, BBCH 81 (2020–2022) (X ± SD)

Cultivar		Content of egoglobin, mg g^{-1}	Active symbiotic potential, thousand kg × day ha^{-1}	Amount of fixed nitrogen, kg ha^{-1}
Romantyka (st)		9.52 ± 0.98	26.17 ± 1.00	143.91 ± 8.61
Fiskeby V		8.30 ± 2.33	25.25 ± 1.70	135.82 ± 6.60
Karikachi		6.75 ± 1.54	27.00 ± 2.16	148.50 ± 11.88
Astra		9.08 ± 1.36	**32.17 ± 2.18**	**161.67 ± 2.36**
Vesta		7.44 ± 0.73	27.47 ± 2.86	145.94 ± 10.00
SybNYYSOH 6		6.41 ± 0.93	29.22 ± 1.38	158.19 ± 4.56
Sac		**12.44 ± 1.92**	**34.38 ± 3.31**	**168.00 ± 4.32**
Fiskeby V-E5		8.92 ± 1.22	29.52 ± 1.24	151.00 ± 2.94
L 380-2-13		7.46 ± 0.52	29.49 ± 1.18	152.60 ± 8.95
Xmed.		8.48	28.96	151.74
SD		1.72	2.75	9.22
CV, %		20	9	6
$LSD_{0.05}$		2.72	3.97	16.76
Year	2020	8.46 ± 1.19	28.64 ± 1.64	152.89 ± 9.13
	2021	9.79 ± 2.13	28.74 ± 3.67	149.60 ± 13.44
	2022	7.18 ± 2.32	29.51 ± 4.30	152.72 ± 12.17
$LSD_{0.05}$		0.46	1.59	8.34

st – standard; * text in bold show significance at the $P \leq 0.05$ probability levels.

Discussion. In conclusion, soybean breeding has shown spectacular results, e.g., average yields have increased from 1,100 kg ha^{-1} in the 1960-s to more than 4,000 kg ha^{-1} today. Breeding has focused mainly on increased crop yield, resistance to diseases, improved seed quality and nutritional traits, in addition to adaptation to edaphoclimatic conditions, such as shorter day length and water-stress tolerance. Transgenic approaches have achieved tolerance of herbicides and resistance to insect predation. Unfortunately, pointed by Nicolás et al. (2006) and Hayashi et al. (2012), relatively little effort has been expended in regard to biological nitrogen fixation (BNF) ability, despite the importance of the process to seed productivity and quality.

The obtained results are similar to the results of other scientists. In Brazil, the average yield of edamame was 6.6 t ha^{-1} (Santos et al., 2013), in the USA (Dakota) it ranged from 6.5 to 11.3 t ha^{-1} (Duppong & Hatterman-Valenti, 2005). A recently conducted study by Jiang et al. (2018(b)), characterised 86 food-grade soybean breeding lines for commercial edamame production in Virginia and found numerous genotypes that appeared to show high yield potential. These findings suggested that utilization of food-grade soybean genotypes already bred to local climatic conditions in the region may present a more immediate remedy for the poor agronomic performance of currently available edamame cultivars.

Yield data are consistent with results obtained in Central Alabama by Ogles et al. (2016), in the range of 13.1–13.5 t ha^{-1} and similar to the results given in the work of Jiang et al. (2018(a)) where yield was in the range of 5.85–10.71 t ha^{-1} and seed yield was 3.29–5.39 t ha^{-1}, which is significantly different from our results.

As noted by Guo et al. (2020), late-ripening edamame genotypes were more productive (had greater mass and number of pods) compared to early-ripening ones. This statement completely coincides with our results, where cultivars edamame ‘Fiskeby V’, ‘Vesta’, ‘SybNYYSOH 6’, ‘Sac’, ‘Fiskeby V-E5’ and ‘L 380-2-13’ were more productive.

Carneiro et al. (2022) notes that the properties of the appearance of vegetables can affect their perception by consumers, as well as the desire to buy, actually for edamame, the dark green color is required, in our research, only the ‘Sac’ variety is suitable for this criterion. Edamame appearance/color variability can be linked to genotype, planting date, harvest, processing conditions, such as blanching, and storage (Amilia et al., 2021; Moseley et al., 2021).

