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Article

Characterization and heritability of fruit from olive cultivars in the south of Brazil

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ABSTRACT: The olive tree (*Olea europaea* L.) is a species of great importance in history and economic, with large phenotypic variability, represented through a wide range of cultivars spread throughout the world. There are several studies on the characterization of a large number of cultivars of the species. However, there is a need to uncover how these phenotypic traits are heritable, and how they can change when environmental conditions vary. For this reason, the objective here was to estimate the heritability coefficients for fruit characters in six commercial cultivars, analyzed under conditions in the state of Rio Grande do Sul, Brazil. The study was carried out in a single year, based on the analysis of fruit and oil traits on the cultivars Arbequina, Arbosana, Frantoio, Koroneiki, Manzanilla de Sevilla, and Picual, under environmental conditions in the state of Rio Grande do Sul. Phenotypic plasticity and broad-sense heritability were estimated in both inter and intra-cultivar comparisons. From the analyses of variance and heritability, it was observed that some cultivars such as Koroneiki or Picual had their characters mainly under genetic control, while Arbequina was more influenced by genotype-environment interaction. The information derived from this work can help guide the selection of cultivars that are best adapted under the local environments of the southern region of Brazil.

Key words: *Olea europaea* L., phenotypic plasticity, genotype, phenotype, fruit measurement, olive oil.

INTRODUCTION

Man throughout history has been responsible for the spread of olive cultivation in the Mediterranean Sea basin, in addition to having introduced it by commercial interests outside its area of origin, taking it to places as far away as Southwest Asia, Oceania, South Africa and America, thus breaking the barriers of natural dispersion (Alfieri et al. 2019). In these new colonized spaces, the crop adapted to new and different climatic conditions, some of them favorable, while others were limiting for their development (Lorite et al. 2018, Mousavi et al. 2019).

Most of the cultivars used nowadays are managed and have traditionally been selected only by agronomic improvements of representative characters, an issue that does not necessarily make them better adapted to the super-intensive productivity conditions of modern agricultural systems in the new colonized places (Lavee and Avidan 2012).

The olive tree can survive and reproduce in different ecological conditions, due to the high genetic variability within the species, and the various natural interactions between the different cultivars and their nearby environments. However, the anthropogenic selection of suitable cultivars, although it manages to overcome local environmental limitations, could be confusedly seen as a greater diversification of phenotypes, when in fact genetic diversity is being reduced (Rallo et al. 2005, Adakalic and Lazovic 2018), complying with the local demands of the producer. Despite the relatively recent description of the olive genome (Cruz et al. 2016) and the existence of numerous investigations on the genetic characterization of several cultivars (Julca et al. 2020), there is little information known on the hereditary behavior of characters, in part due to the slow growth and development of trees (Mora et al. 2008). Additionally, there is limited information on the correlation between genotype and phenotype and on the effectiveness of selecting cultivars well adapted to new environments outside the Mediterranean basin (Mousavi et al. 2019) and especially those in southern Brazil.

The ability of plants to vary physiological and morphologically to face and adapt to various environmental limitations or advantages, expressing differences in their phenotypes, is called phenotypic plasticity. The degree of plasticity heavily depends on genotypic variation, which may increase or decrease the plant's adaptation to the specific conditions of the environment around it (Whitman and Anurag 2009). Heritability can be viewed as a parameter expressing the proportion of total phenotypic variation attributed to the average effect of genes (Falconer and Mackay 2006). However, changes in this idea led to the so-called broad sense heritability (H_2), which involves the proportion of the variance that is due to all genetic effects and heritability in the narrow sense that the proportion of variance is due to the additive effect.. The most important role of estimating heritability is to predict genetic gain (Falconer and Mackay 2006) (e.g., applied by Fernandes et al. 2022).

In this context, the objective of this study was to estimate the heritability coefficients for agronomic traits of fruits of six commercial cultivars, analyzed under conditions of the state of Rio Grande do Sul, Brazil.

MATERIAL AND METHODS

In this study, six commercial olive cultivars (*Olea europaea* L.), Arbequina, Arbosana, Frantoio, Koroneiki, Manzanilla de Sevilla, and Picual were evaluated. The olive trees belong to the company Verde Louro (Fazenda Mato Grande) (UTM 31.474477S; 52.9473309W), municipality of Canguçu, located in the state of Rio Grande do Sul, Brazil. The collection of all the fruits was carried out in a single event on February 13, 2021, of trees from 5 to 10 years old that presented their greatest flowering event in the months of September and October of the previous year. Of each cultivar, ten trees were evaluated (60 trees evaluated in total), each tree being a repetition (ten repetitions per cultivar). Each of the 10 trees was planted on a hillside, numbered for study purposes from 1, starting with the tree located in the highest altitude zone, to 10, for the one located in the lowest zone.

From each tree, a sample of 2-3 kg of fruits was collected, obtaining a variable number of fruits that depended on the size and weight of the fruit in each tree of each cultivar. The number of fruits per tree was: 1,753 fruits for Arbequina, 1,648 fruits evaluated for Arbosana, 1,214 fruits evaluated for Frantoio, 2,059 fruits evaluated for Koroneiki, 620 fruits evaluated for Manzanilla de Sevilla, and 603 fruits evaluated for Picual. Each fruit contained in the sample collected from each tree was measured and weighed individually.

The local climate was characterized during the harvest year, according to data from Canguçu meteorological stations, code (WMO): A811 (UTM 31.403299S; 52.700699W), Region S, UF: RS, belonging to the National Institute of Meteorology (INMET), to the Ministry of Agriculture, Livestock and Supply, Brazil. Climatic conditions were characterized by sparse rainfall, with high relative humidity and solar radiation, showing little variation during the fruit collection period (data not shown).

