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GENETIC DIVERSITY, HERITABILITY AND HETEROSIS ESTIMATION IN F1 STRAWBERRY HYBRIDS

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Abstract

Strawberry (Fragaria × ananassa Duch.) is cultivated and enjoyed globally for early ripening of the fruits, high yields, and special nutritional qualities (high content of minerals and vitamins). In strawberry breeding, agronomic performance and fruit quality attributes highlight the success of strawberry breeding in recent decades. The present study evaluates the heritability of some biometric and biochemical parameters in hybrids derived from intraspecific crosses and their inheritance patterns. Broad sense heritability calculated over the entire experiment with hybrid combinations for most traits indicated a high degree of genotypic control, ranging between 0.59 (hue angle) and 0.91 (yield and chroma index). The values indicate a high proportion of total genetic variance to phenotypic variance, which indicates that hereditary endowment plays a significant role in the expression of traits. Narrow sense heritability estimates were mainly high for yield, fruit size, and fruit colour and low for fruit firmness, total soluble solids, and pH, indicating that, for half of the traits, more than 50% of the total genetic variation was the result of non-additive genetic effects and that the breeding process was quick. The results can use breeders in selecting parents for cross combinations and in maximizing genetic gain, ultimately for creating varieties that support the advancement of commercial strawberry production.

Key words*: Fragaria × ananassa, breeding, cross combinations, genetic gain, fruit quality.*

INTRODUCTION

Strawberry (*Fragaria × ananassa* Duch.) is cultivated and enjoyed globally for early ripening of the fruits, high yields, and special nutritional qualities (high content of minerals and vitamins). Research has demonstrated that consuming berries on a regular basis can help reduce the risk of cancer, cardiovascular disease, and neurodegenerative diseases (Hannum, 2004; Giampieri et al., 2015). Strawberries have a high antioxidant level that can help reduce oxidative stress when consumed fresh (Giampieri et al., 2013; Newerli-Guz et al., 2023). In addition, adding freeze-dried strawberry popping powder to the diets of individuals who are overweight or obese has been shown to reduce cholesterol levels (Richter et al., 2023). Strawberries are among the most recent crops, and they have only been cultivated for the past 275 years after the initial hybridization event in a French botanical garden (Wilhelm, 1974; Nellist, 2018). In 1817, Thomas A. Knight made history by creating the first official strawberry breeding program (Wilhelm, 1974; Hancock et al., 2005; Hummer & Hancock, 2009). The strawberry has undergone rapid evolution from a small, soft, short-season fruit to the large, firm, long-season fruit (Simpson, 2018) through breeding programs. Strawberry breeders have been enhancing strawberry marketable yield and fruit quality (Zorrilla-Fontanesi et al., 2011; Klee and Tieman, 2018; Mezzetti et al., 2018). Fruit quality is a complex trait that includes multiple visual factors (uniformity, colour), organoleptic factors (flavour, texture), and sensory factors (firmness) Cardello (1995); Song et al. (2023); Wang et al. (2025). Environmental influences continue to cause significant variations in strawberry fruit quality and consistency, even though there have been extensive improvements over recent centuries (Schwieterman et al., 2014; Lado et al., 2019). Accurate selection can capture this variation with robust phenotyping protocols, resulting in maximum genetic gain and improved desirable traits. The new objective of strawberry breeding is to create fruit varieties that deliver a satisfying multi-sensory eating experience. Breeding programs require stages of selection for parents and progenies. The selection criteria for elite plants and progenies are determined by the variability in the base population and the relative magnitude of the genes that influence the phenotypic expression of traits. Information