Results from our study corroborated results from Jiang et al. (2018(a); 2020), as many of the food-grade genotypes in this study from different ecological and geographical zones which are better than the standard cultivar. For example, only half of the prospective edamame genotypes observed in this present study showed significantly. Of the remaining genotypes, three (‘Karikachi’, ‘Astra’, and ‘SybNYYSOH 6’) failed to show statistically significant differences in yield with Romantyka (standard) and other cultivars showed even higher yield potential. In addition, many of the food-grade soybean genotypes in our study showed pod characteristics that were comparable to the commercial check. A wide range of pubescence densities was also observed among the genotypes with several showing lower pubescence densities than ‘Romantyka’, which is favourable for its processability.

Different factors such as cultivar, growing conditions, climate, soil type, and plant maturity can infuence the biochemical quality of crop. Not only environmental factors, but also genetic factors can strongly affect the seed biochemical composition. Soybean is an important source of vegetable proteins and lipids, especially of essential fatty acids (Zarkadas et al., 2007). In Japan and Canada, different methods are used for protein quality determination. These methods are used by breeders to select high quality soybean varieties. In Canada, 14 soybean cultivar seeds were analyzed, where average protein content values among these varieties ranged from 29.8 to 36.1% (Zarkadas et al., 2007; Lee et al., 2012), these data coincide with our results shown in Table 7, where protein content was 26.47–36.19%. In Georgia, protein content in dry seeds for different genotypes ranged between 33.3 and 38.6%, and from 5.0 to 6.9% in fresh seeds. The content of sugar ranged from 6.0% to 7.4%. The content of total soluble sugar of the fresh green beans is a signifcant factor that directly affects the organoleptic attribute of seeds (Mentreddy et al., 2002). In China, eight vegetable soybean genotypes were analyzed on biochemical composition. It was found that sucrose concentration ranged between 9.4 and 31.8 mg g^{-1}, which is 78.9 to 93.7% of the total sugar content (Song et al., 2013). In another investigation in India, ten different vegetable soybean genotypes were compared. It was determined that protein content in seeds ranged from 11.6 to 15.3 g 100 g^{-1} of fresh sample. It should be stressed that regarding protein content, the vegetable soybean has the highest ranking among other legumes (Salmani, et al., 2012).

It was reported that a person weighing 60 kg can consume as much as 38.4 g (male) or 57.6 g (female) of soybean oligosaccharides without any gastrointestinal troubles (Hata et al., 1991; Yu, et al., 2021). Therefore, the genotypes used in this study are unlikely to cause diarrhea due to the low content of oligosaccharides. It would be meaningful to investigate which of raffinose and stachyose leads to more severe abdominal discomfort, however, this information is not readily available. Future research might be needed to provide this information.

CONCLUSION

The results show that even with minor variations in genotype, vegetable soybean cultivars are quite similar to grain soybeans. Our results also support the benefits of edamame as a low-oligosaccharide dietary product. The promising cultivars are: ‘Fiskeby V’, ‘Fiskeby V-E5’ and ‘Sac’, which are characterized by large seeds, increased yield of green beans and seeds, have a high protein content in green beans.

The analysis of weather conditions showed their significant influence on the productivity of soybean vegetable plants. It is noticeable that in the year (2021) with optimal HTC, a significantly higher number and mass of pods per plant, a significantly higher yield (almost twice) of edamame and more than twice the seed yield compared to 2020 and 2022 were noted, which is confirmed by a moderate relationship productivity indicators from HTC - $r = 0.7619$ and $r = 0.8625$. However, improved hydrothermal conditions in 2021 contributed to a significant decrease in the concentration of sugars in edamame beans, dry matter, protein, fat and energy value of the product. The same trend was preserved in terms of nitrogen fixation indicators - better weather conditions in 2021 contributed to the development of the nodulation apparatus, but the varieties ‘Fiskeby V’, ‘Karikachi’, ‘L 380-2-13’ reacted negatively to fluctuations in environmental weather conditions and, due to this, the average indicators of nitrogen fixation decreased insignificantly.

In the direction of nitrogen fixation in the selection process, promising cultivars ‘Sac’ and ‘Astra’ should be used, in which the level of biologically fixed nitrogen is 168.0 and 161.7 kg ha^{-1}.

The obtained results provide useful information about the seed, nutritional quality and nitrogen-fixing capacity of edamame for further breeding practice and prove that the introduced vegetable soybean cultivars are suitable both for obtaining vegetable products and for quality seeds, as well as to produce biologically fixed nitrogen.

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