The fruits were quickly transported to the laboratory of the Plant Genomics and Breeding Center (CGF) of the Agronomy Faculty "Eliseu Maciel" , Universidade Federal de Pelotas, where were kept at -20 °C for subsequent biometric analysis.

Biometric parameters evaluated in the fruit

With a digital vernier caliper (0.01 mm), Starrett brand, fruit length (FL) and fruit width (FW) measurements were taken of each fruit stored at -20°C. From these variables, the ratio between length and width (FL/FW) was calculated. With a scale (Shimadzu brand, 0.01 g precision), each fruit was also weighed (fresh fruit weight – FFW).

The exo and mesocarp (pulp) were manually removed from each fruit, pressing with the help of latex gloves each fruit that had already thawed. Using absorbent paper, the endocarp was cleaned and freed of any remaining pulp. Both the endocarp length (EL) and the endocarp width (EW) were measured. From these variables, the ratio between length and width (EL/EW) was calculated. Fresh endocarp weight (FEW) was also measured.

The ratio of the weight of the pulp (exo and mesocarp), regarding the weight of the total fruit (with endocarp), is in turn related to the size of the fruit, being a determining factor of the fat yield (FY), since the oil of the pulp represents more than 95% of the total olive (Rallo and Cuevas 2017).

Parameters measured in oils

From each of the 10 trees sampled per cultivar, an additional 350 g of fruit was collected and weighed for oil extraction, based on the slightly modified protocol of Zarrouk et al. (2008). For the grinding and crushing of the fruits, a Philco PMP1600V (1,400 W) food multiprocessor was used, applying it for 40 minutes at the temperature of 25 °C, obtaining a paste. The oily paste obtained was centrifuged at 3,500 rpm for 3 minutes in an Eppendorf 5810 centrifuge, using 50-mL tubes. The supernatant (oil) was recovered by placing it in four 25-mL tubes previously covered to prevent the passage of light (four replications per tree), leaving plant residues and water at the bottom. The oil obtained was kept at 4 °C in complete darkness until analysis.

To degree of acidity (DA), 4 to 6 g of oil from each tree was weighed into a 250-mL Erlenmeyer flask, and 50 mL of ethanol-ether (50%) was added, neutralized with 0.1 N NaOH, and mixed until the oil completely dissolved. It was added 1 mL of phenolphthalein indicator (1%), and the solution stirred. Titration was done with NaOH until the color changed to pink.

The peroxide index (PI) was determined by the amount (mEq of active O2 kg of olive oil-1) of peroxides present in the samples, which cause the oxidation of potassium iodide under working conditions. For the detection of peroxides, 1.8 to 2.2 g of olive oil was mixed in an Erlenmeyer flask with 25 mL of acetic acid-chloroform (3:2), 1 mL of freshly prepared potassium iodide, 13.7 g of potassium iodide and 10 mL of water. It was gently shaken and left in the dark for 5 minutes. Subsequently, 75 mL of distilled water and several drops of starch were added to act as an indicator. It was vigorously stirred and taken up with sodium thiosulfate (0.002 N) until it changed color from violet to white.

Statistical analysis

Descriptive statistical analyses of the different variables were performed. Data normality was verified with the Shapiro-Wilk's test. Exponential data transformations were performed for the variables FL, FW, EL, and EW. All other variables were normally distributed, therefore, no transformation was applied. A Pearson's correlation ($p < 0.05$ crossed) was performed using the RStudio and PAST statistical package. For these cultivars, the variability of the variables was visualized using Violin Plot with RStudio.

Quantitative estimates of phenotypic plasticity (PP) were calculated using a simplified approach, evaluating the effect of phenotypic plasticity within each tree on each cultivar evaluated separately. The calculation was based on the standard deviation of the means divided by the mean of the adjusted means as a covariate. Such covariate is expected to influence the target variable or trait (Navas and Garnier 2002).

The broad sense heritability (H^2) for all the evaluated traits is estimated as the relationship of the genotypic and phenotypic variations between cultivars using the variation of fruit measurements betwixt cultivars and in each tree evaluated within each cultivar.

RESULTS AND DISCUSSION

Analysis of variance was applied to all variables measured both before (whole fruits) and after ecto and mesocarp extraction, leaving the endocarp free, between and within cultivars. In all cases, at least one cultivar was significantly different (data not shown). It was observed that all the variables analyzed showed great variation between and within cultivars.

A comprehensive study testing cultivars in different locations with various climatic conditions was recently reported (Mousavi et al. 2019). However, the present work proposed a similar study including even more biometric characters under the conditions of Brazil.

A Pearson's correlation analysis was performed with probability of 5% for the traits evaluated (Fig. 1). An associative pattern with positive significance was present between FL and FW of the whole fruit ($r = 0.78378$; $p = 0.002$). Other equally highly correlated variables were FFW, whose values showed a higher correlation with FW (r = 0.72112; p = 0.002), than with FL (r = 0.66715, p = 0.003). In turn, the length of the endocarp (EL) showed high correlation with FL (r = 0.70378; p = 0.001). Equally positive low-magnitude correlation patterns were also observed between EL and EW (r = 0.12208; p = 0.000) and FEW with its EL (r = 0.15389; p = 0.001).

