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Phenotypic correlation and path analysis for fruit traits in genotypes of pineapple

Joseane Luiza Gomes [1,*], José Severino de Lira Júnior [2] and Edson Ferreira da Silva [1]

[1] *Department of Agronomy, Federal Rural University of Pernambuco (UFRPE), Recife, Pernambuco State, Brazil.*
[2] *Department of Research and Development, Experimental Station of Itambé, Agronomic Institute of Pernambuco (IPA), Itambé, Pernambuco State, Brazil.*

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Abstract

The breakdown of the correlation coefficient into direct and indirect effects allows for more balanced genetic gains to be obtained between the explanatory variables on the main variable in genetic improvement programs. This study aimed to estimate the direct and indirect effects on the fruit mass without the crown of pineapple half-sibling genotypes by unfolding the phenotypic correlation matrix obtained between the fruit variables. The phenotypic correlation matrix was estimated for 103 pineapple half-sibling genotypes, which was decomposed into direct and indirect effects, considering eight explanatory variables (Xi) on the main variable mass of the fruit without crown (Y). Phenotypic correlation coefficients ranged from -0.253 to 0.869. The mass of the fruit without the crown showed significant and high magnitude correlations with the length of the fruit (0.792), circumference of the base of the fruit (0.756) and circumference of the middle third of the fruit (0.707). It was concluded, by path analysis, that the fruit's length and the fruit's circumferences (middle third and base of the fruit) are the characteristics that presented the great direct effects on the basic variable.

Keywords: *Ananas comosus* var. *comosus*; Tropical fruit; Plant breeding; Simultaneous gains

1. Introduction

The pineapple (*Ananas comosus* (L.) Merr. var. *comosus* Coppens & Leal) is considered the most important species of the Bromeliaceae family [1]. Its fruit is widely recognized as an excellent source of vitamins A, B, and C, as well as several minerals, including calcium, phosphorus, and iron [2]. Regarding its use, the fruit is consumed fresh and in industrialized products, such as syrups, pulps, sweets, concentrated juices, liqueurs, and others [3].

The external appearance of pineapples with crowns represents the final product, traditionally sold individually in supply centers, supermarkets, and open-air markets in Brazil. Among the physical attributes that attract Brazilian consumers, the size of the pineapple stands out, whose classification by weight is essential to meet the different segments and market niches for fresh consumption [4]. According to the classification established by [5], pineapple fruits must weigh at least 0.9 kg, and larger fruits get the best prices on the Brazilian market. Among the physical attributes that attract Brazilian consumers, fruit size stands out, with classification by weight becoming essential to meet distribution across different segments and market niches, including fresh fruit one. Furthermore, it is worth noting that the fruit mass is directly related to pulp productivity, an essential characteristic of the processing industry. Pineapple is widely cultivated in tropical and subtropical regions, being produced in about 90 countries around the world [6]. World pineapple production in 2024 reached 29.4 million tons, harvested from a cultivated area of 1,056,112 million hectares. The main producing countries were the Costa Rica, Philippines, Indonesia and Brazil, with 3.12, 2.92, 2.74 and 2.23 million tons, respectively [7]. In Brazil, 1.482.136 thousand fruits were produced in 2024, harvested from

*Corresponding author: Joseane Luiza Gomes

56.96 thousand hectares, with the largest yields being the States of Paraíba (300.903 thousand fruits), Pará (290.432 thousand fruits) and Minas Gerais (143.737 thousand fruits) [8].

Pineapple genetic improvement programs seek to develop cultivars with superior characteristics, mainly about plant productivity, resistance to pests and diseases, fruit size, cylindrical shape, small crown, and high soluble solids content [9]. In this context, knowledge of the association between characters is of great importance in breeding work, especially if the selection of one of the characters presents difficulties due to low heritability and has measurement and identification problems [10].

The use of correlation becomes important because, through knowledge of the magnitude of the performance of a variable, it is possible to evaluate its influence on another variable that is of interest to the breeder [11]. In this context, the relationships between traits are generally evaluated through genotypic, phenotypic, and environmental correlations. Phenotypic correlation results from genetic and environmental causes and only causes of gene origin are used in breeding programs, as they are heritable [12]. However, despite being very useful in quantifying the magnitude and direction of influence in determining complex characters, correlation coefficients do not give the exact relative importance of these factors' direct and indirect effects [10].