about heritability, gene action, and correlation among traits is crucial in determining parents and selecting progeny. Selection of individual plants can only be successful if the variables being selected have high heritability values. Genetic parameters for plant and fruit traits of strawberries have been reported in previous studies, including Galleta and Maas (1990), Shaw (1993), Pringle and Shaw (1998), Fort and Shaw (2000), Hancock et al. (2008), Whitaker et al. (2012), Whitaker et al. (2020), Cockerton et al. (2021) and Zhongchi et al. (2023). Broad-sense heritability estimates were presented in the strawberry by Whitaker et al. (2012) and Cockerton et al. (2021) for most traits, which indicate that gains are possible for several economically important characters in the strawberry breeding population in terms of clonal deployment. Narrow-sense heritability estimates based on the means of strawberry families, such as fruit chemical traits, fruit traits including average fruit weight, and plant diameter, have been low to moderate, with little contribution of non-additive variance (Shaw, 1993; Fort and Shaw, 2000; Whitaker et al., 2012; Cockerton et al., 2021). Genetic parameters such as heritability and heterosis estimation for the Romanian strawberry breeding population have not been published until recently, which would be beneficial for shaping breeding and selection strategies (Sturzeanu & Hera, 2019). The effects of trait selection on the long-term and the behaviour of correlated traits, which, if negative, may hinder breeding progress if ignored during selection, are explained in this article. The present study evaluates the genetic diversity, heritability, and heterosis estimation of some biometric and biochemical parameters in hybrids derived from intraspecific crosses and their inheritance patterns. The results can use breeders in selecting parents for cross combinations and in maximizing genetic gain, ultimately for creating varieties that support the advancement of commercial strawberry production.

MATERIALS AND METHODS

Location and Conditions of the Study

The research was carried out at the Research Institute for Fruit Growing Pitesti (RIFG) located in Maracineni village (44°54'12" Northern latitude, and 24°52'18" Eastern longitude, 284 m altitude) within the Department of Small Fruits and Strawberries. The institute was founded in 1967 and has since developed seven strawberry cultivars. The main strawberry breeding objectives were high productivity, high-quality fruit for fresh consumption and processing, large size fruit, color and shape of fruit, good shelf life, a wide early-, medium-, and late-ripening season, and resistance to diseases. The strawberry breeding sector produced 2,000-3,000 hybrids annually and followed selection procedures in the field. Soil type prevailing in the strawberry hybrid fields is the medium-textured and heavy-clay soils: clayey-illuvial luvisols, all showing medium and low humus content. The average annual temperature is 10.1º C and the average annual precipitation is 670.6 mm.

Plant Material and Determination

The experimental material studied comprised of 5 hybrid combinations ('Onebor × Fortuna', 'Onebor × Tecla', 'Elsanta × Onebor', 'Benicia × Sugar Lia', 'Nora × Benicia') and their parents. The optimal time to harvest strawberries was when they were completely red (Voca et al., 2008). After harvesting the strawberry fruit, the fruit samples were immediately analysed. Sample of 20 strawberry fruits was analysed for the indicators studied. To determine fruit production, the weight of ripened fruits at each harvest was weighed, and summing all harvests was done. The weight of each fruit was determined by using an HL-400 digital balance to weigh them individually. The fruit was measured using a digital calliper to determine its length and diameter. The shape index (SI) of the fruit was calculated as the ratio of these two dimensions (Tudor et al., 2014; Jamieson, 2016; Cockerton et al., 2021). The fruit firmness was measured for each sample using a non-destructive penetrometer with a 0.50 cm^2 measurement surface. The content of soluble solids (SSC) was estimated by means of a digital refractometer PR Series. The pH values of strawberry fresh juice were measured with the aid of a pH meter (ISFET pH Meter, IQ 125, Japan), Song et al. 2018. The external fruit colour was determined with a colorimeter Konica Minolta CR 400, based on system Huntel L*, a*, b* on both sides of the fruit (L* corresponds to brightness, a* and b*

chromaticity coordinates from green to red and from blue to yellow, respectively) (Lerceteau-Köhler et al., 2012; Alarfaj et al., 2021). According to McGuire (1992), the chroma index is determined by calculating $C = (a^{*2} + b^{*2})^{1/2}$ and the hue angle of h^0 = arctangent(b*/a*), with 0^0 representing red-purple, 90^0 representing yellow, 180^0 representing bluish-green, and 270^0 representing blue.

