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Simultaneous gains for negatively correlated traits of interest in plantain

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Abstract – The objective of this work was to identify negative correlations between phenotypic characteristics (agronomic and physicochemical) in plantain (*Musa paradisiaca*), and to evaluate selection indices to obtain simultaneous gains for agronomically relevant characteristics. Thirteen plantain genotypes were evaluated in a randomized complete block design with four replicates. Data on 16 agronomic and physicochemical traits were collected. Genotype dispersion regarding the set of traits was evaluated using the principal component analysis and the separation of dissimilarity groups via clustering (Mahalanobis distance). The genotypes were divided into four groups, in which genotypes 13 (commercial) and 9 (wild) formed isolated groups. Positive correlations between yield and plant height, in addition to negative correlations between these two and the content of soluble solids (SS) were identified. Taller plantain plants had the tendency to produce more, but with late fruit, which were more acid and had a lower SS content. Therefore, correlations between yield, plant height, and SS posed a challenge for the development of plantain cultivars. The index of Mulamba & Mock was applied, which allowed of obtaining simultaneous gains in the target traits. The multitrait selection indices are appropriate to identify plants that are shorter, more productive, and that have fruit with a higher SS contents.

Index terms: *Musa paradisiaca*, genetic divergence, nonparametric selection indices, selection gain, undesirable correlations.

Ganhos simultâneos em caracteres de interesse negativamente correlacionados em banana-da-terra

Resumo – O objetivo deste trabalho foi identificar correlações negativas entre características fenotípicas (agronômicas e físico-químicas), em banana-da-terra (*Musa paradisiaca*), e avaliar índices de seleção para obter ganhos simultâneos em características agronomicamente relevantes. Avaliaram-se 13 genótipos de banana-da-terra, em delineamento de blocos ao acaso, com quatro repetições. Dados de 16 características agronômicas e físico-químicas foram coletados. Avaliou-se a dispersão dos genótipos quanto ao conjunto de caracteres, por meio da análise de componentes principais e da separação de grupos de dissimilaridade, via agrupamento (distância de Mahalanobis). Os genótipos foram divididos em quatro grupos, em que os genótipos 13 (comercial) e 9 (silvestre) formaram grupos isolados. Foram identificadas correlações positivas entre produtividade e altura da planta, além de correlações negativas de ambas com o teor de sólidos solúveis (SS). Plantas de banana-da-terra mais altas tenderam a produzir mais, porém, com frutos tardios, mais ácidos e com menor teor de SS. Portanto, as correlações entre produtividade, altura de planta e SS representaram um fator complicador no desenvolvimento de cultivares de banana-da-terra. O índice de Mulamba & Mock foi aplicado, o que possibilitou obter ganhos simultâneos para os caracteres de interesse. Os índices de seleção multicaracteres são apropriados para identificar plantas mais baixas, mais produtivas e com maior teor de SS nos frutos.

Termos de indexação: *Musa paradisíaca*, divergência genética, índices de seleção não paramétricos, ganhos de seleção, correlações indesejadas.

Introduction

Banana trees belong to the Musaceae family and are classified into three genera: *Musa, Ensete*, and *Musella*. The genus *Musa* is the most widely known, produced, and consumed worldwide, having cultivars from several species, namely, *M. acuminata*, *M. cavendishii*, *M. sapintum*, and *M. paradisiaca*, the last one known as plantain (Mohapatra et al., 2010; Mathew & Negi, 2017). Banana is a secondary food crop, and it is important mainly in underdeveloped countries (Yuan et al., 2012; Weber et al., 2017).

The evolutionary progress of commercially cultivated bananas occurred on the Asian continent from the intra and interspecific hybridization between two wild species: *M. acuminata* Colla (genome A) and *M. balbisiana* Colla (genome B), whose resulting cultivars display di, tri or tetraploid chromosomal levels, with 22, 33 or 44 chromosomes (Simmonds & Shepherd, 1995; Robinson & Galán Sauco, 2010). Dessert bananas (AA, AAA, and AAB) are consumed raw at various maturation stages, while plantains (AAB and AAAB) are not palatable when raw, being consumed only after culinary preparations, due to their high starch content (Penna et al., 2019).