The path analysis proposed by Wright in the last century unfolds the estimated correlations into direct and indirect effects of a set of studied variables (explanatory) on a basic variable (principal), generating more accurate estimates of cause and effect [13]. This method has been successfully used in several fruit species, such as passion fruit (*Passiflora edulis* Sims.) [14], papaya (*Carica papaya* L.) [15] and açaí (*Euterpe oleraceae* Mart.) [16]. However, there are no path analysis studies in the pineapple literature.

In this context, this work aimed to estimate the direct and indirect effects on the mass of pineapple fruit without the crown by unfolding the phenotypic correlation matrix obtained between the fruit variables of pineapple half-sibling genotypes under rainfed cultivation.

2. Material and methods

2.1. Experiment location

The experiment was conducted from March 2021 to December 2022 at the Itambé Experimental Station of the Pernambuco Agronomic Institute (IPA) (latitude 7° 24' 16.80'' S, longitude 35° 10' 54.00'' W, alt. 190 m). The region's climate is hot and humid, classified as As (Köppen), with an average annual temperature of 25°C and an average yearly precipitation of 1.200mm [4].

2.2. Plant materials

A total of 103 half-sib pineapple genotypes developed by the Genetic Improvement Program of the IPA, named from IPA 1 to IPA 103, were evaluated. The seeds that originated the genotypes were obtained by [4] by hybridization using the cultivar 'Pérola' as the female parent and a mixture of pollen from the cultivars 'BRS Imperial', 'BRS Vitória', and 'MD-2'. The parental cultivars have contrasting and complementary characteristics, such as fruit size and shape, pulp colour, total soluble solids concentration, leaf margin epinescence, growth vigour, plant adaptability, and distinct response to resistance to fusarium wilt [17, 18].

2.3. Experimental design

Federer's Augmented Block design was adopted due to the limited availability of propagation material and the large number of genotypes to be evaluated (105), as is frequently in the initial phase of breeding programs for vegetatively propagated species. The cultivars 'BRS Imperial' and 'Pérola' were considered common treatments, and 103 half-sib genotypes were considered non-common treatments. Treatments were randomly distributed in ten incomplete blocks, in which the experimental plots varied from two to ten plants planted in double rows with spacing of 1 m between double rows and 0.40 x 0.40 cm between plants.

2.4. Planting and cultural management

Seedlings of the pup type about 20 cm tall were planted. The experiment was conducted under rainfed conditions without artificial floral induction, and flowering occurred naturally. Fertilization was carried out according to soil analysis and recommendations by [19].

2.5. Evaluation of fruit traits

Evaluation was carried out when fruits were ripe, showing a colour change (becoming yellow) in at least 50% of the skin and the flattened shape of the multiple fruits. The following traits were evaluated: fruit mass without crown - FMWC (g), crown mass - CM: (g), fruit length - FL (cm), crown length - CL (cm), fruit base circumference - FBC (cm), circumference of the middle third of the fruit - CMTF (cm), circumference of the fruit apex - CFA (cm), diameter of the central axis - DCA (mm) and soluble solids - SS (°Brix).

2.6. Estimation of the phenotypic correlation matrix

The averages per genotype were used to estimate the phenotypic correlation matrix between all pairs of random variables (X, Y), considering the following equation.

$$\hat{r} = \frac{\hat{Cov}(X,Y)}{\sqrt{\hat{V}(X)\hat{V}(Y)}}, \text{ in which: } \hat{Cov}(X,Y): \frac{\sum_{i=1}^{n} x_i y_i}{n-1}; \ \hat{V}(X): \frac{\sum_{i=1}^{n} x_i^2}{n-1}; \ \hat{V}(Y): \frac{\sum_{i=1}^{n} y_i^2}{n-}$$

The significance of the correlation was estimated by the t-test with (n-2) degrees of freedom at 1% and 5% probability levels, where 'n' corresponded to the number of genotypes evaluated [10].

For path analysis, the multicollinearity diagnosis of the phenotypic correlation matrix was performed according to Montgomery and Peck (1981). This method is based on the number of conditions (NC), which is the ratio of the largest to the smallest value in the matrix. This method is based on the number of conditions (NC), which is the ratio of the largest and smallest values in the matrix.

This criterion considers weak multicollinearity between the explanatory variables when the relationship between the largest and smallest value is equal to or less than 100, moderate to severe when the value is greater than 100, and severe when the NC is greater than 1,000.

For path analysis, the characteristic fruit mass without crown (MFSC) was considered as the dependent variable and the other characteristics as explanatory variables. Considering the following equation was used [10]:

$$Y = \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + \varepsilon$$

In this case, X1, X2,..., Xn correspond to the explanatory variables, and Y to the independent variables.