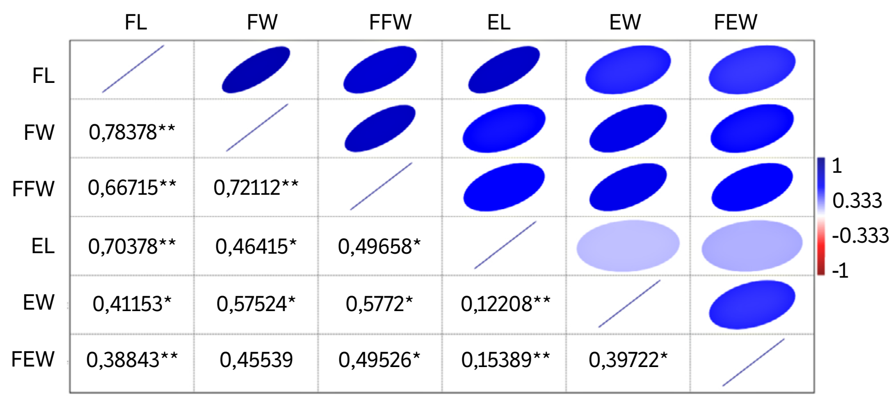

Figure 1. Correlation analysis for the variables fruit length (FL), fruit width (FW), fruit fresh weight (FFW), endocarp length (EL), endocarp width (EW), and fresh endocarp weight (FEW). Asterisks show significance level, *(5%) and **(1%).

Characterization of fruits from different cultivars

The higher mean values of the FL trait were observed in Picual and Manzanilla de Sevilla (22.21 ± 1.95 and 20.63 ± 1.81 mm, respectively), presenting significant differences from the other cultivars, while the higher variability for this trait was detected in Arbequina and Arbosana (Table 1; Fig. 2a). For FW, the highest mean value was observed in Manzanilla de Sevilla followed by Picual (17.75 ± 1.27 and 15.99 ± 1.17 mm, respectively), presenting significant differences from the other cultivars, while Arbequina, despite the majority being concentrated in the range between 5 and 10 mm, showed great variability of scattered data reaching values close to 20 mm (Fig. 2b). When taking into account the values of FFW, both Picual and Manzanilla de Sevilla presented higher values (4.81 ± 1.19 and 3.94 ± 1.10 mm, respectively), being values very similar to those mentioned by Íñiguez et al. (1999) and Villa (2004). It can be seen graphically that these cultivars had the largest range of dispersion among the data (Fig. 2c).

Table 1. Variables of the fruits: fruit length (FL); fruit width (FW); fresh fruit weight FFW; endocarp length (EL); endocarp width (EW); fresh endocarp weight (FEW); ratio between length and width (FL/FW); ratio between length and width (EL/EW); and fat yield (FY). Measurements indicates different dimensions of the olive cultivars.

Cultivars		FL	FW	FFW	EL	EW	FEW	FL/FW	EL/EW	FY
Arbequina	$\bar{x}$	10.22 [d]	10.0 [c]	1.48 [b]	8.35 [b]	6.84 [a]	0.48 [a]	1.00 [b]	1.24 [c]	67.22 [b]
	s	2.80	2.83	0.50	0.96	1.05	0.28	0.05	0.15	18.28
Arbosana	$\bar{x}$	14.99 [c]	12.54 [b]	1.48 [b]	9.77 [b]	7.60 [a]	0.48 [a]	1.15 [b]	1.29 [c]	66.90 [b]
	s	2.20	0.90	0.49	1.16	0.59	0.27	0.05	0.18	17.49 [b]
Frantoio	$\bar{x}$	16.80 [b]	12.03 [b]	1.90 [b]	12.08 [a]	6.78 [a]	0.92 [a]	1.41 [a]	1.81 [b]	49.80
	s	1.78	1.16	0.42	1.17	0.84	0.31	0.20	0.29	19.00
Koroneiki	$\bar{x}$	14.81 [c]	9.97 [c]	1.21 [b]	12.81 [a]	5.16 [a]	0.31 [a]	1.52 [a]	2.62 [a]	70.86 [a]
	s	1.30	1.32	0.38	1.28	1.10	0.08	0.27	0.69	15.76
Manzanilla de Sevilla	$\bar{x}$	20.63 [a]	17.75 [a]	3.94 [a]	12.52 [a]	7.44 [a]	0.84 [a]	1.17 [b]	1.75 [b]	76.72 [a]
	s	1.81	1.27	1.10	1.09	1.37	0.32	0.12	0.44	11.72
Picual	$\bar{x}$	22.21 [a]	15.99 [a]	4.81 [a]	15.57 [a]	8.76 [a]	0.78 [a]	1.40 [a]	1.79 [b]	82.48 [a]
	s	1.95	1.17	1.19	1.84	0.78	0.15	0.16	0.25	6.50

[a]The measures FL, FW, EL and EW are expressed in mm; FFW and FEW are expressed in g; FL/FW and EL/EW are unitless; and FY is expressed in percentage; [b]the data is presented as means ($\bar{x}$) and standard deviation (s). Different letters within a column indicate significant differences by Tukey's test ($P \leq 0.05$).