Statistical Analysis

The basic data were organized, calculated, and plotted using Excel 2019. On this basis, one-way ANOVA was conducted using SPSS 26.0. We also introduced the LSD method to compare the differences among data groups, with the significance level set as $\alpha = 0.05$. Broad-sense heritability (H^2) was calculated using the following formula: H^2 = VG/VP (VG = genotypic variation and VP = phenotypic variance) and narrow-sense heritability was calculated according to the formula h^2 = VGA/VP (VGA = additive genetic variance and VP = phenotypic variance) Falconer and Mackay (1996), Titirică et al. (2023). The coefficient of variability/variation (CV%) was calculated using the following formula: CV% = σ/ x̄ (σ - square root of the total variance among families; x̄ - mean of trait), Dan et al. (2010). The procedures outlined by Bakhsh et al. (2007) and Murti et al. (2012) were used to calculate the heterosis percentages relative to the mid-parents for the studied characters, as follows: Mid-parent heterosis (%) = ((F1-MP) x100)/MP. The dominance estimated was calculated "potence ratio" (hp) using the methods Petr and Frey (1966), Murti et al. (2012). hp = ((F1-MP)/ (BP-MP)). Where; F1 = mean value of the particular hybrid population, M.P. = mean value of the two parents for that hybrid (P1 + P2)/2, and BP = better parent. Complete dominance was indicated when P = +1; while partial dominance is indicated when "P" is between (-1 and +1), except the value zero, which indicates absence of dominance. Over dominance was considered when potence ratio exceeds ±1. The positive and negative signs indicate the direction of dominance of either parent.

RESULTS AND DISCUSSIONS

The variation in biometric parameters among different F1 strawberry hybrid combinations is shown in Table 1, demonstrating how parental genotypes have an impact on these key fruit size characteristics. Variations in production were observed in the strawberry hybrid combinations that were studied. The 'Nora × Benicia' hybrid combination (556.82 g/plant) was found to yield the highest production, as indicated in Table 1.

Table 1. Productivity and fruit size characteristics of strawberry hybrid combination

Hybrid Combination	Yield (g/plant^{-1})		Fruit weight (g/fruit^{-1})		Shape index	
(Parent♀×♂)	Mean ± SD	CV%	Mean ± SD	CV%	Mean ± SD	CV%
Onebor × Fortuna	337.70±6.74^{b}	15.40	19.13±0.90^{b}	14.50	1.53±0.58^{a}	12.20
Onebor × Tecla	355,02±1.75^{b}	14.40	19.81±0.72a^{b}	12.70	1.17±0.14^{a}	9.40
Elsanta × Onebor	556.82±4.79^{a}	14.01	27.55±1.12^{a}	9.90	1.19±0.55^{a}	10.20
Benicia × Sugar Lia	430.93±8.47^{ab}	13.50	26.35±6.45^{ab}	15.30	1.23±0.11^{a}	8.20
Nora × Benicia	332.09 ±1.95^{b}	15.40	21.19±5.99^{ab}	13.20	1.26±0.55^{a}	6.50
Mean	402.51±6.68	-	22.81±4.93		1.20±0.08	

*The values in the table that do not have common letters differ significantly for a statistical assurance level of 5% (P≤0.05).

The differences in productivity among the hybrid combinations studied were large, with a variation in production from 332.09 g/plant^{-1} ('Onebor × Fortuna') to 556.82 g/plant^{-1} ('Nora × Benicia') being significantly different. In 2025, the average marketable yield per plant was between 176 g/plant^{-1} and 331 g/plant^{-1}, according to Menzel, (2025). The size of the fruit is influenced by the genotype, ecological factors, and cropping system. The size of fruits is expressed through their average weight, which is highly commercially important for fresh consumption. In our study, we observed a significant impact of hybrid combinations on fruit weight, particularly in the 'Nora × Benicia' hybrid combination (27.55 g), which had a significantly higher fruit weight than the 'Onebor × Tecla' hybrid combination (19.13 g) (Table 1). The average fruit weight recorded in the present study was similar to the findings of Menzel (2025), which showed that strawberry cultivars produced fruits ranged of 18.20 g to 24.30 g. To evaluate strawberry shape as an ordinal trait, a quantitative measure was used to