The path coefficients were estimated from the system of equation. $X\hat{\beta} = X'Y$, In which:

$$X'Y = \begin{bmatrix} r_{1y} \\ r_{2y} \\ \cdots \\ r_{ny} \end{bmatrix}, \quad X'X = \begin{bmatrix} 1 & r_{12} & \cdots & r_{1n} \\ r_{12} & 1 & \cdots & r_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ r_{1n} & r_{2n} & \cdots & 1 \end{bmatrix} \text{ e } \quad \hat{\beta} = \begin{bmatrix} p_1 \\ p_2 \\ \cdots \\ p_n \end{bmatrix}$$

In this way, the correlation between the dependent and explanatory variables was decomposed according to [10] according to the following Equation.

$$r_{iy=} \ p_i + \sum_{j \neq i}^{n} p_j \, r_{ij}$$

Where:

r_{ij}- Corresponds to the correlation between the main variable (y) and *I* the variables explanatory; p_i- corresponds to the average of the direct effect of I variable on the main variable and $p_j r_{ij}$ - corresponds to the measure of the indirect effect of the variable by j variable on the main variable.

The determination of the track diagram was given by Equation:

$$r_{1y} = p_1 + p_2 r_{12} + \ldots + p_n r_{1n}$$

$$r_{2y} = p_1 r_{12} + p_2 + \dots + p_n r_{2n}$$

$$\dots \dots \dots$$

$$r_{ny} = p_1 r_{1n} + p_2 r_{n2} + \dots + p_n$$

In which:

$$r_{iy=}\ p_i + \sum_{j \neq i}^{n} p_j\, r_{ij}$$

The determination of the track diagram was given by the equation:

$$R^2 = p_1 r_{1y} + p_2 r_{2y} + \dots + \ p_n r_{ny}$$

And the effect of the residual variable was estimated using the equation:

$$\widehat{p_\varepsilon} = \sqrt{1 - R^2}$$

All analyses were performed using GENES: a software package for analysis in experimental statistics and quantitative genetics [20].

3. Results and discussion

3.1. Phenotypic correlations

The estimated correlations ranged from -0.253 to 0.824 (Table 1), whose values are within the parametric space of -1 to 1, indicating good reliability of results according to [21].

Table 1 Estimated phenotypic correlation coefficients between the nine fruit variables, measured in 103 half-sibling genotypes of pineapple (*A. comosus* var. comosus), evaluated in the field under rainfed cultivation in the municipality of Itambé, Zona da Mata Norte of Pernambuco, Agronomic Institute of Pernambuco–IPA

Traits	**CM**	**FL**	**CL**	**CBF**	**CTMF**	**CBF**	**DCA**	**SS**
FMWC	0.065	0.792**	-0.011	0.756**	0.707*	0.199	0.391	-0.199
CM		-0.253*	0.824**	0.179	0.306	0.300	0.295	-0.071
FL			-0.229*	0.387	0.238	-0.199	0.073	-0.034
CL				0.093	0.181	0.176	0.154	-0.098
CBF					0.869**	0.354	0.490	-0.235*
CTMF						0.553	0.563*	-0.240**
CAF							0.430	-0.081
DCA								-0.176*

**, *: significant at 1% and 5% probability, by t-test, respectively.FMWC -fruit mass without crown (g), CM - crown mass (g), FL -fruit length (cm), CL - crown length (cm), CBF - circumference of the base of the fruit (cm), CMTF -circumference of the middle third of the fruit (cm), CAF - circumference of the apex of the fruit (cm), DCA -diameter of the central axis (mm) and, SS - soluble solids (°Brix).

The highest positive and significant correlations were estimated between the circumference of the base and middle third of the fruit (0.869), crown mass, and crown length (0.824), (Table 1). These results are relevant, as positive, significant correlations among variables can serve as important indicators of desirable phenotypic traits, contributing to success in plant breeding. According to [22], one possible cause of the high correlation between two variables is pleiotropy, a form of inheritance in which a single gene controls or influences the expression of more than one trait. This genetic control is proper in plant breeding because it allows the simultaneous selection of two or more variables based on the phenotypic evaluation of only one of these traits, which is relatively easier to measure and/or has high heritability.