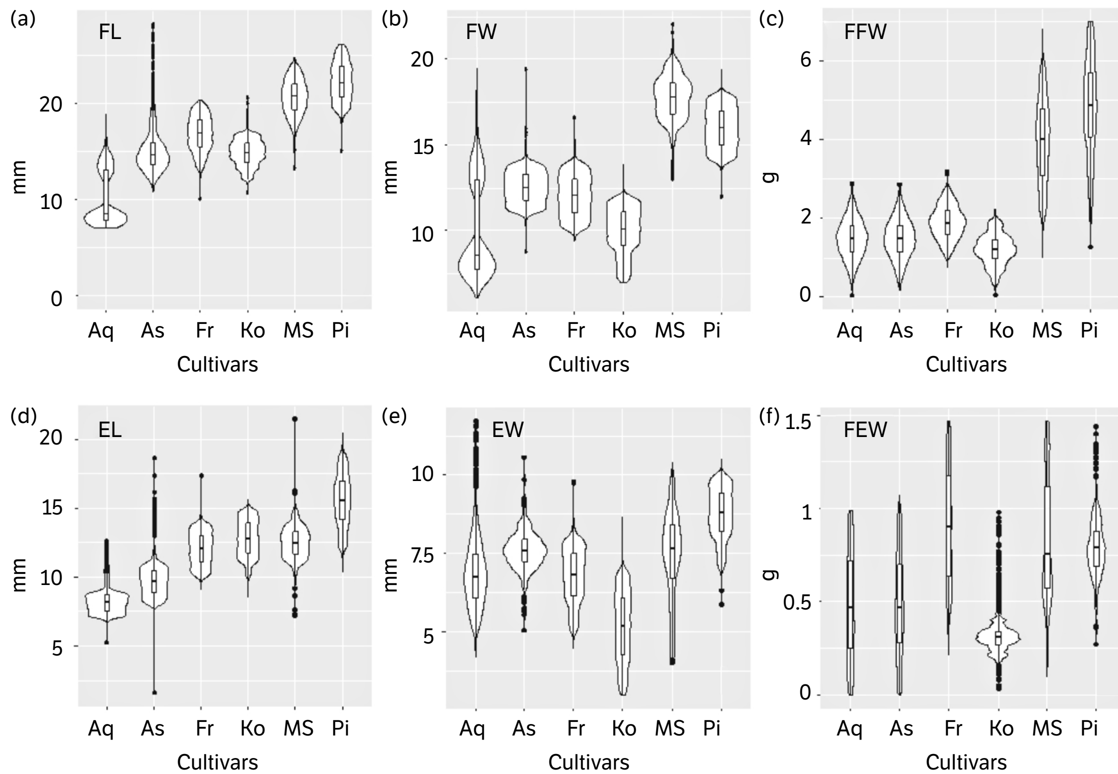

Figure 2. Violin graphs representing the variation of the fruits measurement: (a) fruit length (FL); (b) fruit width (FW); (c) fresh fruit weight (FFW); (d) endocarp length (EL); (e) endocarp width (EW); and (f) endocarp weight (FEW) in each cultivar studied within the developed environment. Each fiddle shows the distribution of data from minimum to maximum level, with internal horizontal lines showing the average of the data. The boxplots represent the lower and upper limits of the first and third quartiles. Outliers are indicated with black dots. The horizontal width of the violin depends on the data density.

After the elimination of the ecto and mesocarp, a smaller amplitude of variation of the data in the EL character was observed. The highest value was observed in Picual (15.57 ± 1.84). Koroneiki, Frantoio and Arbosana cultivars showed similar values between the means (Table 1), but Arbosana and Manzanilla de Sevilla presented scattered or erratic data (Fig. 2d).

Considering the EW trait, one can denote high dispersion of data in each of the analyzed cultivars (Fig. 2e), not showing significant differences. An even more notorious case occurs when analyzing the behavior of the FEW data (Fig. 2f), in which a great variability is observed between the weight of each endocarp without distinguishing between the trees.

When considering each tree as an individual production unit, it can be seen that, for the FL and EL characters, all the cultivars presented a dispersion of values centered at intervals close to each other. Arbequina was the exception, whose individuals showed a higher difference in LF and WF, being larger when these trees were planted in high lands, exposed to the wind, when compared to those planted in lowlands (Figs. 2a and 2b). However, the differences for Arbequina became less notable between each of the trees when the weight of each fruit was compared. For Koroneiki and Picual, an opposite trend of variation was observed in the weight of their fruits, being heavier fruits produced in Koroneiki trees positioned in the high areas with higher exposure to the wind, while for Picual the heaviest fruits were observed in trees planted in lowland areas.

Taking into account the variability within each tree, analyzing each cultivar individually, it can be seen that, in the cultivar Arbequina, both FL and FW presented differences between the many positions of each tree in the locality when compared to the rest of the cultivars, cultivars that, although they present differences between trees, presented low variance (Figs. 3a and 3b). In addition, it can be seen how the average in each tree can, on several occasions, undermine the averages of other trees of other cultivars, in the absence of bands of defined variability.

The fruits with the highest pulp content, a factor that is related to fat yield (FY), were those of the Picual (82.48%), followed by Manzanilla de Sevilla (76.72%) and Koroneiki (70.86 %) cultivars. However, these values were very low when compared to the standards established by Rallo and Cuevas (2017), who mentioned that they can be higher than 95%. These results can infer that the fruit harvest is being carried out in phenological phase III, characterized by rapid fruit growth due to the widening of the mesocarp cells, which determines its final size. During this phase, oil biosynthesis and its accumulation in the parenchymal cells of the pulp (lipogenesis) begin to take place. The availability of water in this phase determines the final size of the fruit and its oil content. However, although swollen with water, they have not yet developed the necessary oils for harvesting with optimal yields (Rallo and Cuevas 2017).