measure the length and diameter of each berry. The length and diameter ratio is a trait that is continuous and can be used for genetic analysis with data from across the population Cockerton et al. (2021). The fruit shape index did not show any significant differences between hybrid combinations during this study. It varied from 1.15 ('Onebor × Tecla') to 1.26 ('Onebor x Fortuna') (Table 1). The results of fruit shape recorded in the present study were similar to the findings of Tudor et al. (2014), which showed that 'San Andreas's fruit is conical, with a shape index of 1.21, 'Albion' cultivar develops long conical fruits with a shape index of 1.26, and 'Benicia' cultivar has long, conical fruit with a shape index of 1.32.

Table 2. Firmness, total soluble solid, and pH characteristics of strawberry hybrid combinations

Hybrid Combination	Fruit firmness (Ncm^{-2})		Total soluble solid (^{o}Brix)		pH	
(Parent♀×♂)	Mean ±SD	CV%	Mean ±SD	CV%	Mean ±SD	CV%
Onebor × Fortuna	40.62±2.76^{a}	30.90	8.11±0.60^{a}	10.10	3.84±0.04^{a}	6.70
Onebor × Tecla	45.74±5.34^{a}	23.40	8.83±0.35^{a}	12.90	3.90±0.04^{a}	4.60
Elsanta × Onebor	38.76±3.72^{a}	17.10	7.91±0.99^{a}	8.90	3.70±0.08^{a}	4.40
Benicia ×Sugar Lia	39.48±10.34^{a}	25.20	8.31±1.23^{a}	10.80	3.76±0.29^{a}	4.70
Nora × Benicia	40.08±6.48^{a}	20.70	8.56±2.23^{a}	13.40	3.86±0.11^{a}	5.90
Mean	40.94±5.91	-	8.34±1.12	-	3.81±0.14	-

*The values in the table that do not have common letters differ significantly for a statistical assurance level of 5% (P≤0.05).

The fruits were found to be more resilient, with a higher resistance value for the hybrid combination 'Elsanta × Onebor' (45.47 N) than for 'Nora x Benicia' (38.78 N) (Table 2). Genetic factors, fruit ripeness, climate, and other factors can affect the quantitative variation of the SSC. In our study, we recorded a significant influence of the hybrid combination on the SSC in the 'Elsanta × Onebor' hybrid combination (8.83), which had the highest value of this parameter among the studied hybrid combinations. Sehrish et al. (2021) discovered that fruit SSC, in a similar manner to our research, with a range of 7.21 ^{o}Brix in the 'Everly' cv. to 12.63 ^{o}Brix in the 'Brighton' cv. (Table 2). The results of the study indicated that the 'Elsanta × Onebor' hybrid combination had the highest pH level, measuring 3.90, whereas 'Nora x Benicia' showed the lowest values of 3.70 (Table 2). The study by Ozkurt and Altuntas (2018) provides information about fruit acidity. It suggests that, in general, their acidity ranges between 3.36 and 3.39. The study by Ozkurt and Altuntas (2018) provides information about fruit acidity. It suggests that, in general, their acidity ranges between 3.36 and 3.30. Strawberries are a popular fruit worldwide, and their colour has a major impact on their appeal. The ripeness and sweetness of strawberries are both visually appealing and are indicated by their bright red colour. The colour of strawberries may change depending on various factors, such as the variety, the stage of ripeness, and the growing conditions, and it is not always consistent. The presence of different pigments, such as anthocyanins, carotenoids, and chlorophyll, determines the colour of strawberries (Denoyes et al., 2023; Zhongchi et al., 2023; Yue et al., 2024). Anthocyanins play a role in the red, purple, and blue hues of many fruits and vegetables, including strawberries.