In Brazil, the plantain cultivation is predominantly practiced by family farmers (Alves et al., 2015). Anuário… (2017) reported the estimated production of 620,000 tonnes, which corresponds to about 9% of the total volume of bananas produced in the country, and 1.7% of the world plantain production in that period. According to Borges et al. (2016), plantain production is concentrated in the African continent, which accounts for 70% of the global production. Due to the potential economic contribution of banana cultivation in several countries located in tropical and subtropical zones, studies on the development of more adapted cultivars have been carried out in recent years (Gonçalves et al., 2021).

The plantain genetic improvement requires the seeking of genotypes that show a greater productivity than the present known ones, besides showing production precociousness, low-size plants aiming at easy harvesting, vigorous pseudostem to prevent falling off, disease resistance, and good quality fruit of adequate size, shape, high contents of soluble solids, and pleasant aroma (Silva et al., 2016; Gonçalves et al., 2021). Despite the obtention of genotypes that combine all these traits (the so-called ideotype genotype) is the goal of plantain breeders, it can be hampered by the existence of undesired correlations among these traits. In a study on plantain genotypes with different ploidy levels, positive correlations were observed between plant height and bunch weight in tetraploid individuals (Ortiz, 1997). This correlation represents a challenge for breeding programs that aim to obtain productive cultivars (higher bunch mass) and low-size cultivars (smaller plant height).

Some strategies, such as the use of selection indices, have become a promising technique for the genetic improvement of plants; however, the breeder should have the common sense to choose those that best suit the study methodology, to allow the selection of the most important traits, minimizing errors that can generate unsatisfactory results (Lessa et al., 2010). Selection indices are routinely used in breeding programs aimed at selecting superior genotypes, considering multiple traits simultaneously (Kang, 2015). In this sense, many studies have been carried out on sugarcane (Tahir et al., 2014), popcorn (Vieira et al., 2016), banana (Swain et al., 2017), and mustard (Sandhu et al., 2019). In plant breeding, in general, selection indices are used to obtain simultaneous gains in weakly or negatively correlated traits (Tardin et al., 2007; Berilli et al., 2013; Crevelari et al., 2019). Although these possibilities are reported in some works with plantain, it is difficult to find results that show the potential use of this tool in the genetic improvement of the crop. In addition, correlations between physicochemical traits of interest and agronomic traits usually evaluated are hardly found in the literature.

Dépigny & Damour (2022) reports the possibility of correlating agronomic traits with cultivar plantain groups; this study showed that links were found between the monitored agronomic characteristics and the morphotaxonomic classification, suggesting the existence of specific operating laws for each subgroup of plantain. Kouassi et al. (2021) reports strong correlation between hardness and puncture force in plantain fruit, while lower correlation between textural traits and physicochemical traits. Although there are important studies on trait correlations in plantain, there is a lack of information on the impact of these correlations in genetic gains, as well on the impact of the use of selection indices involving agronomic and physicochemical traits in the plantain breeding.

Thus, the use of selection indices can help plantain breeders to obtain greater simultaneous gains for physicochemical and agronomic traits that present undesirable phenotypic correlations for the development of more promising cultivars.

The objective of this work was to identify negative correlations between phenotypic characteristics (agronomic and physicochemical) in plantain, and to evaluate selection indices to obtain simultaneous gains for agronomically relevant characteristics.

Materials and Methods

The experiment was carried out between 2018 and 2020, in the fruit growing experimental sector at Instituto Federal do Espírito Santo (IFES), in Campus de Itapina (19º31'49"S; 40º48'54"W, at 62 m altitude). The climate according to the Köppen-Geiger's classification is Aw – humid tropical, with rainy summer and dry winter. The soil in the experimental area is a Latossolo Amarelo distrófico típico (Santos et al., 2018), a typical dystrophic Ferralsol (IUSS, 2015). The accumulated rainfall in the period was 1265 mm, and mean temperature was 24.2°C (Figure 1).

The studied plantain genotypes (13) were micropropagated and developed by Embrapa Mandioca e Fruticultura, in Cruz das Almas, Bahia state, Brazil (Table 1). A randomized complete block experimental design was carried out with four replicates, making up 52 experimental plots. Each experimental plot consisted of three useful plants, spaced at 3.0×3.0 m.