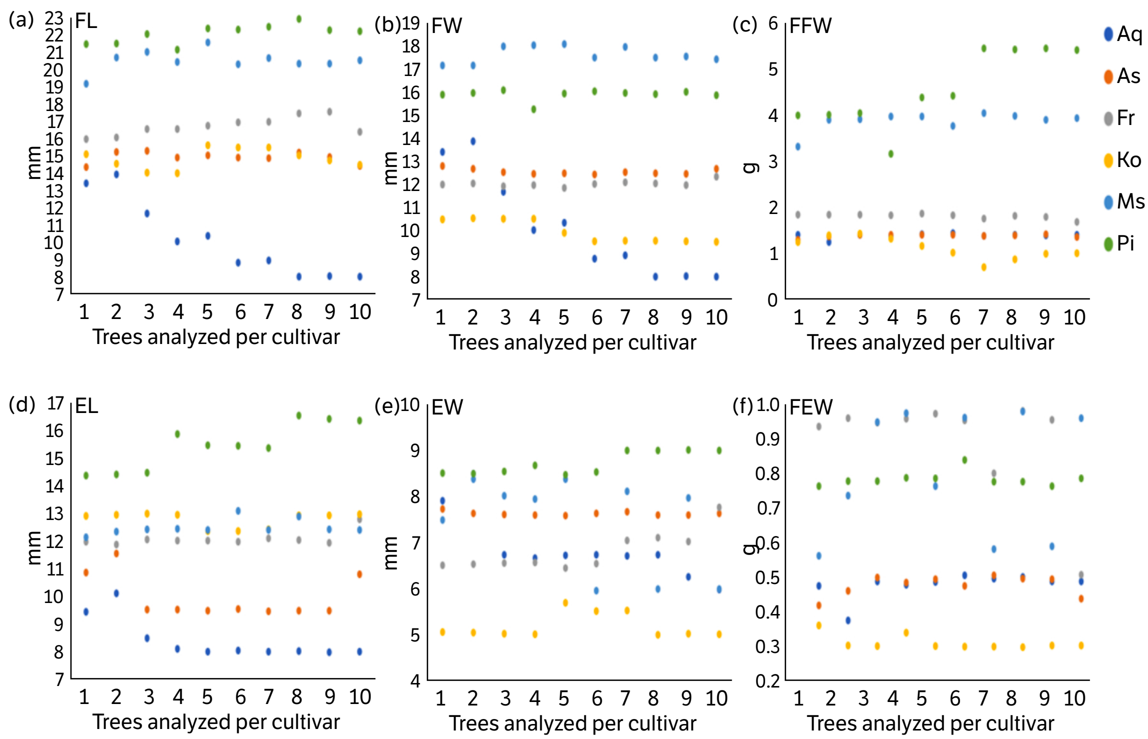

Figure 3. Scatter plots showing the variation of traits: (a) fruit length (FL); (b) fruit width (FW); (d) fresh fruit weight (FFW); (d) endocarp length (EL); (e) endocarp width (EW); (f) endocarp weight (FEW) in each cultivar studied within the developed environment. Each colored circle is the average value of the trait of each tree for each cultivar. The x-axis in all graphs represents each tree, while the y-axis corresponds to the trait values.

Parameters measured in oils

Acidity is one of the parameters that define the quality of olive oil, being expressed in grams of oleic acid per 100 g of oil, measuring the amount of free fatty acids present in the oil sample (Tous et al. 1997). Therefore, it is an index linked to the fruit change sand to the hydrolysis of glycerides in the process of elaboration and conservation, alerting to the hydrolytic alterations suffered by the oils. Its increase is mainly due to the hydrolysis of triglycerides, which may be due to the ripening time of the fruits at the time of harvest or inadequate storage before milling (Tous et al. 1997).

In the case of DA values, almost all cultivars showed values between 0.6 and 2 (within the range of virgin oils), with the exception of 'Arbequina' cultivar, which showed higher values (3.05). This value indicated low quality of olive oil at the time of analysis. The higher variability for this trait was detected in Arbequina, Picual, and, to a lesser extent, Manzanilla de Sevilla, for which the data was more spread when compared to 'Arbosana', 'Frantoio' and 'Koronoiki', which presented lower averages and variances (Fig. 4a).

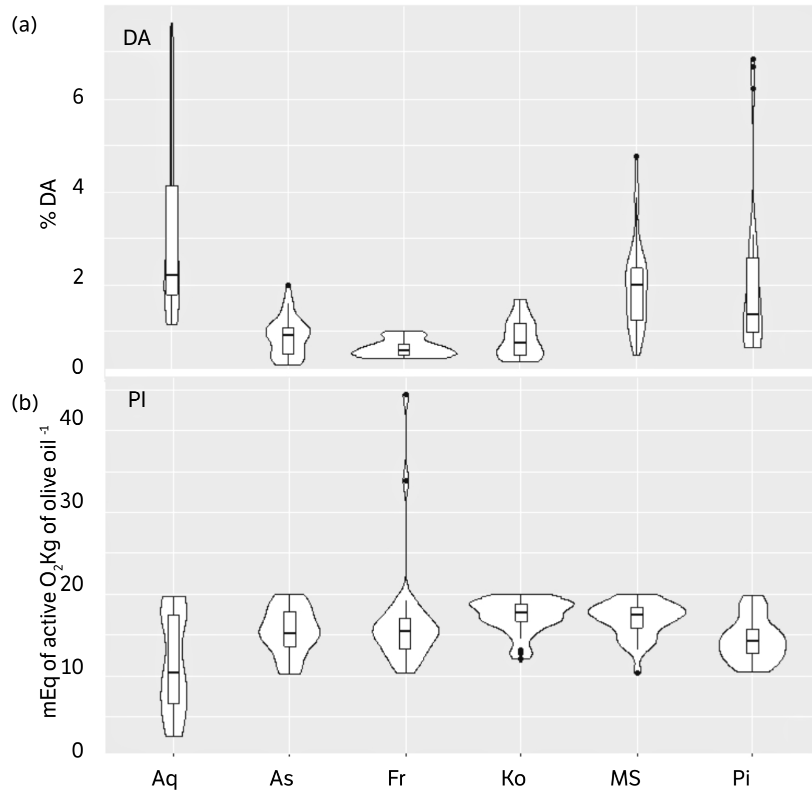

Figure 4. Violin graphs representing the variation of variables (a) degree of acidity (DA), and (b) peroxide index (PI) in each cultivar studied within the developed environment. Each fiddle shows the distribution of data from minimum to maximum level, with internal horizontal lines showing the average of the data. The boxplots represent the lower and upper bounds of the first and third quartiles. Outliers are indicated with black dots. The horizontal width of the violin depends on the data density.