Table 3. Fruit colour characteristics of strawberry hybrid combinations

Hybrid Combination	Brightness (L*)		Chroma Index (C*)		The angle (h °)	
(Parent♀×♂)	Mean ±SD	CV%	Mean ±SD	CV%	Mean ±SD	CV%
Onebor × Fortuna	30.20±0.80^{a}	5.70	28.92±1.76^{c}	6.60	23.16±0.69^{a}	10.50
Onebor × Tecla	29.72±0.93^{a}	7.10	30.29±0.32^{abc}	8.40	22.98±0.44^{a}	9.30
Elsanta × Onebor	31.61±1.40^{a}	5.70	32.58±1.43^{a}	7.30	23.57±0.74^{a}	7.80
Benicia × Sugar Lia	30.54±1.08^{a}	6.00	29.05±1.53^{bc}	2.90	25.81±2.12^{a}	7.00
Nora × Benicia	31.47±1.74^{a}	7.50	31.42±0.66^{ab}	11.90	25.60±2.81^{a}	10.30
Mean	30.71±1.29	-	30.45±1.80	-	24.35±1,82	-

* The values in the table that do not have common letters differ significantly for a statistical assurance level of 5% (P≤0.05)

These pigments are strong antioxidants that aid in defending the fruit against the harm caused by free radicals (Carbone et al., 2009). Strawberry is also a source of carotenoids, which are

pigments that are yellow, orange, and brown. Strawberry contains chlorophyll, a green pigment found in plants, but it is not as obvious as the other pigments. There was no significant difference in the L* and h values of the strawberry hybrid combinations, but there was a significant difference in the C* values. L* values increased from 29.72 ('Onebor × Tecla') to 31.47 ('Nora × Benicia'), C* from 28.92 ('Onebor × Fortuna') to 31.42 ('Nora x Benicia') and h^o from 22.98 ('Onebor x Tecla') to 25.81 ('Benicia × Sugar Lia') (Table 3). The lower L* and h^o values in the colour sphere indicate the darker sample colour with a dark red, while the higher values indicate the lighter sample with a red colour. It can be concluded that the 'Onebor × Tecla' hybrid combination was the dark-red genotype and 'Nora × Benicia' hybrid combination light-red colour, as stated by the results described above. Present findings are also confirmed by Henschel et al. (2017): L* values ranged from 32.12 to 33.61, C* from 27.19 to 31.26, and h^o from 20.51 to 27.48. The coefficient of variation (CV%) is a significant indicator of the stability and consistency of the traits that were evaluated. Low CV% is associated with low variability and stable performance, making it an ideal choice for large-scale production and enhancing fruit quality predictability. In contrast, a high CV% suggests more variation, which can result in fruit characteristics that are unpredictable and may be less favourable for selecting hybrids for commercial production. The coefficient of variation in biometric parameters among F1 strawberry hybrid combinations showed moderate variability for yield, fruit weight, and shape index. Among these, they are excepted 'Elsanta × Onebor' for fruit weight, whose CV% value was 9.90 and 'Onebor × Tecla' for shape index, with CV% value of 9.40, which indicates low variability. The coefficient of variation for fruit firmness showed a value over 20.00 which indicates high variability, except for 'Elsanta × Onebor', which showed moderate variability (CV% = 17.10) (Table 2). The coefficient of variation for fruit taste among the analysed families was low to moderate, consistent with the results of Simkova et al. (2023) (Table 2). Also, the coefficient of variation in colour parameters among F1 strawberry hybrid combinations showed low variability and stable performance, making it an ideal choice for selection (Table 3). Overall, the results obtained for the analysed hybrids that were analysed are similar to those found in the published literature regarding parent cultivars and other strawberry varieties (Cervantes et al., 2020; Simkova et al., 2023). The developed hybrids' quality, agronomic potential, and commercial viability are confirmed. Broad sense heritability calculated over the entire experiment with the hybrid combinations for most traits indicated a high degree of genotypic control, ranging between 0.59 (hue angle) and 0.91 (yield and chroma index) (Tables 4, 5, 6). In addition to the lowest heritability value observed for hue angle, low broad-sense heritability was also recorded for brightness (0.62) and fruit weight (0.66). The values indicate a high proportion of total genetic variance to phenotypic variance, which indicates that hereditary endowment plays a significant role in the expression of traits.