High positive and significant correlations were found between the mass of the fruit without the crown and the following variables: fruit length (0.792), circumference of the fruit base (0.756), and circumference of the middle third of the fruit (0.706), (Table 1). According to [23], positive correlations indicate variations in the characteristics' means occur in the same direction. Therefore, selecting genotypes to increase mean fruit mass without the crown will also imply increases in fruit length, the circumference of the fruit base, and the circumference of the fruit's middle third, as these were positively correlated. These findings suggest that selection based on the variables: fruit length, base circumference, and the middle third of the fruit would be highly effective, as these characteristics are strongly associated with the fruit's mass without the crown. These results are in agreement with those obtained by [24], who, when studying the Person's correlation coefficients between characteristics of the pineapple' BRS Imperial', observed that the greater the mass of the fruit without a crown, the greater the diameter and length of the fruit.

The correlation between the variable crown mass and fruit length was statistically significant but negative. The crown mass with crown length was statistically significant, positive, and of high magnitude (0.823), and the other characteristics were insignificant. These results suggest that increasing crown mass will consequently increase crown length. A negative and significant correlation was observed between fruit length and crown length (-0.229); however, it is of low magnitude, indicating an inversely proportional relationship between these variables. According to [23], the means vary in the opposite direction for characteristics with negative correlations. Therefore, selecting genotypes to increase fruit length will reduce crown length, as these were negatively correlated characteristics. No significant correlation was observed between crown length and the variables analyzed, evidencing that this variable does not influence the evaluated characters. Thus, the commercialization of fresh fruit can be carried out without any harm to the end consumer since the length of the crown is a characteristic of lesser relevance compared to the other characteristics evaluated that impact the quality of the fruit.

Considering the variable circumference of the fruit base, a high magnitude and significant phenotypic correlation was observed with the trait circumference of the middle third of the fruit (0.869), demonstrating that the increase in the circumference of the fruit base will cause an increase in the circumference of the middle third of the fruit due to the strong correlation observed. On the other hand, the correlation between the variables, the circumference of the fruit base and soluble solids, was significant but of a negative value (-0.235), suggesting that larger fruits tend to have lower soluble solids levels. The correlation between the circumference of the fruit base and the other traits was insignificant, indicating that they act independently despite the low correlation. Therefore, it is disadvantageous because, in this way, it is not possible to obtain gains through indirect selection. According to [12], when there is a significant correlation between two traits, it is possible to obtain gains in one of them through indirect selection of the other. Therefore, it is particularly favourable when a trait that has high economic value has low heritability or is difficult to evaluate compared to another trait with which it is associated.

The variable circumference of the middle third of the fruit had a positive and significant correlation with the diameter of the central axis (0.555) and an important but negative correlation with soluble solids (-0.240). Likewise, the diameter of the central axis had a significant and negative correlation with soluble solids (-0.176). These results suggest that genotypes that present an increase in the variable circumference of the middle third of the fruit will also have an increase in the diameter of the central axis, but may present lower levels of soluble solids.

In this study, the correlation coefficient measured only linear relationships; however, there may be an association between non-linear variables. The high correlations observed do not necessarily imply a cause-and-effect relationship, as they may be due to the indirect effect of another variable or even a group of variables. Path analysis breaks down the correlation coefficient into direct and indirect effects, providing greater reliability in interpreting the cause-and-effect relationships between the characteristics evaluated [24].

3.2. Path analysis (one chain)

The multicollinearity diagnosis in the correlation matrix revealed weak collinearity, with a condition number (CN) of 79.59, less than 100. Therefore, it indicates a low degree of linear dependence between the variables, which does not distort the estimates and eliminates the possibility of incorrect interpretations of the correlation coefficients, making the results reliable.

The coefficient of determination (R2) value was 0.924. The effect of the residual variable was 0.276, which indicates that 92% of the increase in the variable mass of the fruit without crown is explained by the effect of the variables analyzed; that is, the model was well adjusted to explain the genetic effects related to the variable under analysis.

Table 2 presents the results of the path analysis for the mass of the fruit without crown (MFSC), the main variable, based on the explanatory variables (MC, CF, CC, CBF, CTMF, CAF, DEC, and SS). The sum of the direct and indirect effects results in the correlation coefficient [25]. In this context, the variables fruit length, fruit base circumference and circumference of the middle third of the fruit had the highest correlation coefficients, with values of 0.792, 0.755 and 0.707, respectively. These results corroborate the estimates of phenotypic correlations that obtained positive and high-magnitude correlations between these variables.