Peroxides or initial oxidation compounds originate if the oil is not protected from light and heat, or if not stored in unsuitable containers. Virgin oils must not exceed a peroxide value of 20 milliequivalents of oxygen per kg of olive oil. Therefore, the higher the peroxide value, the lower the antioxidant capacity of the oil (Tous et al. 1997).

For the analysis of the peroxide index (PI) values, the highest mean value was related to Koroneiki (17.34). However, all mean values showed apparently similar conditions, although the analysis of variance showed significant differences between the means of the various cultivars. The highest variability for this trait was observed in Frantoio, for which the data were more spread when compared with the other five analyzed cultivars (Fig. 4b).

Heritability of traits

Heritability is the proportion of variation in a trait that can be attributed to inter-individual genotypic variation. If a character has a high heritability, it means that its variation in the population is mostly influenced by the genetics of each individual, while, if it has a low value, the environment surrounding each individual and gene-environment interactions will have a fundamental role in determining the heritability of the variation of this trait (Falconer and Mackay 2006) (concepts recently applied by Fernandes et al. 2022).

The results of broad sense heritability for the variables FL, FW, FFW, EL, EW and FEW, for the different cultivars, showed high values between 0.98 and 0.99, indicating that each cultivar shows genotypic stability and is apparently little influenced by the environment. A special case for FL, it was much higher than that mentioned by Mousavi et al. (2019). However, in the case of the results evaluated in oils, these values are close to those presented in the same work.

When the heritability values were evaluated within each of the cultivars individually, it can be observed that in the case of Arbequina and Arbosana they presented averaged to low values, indicating that the environment has high influence, and, therefore, their fruits depend to a great extent on the environment that surrounds them (Table 2). The opposite case can be evidenced for the case of Koroneiki and Picual, whose values showed that a large part of the phenotypic variation found was due to the genotype without presenting strong variations due to the environment.

Heritability has been widely studied in plant breeding, being estimated in a broad sense as the proportion of observed variability caused by total gene effects and their interaction with the environment (Falconer and Mackay 2006) (Mousavi et al. 2019, Fernandes et al. 2022).

Table 2. Broad sense heritability in broad sense for six cultivars, comparing the production of 10 trees; fruit weight (FW); and ratio between length and weight (LF/WF).

Genetic Parameters	FL	FW	FFW	EL	EW	FEW	DA	PI
H^2	0.98	0.99	0.99	0.99	0.99	0.99	0.64	0.56
$H^2_{\_Aq}$	0.69	0.72	0.76	0.89	0.39	0.84	0.49	0.52
$PP_{\_Aq}$	27.96	28.28	33.45	11.55	15.29	58.28	37.30	27.32
$H^2_{\_As}$	0.80	0.76	0.76	0.69	0.34	0.60	0.53	0.61
$PP_{\_As}$	14.67	7.21	33.20	11.84	7.76	55.52	26.10	26.54
$H^2_{\_Fr}$	0.88	0.76	0.84	0.74	0.79	0.98	0.48	0.60
$PP_{\_Fr}$	10.59	9.62	21.94	9.69	12.40	33.47	38.15	21.56
$H^2_{\_Ko}$	0.96	0.95	0.99	0.88	0.89	0.98	0.85	0.79
$PP_{\_Ko}$	8.78	13.27	31.50	10.00	21.33	26.68	5.27	7.96
$H^2_{\_MS}$	0.77	0.75	0.86	0.92	0.79	0.88	0.74	0.67
$PP_{\_MS}$	8.77	7.13	27.85	8.70	18.38	38.04	7.88	16.35
$H^2_{\_Pi}$	0.97	0.90	0.99	0.99	0.98	0.89	0.83	0.85
$PP_{\_Pi}$	8.79	7.31	24.78	11.82	8.87	19.09	9.68	8.93

Measured variables: fruit length (FL); FFW: fresh fruit weight, EL: endocarp length: EW, endocarp weight. EL/EW, ratio between endocarp length and weight; FEW: fresh endocarp weight; DA: degree of acidity; PI: peroxide index; H^2: broad sense of heritability comparing all genotypes; $H^2_{\_Aq}$: Arbequina; $H^2_{\_As}$: Arbosana; $H^2_{\_Fr}$: Frantoio; $H^2_{\_Ko}$: Koroneiki; $H^2_{\_MS}$: Manzanilla de Sevilla; $H^2_{\_Pi}$: Picual; PP: phenotypic plasticity.

This study represented a new effort to evaluate the plasticity of the phenotype of a sample of commercial cultivars of cultivated olive trees, taking into consideration characters of great economic importance, related to the composition of the fruit and olive oil, the first being done under the environmental conditions of the south of Brazil.

The variation of the different traits could be due to hereditary differences between cultivars, but the variability within each cultivar may be the result of phenotypic plasticity in the face of different environmental conditions (Mousavi et al. 2019). Understanding how the environment and the genotype share the responsibility for the variability of the characters is crucial to predict the response of the plant to various stress conditions, temperatures, or water regimes (Moran et al. 2016). When heritability was analyzed in a broad sense comparing the six cultivars analyzed in this study, the values are around 99%, demonstrating the stability of each of the genotypic identities studied. However, when each of the cultivars was analyzed individually, they showed different levels of plasticity for each trait, that is, a different environmental influence was observed for each combination of cultivar and trait.

Despite the data limited to a single harvest for this study, the conceptualization of Falconer and Mackay (1996) was used, which mentions that, when more than one character measurement can be made in each individual, as the case for each tree in which each fruit comprises a repetition of the variable, the phenotypic variation can be divided into variation within individuals and variation between individuals, being able to observe what happens within each cultivar. This partitioning leads to a variance component ratio called repeatability, which shows how much is gained by repeating measurements, predicting future performance from past records. The partition of the variance corresponding to the repeatability is not part of the genetic theory, because it is the environmental variance. With this, it could be taken as the environmental variance that derived from the variability between fruits within each tree.