Table 4. Statistical analysis of productivity and fruit size characteristics in strawberry hybrid combination

Hybrid Combination	Yield (g/plant^{-1})				Fruit weight (g/fruit^{-1})				Shape index			
(Parent♀×♂)	H^2	h^2	MPH	hp	H^2	h^2	MPH	hp	H^2	h^2	MPH	hp
Onebor × Fortuna	0.91	0.76	-0.45	-12.08	0.66	0.25	0.05	1.54	0.69	0.29	0.11	0.80
Onebor × Tecla	0.91	0.77	0.08	0.32	0.90	0.74	-0.10	-0.74	0.89	0.71	0.13	3.07
Elsanta × Onebor	0.90	0.74	0.33	2.79	0.94	0.84	0.32	3.55	0.67	0.27	0.25	5.97
Benicia × Sugar Lia	0.88	0.68	0.34	3.14	0.85	0.61	0.32	4.33	0.76	0.43	1.01	2.15
Nora × Benicia	0.94	0.84	0.28	-2.99	0.90	0.74	0.02	-0.23	0.86	0.64	0.07	0.56

H^2 = heritability in broad sense; h^2 = heritability in narrow sense; MPH = Mid parent heterosis; hp = potence ratio

Narrow sense heritability estimates were mainly high for yield, fruit size, and fruit colour, and low for fruit firmness, total soluble solids, and pH, indicating that, for half of the traits, more than 50% of the total genetic variation was the result of non-additive genetic effects, and the breeding process was quick. The yield and size of the fruit are the most desired traits in strawberry breeding, as they have a direct impact on market acceptance and consumer preference. Table 4 displays a range of genetic responses dependent on the specific parent

combinations, emphasizing the potential for cultivar development. The success of strawberry breeding can be achieved through judicious parent choices, as demonstrated by the heterosis, dominance, broad-sense, and narrow-sense heritability values of certain traits. The yield in 'Nora × Benicia' hybrid combination is mostly influenced by additive genetic factors, as evidenced by the exceptional broad-sense heritability of 0.94 and the narrow-sense heritability of 0.84 (Table 4). Heterosis, also known as hybrid vigour, is the definition of an improvement in performance compared with the parental varieties. The heterosis values for yield were predominantly positive for all hybrid combinations, ranging 0.08 ('Onebor × Tecla') and 0.34 ('Benicia × Sugar Lia'), excepted 'Onebor × Fortuna' hybrid combination, negative (-0.45). In F1 hybrids for yield, the potence ratio ranged from -12.08 ('Onebor × Fortuna') to 3.14 ('Benicia × Sugar Lia') with two hybrid combinations indicating over dominance positive (>±1), and three combinations exhibiting partial dominance (-1 to +1). The high broad-sense and narrow-sense heritability values for fruit weight, specifically in 'Elsanta × Onebor', show that genetic variation plays a significant role in this trait. Thus, selecting fruits for weight in early generations can be a highly successful approach for these crosses. Also, heterosis values were predominantly positive in all combinations: 'Nora × Benicia' (0.02) and 'Elsanta × Onebor' respectively 'Benicia × Sugar Lia' (0.32), indicating that the performance of hybrid combinations was often higher than the average of the two parents. The exception is 'Onebor × Tecla' (-0.10), performance of hybrid combinations a lower compared to the parental mean. For fruit weight, the potence ratio ranged from -0.23 ('Nora × Benicia') to 4.33 ('Benicia × Sugar Lia') with three hybrid combinations indicating overdominance (>±1), and two combinations exhibiting partial dominance (-1 to +1). The high broad-sense heritability (0.89), and narrow-sense heritability (0.71) values for the shape index, particularly in 'Onebor × Tecla', indicate that a substantial proportion of the phenotypic variation in this trait is genetically determined. However, the low values of narrow-sense heritability for the other hybrid combinations indicated that the character is principally influenced by the environment. Heterosis values were predominantly positive in all combinations, ranging from 0.07 ('Nora × Benicia') to 1.01 ('Benicia × Sugar Lia'), indicating that the performance of hybrid combinations was greater than the average of the two parents. In F1 for shape index trait, the potence ratios ranged from 0.56 ('Nora × Benicia') to 5.97 ('Elsanta × Onebor'), with three crosses indicated over dominance (>±1) and two indicating partial dominance (-1 to +1). The firmness of the fruit is influenced by its size and shape, ripening stage, season, and year (Moore, 2001; Rasing et al., 2003). According to Santiago-Domenech et al. (2008), firmness during fruit ripening was related to a decrease in pectin level, a slight decrease in pectin covalently bound to cell walls, and a decrease in pectin depolymerization.