For breeding purposes, it is important to identify, among the traits with high correlation with the main variable, those with the greatest direct effect on selection so that the correlated response through indirect selection is efficient [10]. In this context, among the variables analyzed, fruit length was the one that had the greatest direct effect (0.687), followed by the circumference of the middle third of the fruit, which had the second greatest direct effect (0.349), being superior to the effect of the residual variable, Table 2. These results show that the length of the fruit and the circumference of the middle third of the fruit are the variables that directly contribute to the increase in the mass of the fruit without crown.

Table 2 Direct and indirect effects of eight fruit variables on the weight of pineapple without crown, measured in 103 half-sib genotypes of pineapple (*A. comosus* var. comosus), evaluated in the field, under dry land cultivation in the municipality of Itambé, Zona da Mata Norte, Pernambuco, Agronomic Institute of Pernambuco – IPA

Variables	**Effects**	**CM**	**FL**	**CL**	**CBF**	**CTMF**	**CAF**	**DCA**	**SS**
FMWC	Direct	0.12	0.687	-0.046	0.127	0.349	0.056	0.021	-0,049
CM	Indirect	-	-0.031	-0.157	0.022	0.037	0.036	0.036	-0,009
FL	Indirect	-0.174	-	0.099	0.266	0.164	-0.137	0.499	-0,025
CL	Indirect	-0.038	0.013	-	-0.004	-0.008	-0.008	-0.007	0,005
CBF	Indirect	0.023	0.049	0.012	-	0.111	0.045	0.062	-0,030
CTMF	Indirect	0.107	0.083	0.063	0.304	-	0.193	0.197	-0,083
CAF	Indirect	0.017	-0.011	0.009	0.019	0.301	-	0.023	-0,005
DCA	Indirect	0.006	0.002	0.003	0.01	0.012	0.009	-	-0,004
SS	Indirect	0.0034	0.002	0.005	0.011	0.012	0.003	0.009	-
Total		0.065	0.792	-0.011	0.756	0.707	0.198	0.391	-0,199
R^2		0.924							
ERV		0.276							

FMWC -fruit mass without crown (g), CM - crown mass (g), FL -fruit length (cm), CL - crown length (cm), CBF - circumference of the base of the fruit (cm), CMTF -circumference of the middle third of the fruit (cm), CAF - circumference of the apex of the fruit (cm), DCA -diameter of the central axis (mm) and, SS - soluble solids (°Brix).R^2: Coefficient of determination. ERV: Effect of residual variable.

The variable circumference of the fruit base had a low direct effect (0.127) on fruit mass without the crown; however, a high phenotypic correlation was observed between these two variables. This result indicates that the circumference of the fruit base does not directly contribute to the increase in the mass of the fruit without a crown, suggesting that the high correlation observed may be due to indirect effects of the other characteristics evaluated. According to [10], characters with a high correlation and a low direct effect indicate that their selection may not provide satisfactory gains for the main variable. In this case, the best strategy is to use a simultaneous selection of characters, emphasizing characters whose indirect effects are significant.

Considering the indirect effects, high values were obtained between the circumference of the base and the middle third of the fruit (0.304) and between the circumference of the middle third and the apex of the fruit (0.301). These results were higher than the residual variable (0.276), indicating that indirect gains through selection can be obtained. However, the other indirect effects between the variables evaluated were low and lower than the residual effect, indicating that indirect selection in these characters is not viable.

The total correlation coefficient and the direct effect of the soluble solid variable on the mass of the fruit without crown were low and negative, with values of -0.199 and -0.049, respectively. These results indicate that this variable does not influence the selection for increasing the fruit mass without a crown, and there is no cause-and-effect relationship. Therefore, the soluble solids variable does not contribute to the increase in the mass of the fruit without crown, which is mainly influenced by the variables that presented the greatest direct and positive effect.

Therefore, it can be inferred that the trait mass of the fruit without a crown, the length of the fruit and the circumference of the middle third of the fruit can be used as selection criteria in the genetic improvement of pineapple (*A. comosus* (L.) Merr. var. *comosus*), to select fruits with a greater mass of the fruit without crown since larger fruits with a small crown are favourable to consumer markets. However, the inverse relationship with total soluble solids must be considered. Genotypes with greater fruit mass without a crown can be selected, but they have lower soluble solids content, which is a disadvantage for the consumer market.

4. Conclusion

Fruit length and circumferences of the base and middle third of the fruit are the variables with the greatest potential to select pineapple genotypes with higher averages for fruit mass without crown, as they are highly correlated and have a greater direct effect on fruit mass without crown. However, genotypes with higher averages for fruit mass without crown will have low soluble solids content due to negative correlations and a lower direct effect observed.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare that they have no conflict of interest related to the content of this manuscript**.**

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