Despite Arbequina ranking as one of the most cultivated olive varieties in the world and highly preferred in Brazil, the values obtained in this study showed a high variation in terms of fruit sizes, weights and parameters measured in the oil, obtaining low heritability values, due to the influence of the surrounding environment. These values contrast with the low values obtained by Mousavi et al. (2019), which mention its genotypic plasticity. The variables measured for the Picual and Koroneiki cultivars presented high and stable values that agree with those indicated for the same cultivars in Spain and Greece in all environments. This may indicate that the cultivars mentioned, like Manzanilla de Sevilla and Frantoio, have a greater adaptation capacity (Nicotra et al. 2015, Mousavi et al. 2019), being in this case minimal the unfavorable interaction G × E, but sometimes this interaction can be very favorable.

High broad-sense heritability values were found for the variables measured in the oil for the cultivars Picual, Koroneiki and Manzanilla, being similar or even higher than those mentioned by Mousavi et al. (2019) and Navas-Lopez et al. (2019). Apparently, high values of maximum and minimum temperatures could negatively affect the percentage of oleic acid, particularly if they occur during the warmer months, when the fruits are developing and the oil accumulates in the mesocarp (Servili et al. 2015, Mousavi et al. 2019). There are reports that, in Argentine environments, the oleic acid content was at the minimum level in all environments. Therefore, olive oils from warm areas consistently had lower oleic acid content and a higher proportion of monounsaturated fatty acids, regardless of cultivars (Mousavi et al. 2019), resulting between 50 and 85% fatty acids for this study.

Works such as the one of Mousavi et al. (2019) suggest that, from a breeding perspective, selection criteria should consider cultivars with high stability and adaptive plasticity, particularly in relation to adaptation to climate change. Extrapolating these criteria in this study, despite the apparent adaptability of Arbequina in southern Brazil, this cultivar seems to depend its yield to a great extent on the environment when compared to Koroneiki or Picual.

Many studies have used PP indices to summarize the expression of environmentally contingent traits for a given species, set of species, or populations within a given species (Valladares et al. 2006). In this research, the potential for comparing genotypes of a quantitative approach to PP based on the grand plasticity index was explored. Large differences between each of the values of the variables analyzed within each cultivar separately are seen in Table 2. PP has been extensively studied in plants, which can have very drastic effects on their growth and development induced by the environment. Recently, some studies have focused on the aspects of plasticity that are more directly related to the reproductive and functional success of plants, being able to respond to changes in environmental conditions through the plasticity of many aspects of their phenotypes.

CONCLUSION

Despite the fact that olive cultivation has spread throughout the world through clonal replicas of a diverse group of cultivars, and the complete genome of the olive tree has recently been disclosed, there are still many unanswered questions regarding heritability and how different traits may be strongly influenced by environmental conditions.

Of the measured variables, when performing a Pearson's correlation analysis, an associative pattern with positive significance could be observed between the length and width of the whole fruit, or the fresh weight and width. Likewise, a significant pattern was shown between the length of the endocarp and the length of the whole fruit.

When considering each tree as an individual production unit, it was observed that the length of the fruit and the endocarp presented centered dispersion values, except for Arbequina, whose values showed different patterns possibly associated with the location of the trees planted on altitude different.

In the case of the DA, almost all the cultivars showed values within the range of virgin oils between 0.6 and 2, with the exception of the Arbequina cultivar, which showed high values close to 3. For the peroxide index analysis, the highest mean value was related to Koroneiki, and the greatest variability was observed in Frantoio.

The heritability values within each of the cultivars showed that Koroneiki or Picual had their traits mainly under genetic control, while Arbequina was particularly regulated by the genotype-environment action, under local growing conditions study in the southern region of Brazil. Therefore, this study could generate a series of concerns about the behavior of the cultivars in other regions of the country.

AUTHORS' CONTRIBUTION

Design: Chacón-Ortiz, A., Pegoraro, C.; **Data collection:** Chacón-Ortiz, A., Venske, E.; **Formal analysis:** Chacón-Ortiz, A., Maia, L., Pegoraro, C.; **Writing – Original Draft:** Chacón-Ortiz, A., Pegoraro, C.; **Writing – Review and Editing:** Maia, L., Oliveira, A. C., Venske, E.

DATA AVAILABILITY STATEMENT

All dataset were generated and analyzed in the current study.

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REFERENCES

Adakalic, M. and Lazovic, B. (2018). Morphological, chemical and molecular characterization of 'old olive' (*Olea europaea* L.) from Montenegro. Brazilian Archives of Biology and Technology, 61, 1-13. https://doi.org/10.1590/1678-4324-2018170767

Alfieri, S. M., Riccardi, M., Menenti, M., Basile, A., Bonfante, A. and De Lorenzi, F. (2019). Adaptabilidad de los cultivares de olivo a nivel mundial a la disponibilidad de agua en el futuro clima mediterráneo. Mitigation and Adaptation Strategies for Global Change, 24, 435-466. https://doi.org/10.1007/s11027-018-9820-1

Cruz, F., Julca, I., Gómez-Garrido, J., Loska, D., Marcet-Houben, M., Cano, E., Galán, B., Frias, L., Ribeca, P., Derdak, S., Gut, M., Sánchez-Fernández, M., García, J. L., Gut, I. G., Vargas, P., Alioto, T. S. and Gabaldón, T. (2016). Genome sequence of the olive tree, *Olea europaea*. Gigascience, 5, s13742-016-0134-5. https://doi.org/10.1186/s13742-016-0134-5

Falconer, D. S. and Mackay, T. F. C. (1996). Introduction to Quantitative Genetics. 4. ed. Harlow: Longmans Green.