Table 5. Statistical analysis of firmness, total soluble solids, and pH characteristics in strawberry hybrid combinations

	Fruit firmness (Ncm^{-2})				Total soluble solid (ºBrix)				pH			
Hybrid Combination (Parent♀×♂)	H^2	h^2	MP H	hp	H^2	h^2	MPH	hp	H^2	h^2	MPH	hp
Onebor × Fortuna	0.79	0.49	0.41	8.50	0.73	0.37	0.00	0.02	0.84	0.60	0.10	7.16
Onebor × Tecla	0.77	0.43	0.43	3.07	0.73	0.37	0.05	2.16	0.76	0.42	0.17	4.16
Elsanta × Onebor	0.86	0.63	0.48	11.86	0.82	0.54	-0.06	-6.00	0.66	0.24	0.02	0.41
Benicia × Sugar Lia	0.62	0.17	0.17	1.64	0.83	0.56	0.07	0.78	0.83	0.57	0.10	1.69
Nora x Benicia	0.80	0.51	0.37	8.34	0.80	0.50	0.19	3.33	0.68	0.28	0.15	6.67

H^2 = heritability in broad sense; h^2 = heritability in narrow sense; MPH = Mid parent heterosis; hp = potence ratio

Heritability estimates of 0.62-0.80 (H2) and 0.68-0.84 (h2) for firmness suggest a strong genetic basis for selection. Table 5. The results of Whitaker et al., 2012, Cockerton et al., 2021, and Hera et al., 2025 back these estimations. Heritability estimates increased by 0.542 and 0.85 from Coman and Popescu (1997) and Ukalska et al. (2006). Parent firmness appears to have had an impact on the heterosis and potence ratio values of F1 fruit firmness. All crossing

combinations resulted in F1 progenies having positive heterosis and potence ratio values (Table 5). The combination of genotypes determines how genes interact to control the firmness of strawberries, making it a complex process. As Ohtsuka et al. (2004) and Murti et al. (2013) noted, it meant that the octoploid plants were not pure lines. The accumulation of genes that are favourable for firmness could be expected to have a highly additive genetic effect (Mori, 2000; Murti et al. 2012). According to estimates of broad and narrow-sense heritability for SSC, parental selection can yield additional gains in this trait (Table 5). In addition, this trait had high broad-sense heritability (H^2 = 0.72 to 0.83) and narrow-sense heritability was moderate to high for SSC (h^2 = 0.37 to 0.56), suggesting that clonal selection will allow the capture of non-additive variance in the deployment population. This is consistent with previous estimates of sizable non-additive genetic effects for these traits (Whitaker et al. 2012; Cockerton et al., 2021). These combinations are particularly valuable in commercial breeding programs because high TSS is directly related to fruit sweetness and consumer preference. Positive heterosis and potence ratio values in all hybrid combinations, except for 'Elsanta × Onebor' (-0.06 and -6.00), reflect hybrid vigour and indicate that these progenies exceed the average of their parents in terms of TSS content. For pH, broad-sense heritability (H^2) was moderate to high, with estimates ranging from 0.66 for 'Elsanta × Onebor' to 0.84 for 'Onebor × Fortuna' (Table 6). Narrow-sense heritability (h^2 = 0.24 to 0.60) was low and moderate, suggesting that breeding and selection can result in certain gains, and that genetic gains can be doubled by simply using clonal selection (Table 6). Heterosis values were predominantly positive in all combinations, ranging from 0.02 ('Elsanta × Onebor') to 0.17 ('Onebor × Tecla'), indicating that the performance of hybrid combinations was often greater than the average of the two parents Table 6. In F1 pH trait, the potence ratios were positive in all hybrid combinations; three crosses indicated over-dominance (>±1), hybrids performing better than the superior parent, and two indicated partial dominance (0 to +1), hybrids outperforming the average but not as good as the superior parent.

Table 6. Statistical analysis of fruit quality colour characteristics in strawberry hybrid combination

Hybrid Combination	Brightness (L*)				Chroma Index (C*)				The angle (h °)			
(Parent♀×♂)	H^2	h^2	MPH	hp	H^2	h^2	MPH	hp	H^2	h^2	MPH	hp
Onebor × Fortuna	0.77	0.43	0.03	0.49	0.76	0.42	0.01	0.00	0.59	0.13	0.01	-0.40
Onebor × Tecla	0.86	0.65	0.25	3.13	0.91	0.76	12.02	0.24	0.77	0.45	0.04	0.34
Elsanta x Onebor	0.84	0.60	0.05	0.66	0.78	0.47	0.90	0.08	0.78	0.47	0.00	0.33
Benicia × Sugar Lia	0.76	0.43	0.31	0.43	0.73	0.37	2.21	0.04	0.79	0.49	0.05	0.39
Nora × Benicia	0.62	0.17	0.02	0.28	0.59	0.13	-2.13	-0.12	0.64	0.21	0.11	2.65

H^2 = heritability in broad sense; h^2 = heritability in narrow-sense; MPH = Mid parent heterosis; hp = potence ratio

Statistical analysis of colour characteristics: L*, C* and h° in F1 strawberry hybrids (Table 6) provides important insights into the genetic potential of different parental combinations to improve fruit colours. Statistical analysis of colour characteristics: L*, C* and h° in F1 strawberry hybrids (Table 6) provides important insights into the genetic potential of different parental combinations to improve fruit colours. Moderately to high heritability of colour values indicated that the colour of progenies depends on the estimated high heritability of skin colour. The majority of the hybrid combinations had positive heterosis and potence ratio values for colour characteristics, except for the hybrid combination 'Onebor × Fortuna'. Value of the potence ratio for the chroma index in the hybrid combination 'Onebor × Fortuna' was 0, the character is non-dominant. The F1 hybrids have exactly the average value of the two parents, with no dominance effects; the action of the genes is purely additive.

CONCLUSIONS

The genetic parameters of nine commercially significant traits of strawberries for the Romanian strawberry breeding population were calculated by using clonally replicated plant genotypes from controlled crosses in controlled crosses. The presence of high broad-sense heritability for most traits suggests that gains could be achieved for these important characteristics in the strawberry breeding population with regard to clonal deployment. Moderate to high narrow-sense heritability for pH and some colour characteristics indicates a high probability of long-term gains through recurrent selection for these traits. From a yield and biometric parameters perspective, the strawberry hybrid combinations studied showed moderate variability for yield, fruit weight, and shape index. Among these, they are excepted 'Elsanta × Onebor' for fruit weight, whose CV% value was 9.90, which indicates a low variability producing the largest fruits, which may increase market appeal. The hybrid combination that uses 'Onebor' as the male parent was the most successful in terms of productivity and fruit size parameters, with the highest yield and fruit weight among all hybrid combinations studied. Hybrid combinations with 'Onebor' as the female parent, especially when crossed with 'Tecla', showed superior performance in fruit firmness, SSC, and pH. The comparative outcomes demonstrate the strong potential of the tested hybrid combinations to create fruit of quality that is equal to or better than that of the parent varieties and other commercial cultivars. High values for morphometric and biochemical parameters have been observed in hybrid combinations such as 'Elsanta × Onebor' and 'Onebor × Tecla', which indicate great potential as candidates for the development of highly nutritious and commercially valuable crops.

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