Fernandes, R. C., Busanello, C., Viana, V. E., Venske, E., Oliveira, V. F., Lopes, J. L., Maia, L. C., Oliveira, A. C. and Pegoraro, C. (2022). Genetic variability and heritability of agronomic traits in a wheat collection used in southern Brazil. Journal of Crop Science and Biotechnology, 25, 337-348. https://doi.org/10.1007/s12892-021-00135-z

Íñiguez, A., Paz, S. and Sánchez, L. (1999). Variedades del olivo de la Comunidad Valenciana. Cuadernos de Tecnología Agraria Generalitat Valenciana. Serie Olivicultura, 1, 1-24.

Julca, I., Marcet-Houben, M., Cruz, F., Gómez-Garrido, J., Gaut, B. S., Díez, C. M., Gut, I. G., Alioto, T. S., Vargas, P. and Gabaldón, T. (2020). Genomic evidence for recurrent genética mixture during the domestication of Mediterranean olive trees (*Oleaeuropaea* L.). BMC Biology, 18, 148. https://doi.org/10.1186/s12915-020-00881-6

Lavee, S. and Avidan, B. (2012). Aspects of female heredity in the breeding progeny of different olive cultivars. Acta Horticulturae, 949, 85-92. https://doi.org/10.17660/ActaHortic.2012.949.11

Lorite, I. J., Gabaldón-Leal, C., Ruiz-Ramos, M., Belaj, A., Rosa, R., León, L. and Santos, C. (2018). Evaluation of olive response and adaptation strategies to climate change under semi-arid conditions. Agricultural Water Management, 204, 247-261. https://doi.org/10.1016/j.agwat.2018.04.008

Mora, F., Tapia, F, Ibacache, A., Nunes-Martins, E. and Scapim, C. A. (2008). Evaluación genética de clones de olivo en el desierto de Atacama, Chile. Agrociencia, 42, 777-786.

Moran, E. V., Hartig, F. and Bell, D. M. (2016). Intraspecific trait variation across scales: implications for understanding global change responses. Global Change Biology, 22, 137-150. https://doi.org/10.1111/gcb.13000

Mousavi, S., de la Rosa, R., Moukhli, A., El Riachy, M., Mariotti, R., Torres, M., Pierantozzi, P., Stanzione, V., Mastio, V., Zaher, H., El Antari, A., Ayoub, S., Dandachi, F, Youssef, H., Aggelou, N., Contreras, C., Maestri, D., Belaj, A., Bufacchi, M., Baldoni, L. and Leon, L. (2019). Plasticity of fruit and oil traits in olive among different environments. Scientific Reports, 9, 16968. https://doi.org/10.1038/s41598-019-53169-3

Navas, M. L. and Garnier, E. (2002). Plasticity of whole plant and leaf traits in Rubiaperegrina in response to light, nutrient and water availability. Acta Oecologica, 23, 375-382. https://doi.org/10.1016/s1146-609x(02)01168-2

Navas-Lopez, J. F., León, L., Trentacoste, E. R. and de la Rosa, R. (2019). Multi-environment evaluation of oil accumulation pattern parameters in olive. Plant Physiology Biochemistry, 139, 485-494. https://doi.org/10.1016/j.plaphy.2019.04.016

Nicotra, A. B., Segal, D. L., Hoyle, G. L., Schrey, A. W., Verhoeven, K. J. and Richards, C. L. (2015). Adaptive plasticity and epigenetic variation in response to warming in an Alpine plant. Ecology Evolution, 5, 634-647. https://doi.org/10.1002/ece3.1329

Rallo, L. and Cuevas, J. (2017). El Cultivo del Olivo. Fructificación y Producción. Madrid: Mundi-Prensa.

Rallo, L., Barranco, D., Caballero, J. M., Del Río, C., Martín, A., Tous, J. and Trujillo, I. (2005). Variedades de olivo en España. Madrid: Junta de Andalucía, MAPA y Ediciones Mundi-Prensa.

Servili, M., Esposto, S., Taticchi, A., Urbani, S., Di Maio, I., Veneziani, G. and Selvaggini, R. (2015). New approaches to virgin olive oil quality, technology, and by-products valorization. European Journal of Lipid Science and Technology, 117, 1882-1892. https://doi.org/10.1002/ejlt.201500138

Tous, J., Romero, A., Plana, J., Guerrero, L. and Diaz, I. and Hermoso, F. (1997). Características químico-sensoriales de los aceites de oliva arbequina obtenidos en distintas zonas de España. Grasas y Aceites, 48, 415-424. https://doi.org/10.3989/gya.1997.v48.i6.814

Valladares, F., Sanchez-Gomez, D. and Zavala, M. (2006). Quantitative estimation of phenotypic plasticity: bridging the gap between the evolutionary concept and its ecological applications. Journal of Ecology, 94, 1103-1116. https://doi.org/10.1111/j.1365-2745.2006.01176.x

Villa, L. (2004). Guía completa del cultivo del olivo. Barcelona: Editorial De Vecchi.

Whitman, D. W. and Anurag, A. (2009). What is phenotypic plasticity and why is it important? In D. W. Whitman and T. N. Ananthakrishnan (Eds.). Phenotypic plasticity of insects: mechanisms and consequences (p. 1-63). New York: Science Publishers.

Zarrouk, W., Haddada, F. M., Baccouri, B., Oueslati, I., Taamalli, W., Fernandez, X., Lizzani-Cuvelier, L., Daoud, D. and Zarrouk, M. (2008). Characterization of virgin olive oil from Southern Tunisia. European Journal of Lipid Science and Technology, 110, 81-88. https://doi.org/10.1002/ejlt.200700085