At the beginning of the experiment, the soil chemical properties were: total organic carbon, 1.5 g dm^{-3}; pH in $CaCl_2$, 5.5; Ca, 1.1 cmol$_c$ dm^{-3}; Mg, 0.6 cmol$_c$ dm^{-3}; Al, 0.10 cmol$_c$ dm^{-3}; K, 118 cmol$_c$ dm^{-3}; P (Mehlich^{-1}), 25.2 mg dm^{-3}; Al+H, 2.0 cmol$_c$ dm^{-3}; sum of bases, 2.0 cmol$_c$ dm^{-3}; and base saturation, 50.0%. Soil acidity was corrected with the application and incorporation of dolomitic limestone at 1.25 g dm^{-3}, according to the recommendation for the region (Ventura & Gomes, 2005).

Pits with 0.30×0.30×0.30 m were opened, as recommended by Ventura & Gomes (2005). After opening, 1.33 g dm^{-3} P_2O_5 were applied in the pits. Plants were irrigated under a microsprinkler irrigation system, and fertilization was monthly performed and distributed at the following doses: 5.0 g N, 1.0 g P_2O_5, and 5.0 g K_2O per plant, during the experimental time.

For the orchard managing until bunches were harvested, all cultural practices – such as shoot thinning, plant shoring, navel cutting (heart), removal of nonphotosynthetic leaves, manual weeding, pesticide and fertilization applications – were performed according to technical recommendations for the crop prescribed by Ventura & Gomes (2005).

The following agronomic traits were evaluated in the development phase of plantain tree: days to flowering (DF), from the interval of days between planting and inflorescence emission; pseudostem diameter (PD,

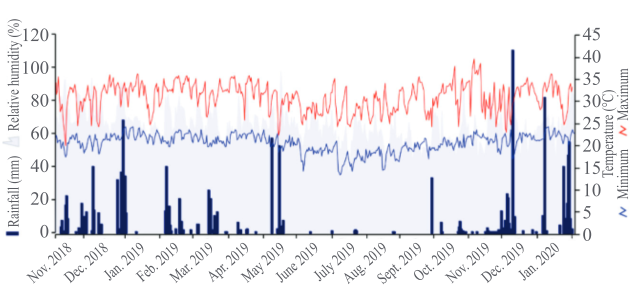

Figure 1. Accumulated rainfall, relative humidity, maximum and minimum temperatures, registered daily between November 2018 and January 2020, at the experimental field of Instituto Federal do Espírito Santo, Campus Itapina, Distrito de Itapina, ES, Brazil.

Table 1. Description of 13 plantain (*Musa paradisíaca*) genotypes from the germplasm bank of Embrapa Mandioca e Fruticultura, evaluated in a field experiment in Itapina, Espírito Santo, Brazil.

Genotype code	Access name (BAG)	Breeding stage
G1	Terra Maranhão	Cultivar – Experimental(1)
G2	Embrapa 41	Experimental
G3	Embrapa 42	Experimental
G4	Embrapa 43	Experimental
G5	Embrapa 44	Experimental
G6	Embrapa 45	Experimental
G7	Embrapa 46	Experimental
G8	Embrapa 47	Experimental
G9	Embrapa 48	Experimental – wild genotype
G10	Embrapa 52	Experimental
G11	D'Angola	Cultivar(1)
G12	Terrinha	Cultivar(1)
G13	BRS Terra Anã	Commercial Cultivar(2)

(1) Cultivars collected in small farms and under experimental analysis for registering. (2) Commercial cultivar developed by Embrapa and registered in 2023, considered in the study as a commercial type for producers and for consumer acceptance in Brazil.

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mm), using a tape by surrounding the pseudostem at 0.3 m height from the ground; plant height (H, m), by positioning a millimeter ruler from the ground to the intersection of the flag leaf; and number of photosynthetically active leaves (NPL), by counting the number in algebraic units.

For production-related traits, the following parameters were considered: days to harvest (DH), counted from the interval of days between planting and harvesting of bunches; number of fruit in the bunch (NF), by counting method (the farthest bunch from the stem was discarded, as it contained malformed and nonrepresentative fruit); fruit length (FL, cm), obtained by the arithmetic mean of values measured in 10 fruit with a digital caliper; and yield per hectare (Y), estimated from the total mass of bunches, with final value extrapolated to 1 ha (in kg ha^{-1}).

The second hand of each bunch was stored under environmental conditions for temperature and relative humidity, until it reached complete maturation (equivalent to stage 6 of skin color), according to the Von Loesecke grade scale (Banana…, 2006).

From ten stored fruit, the following physical traits were measured: skin thickness (ST), measuring in the middle third of the fruit, with a digital caliper; fresh mass of fruit with skin (MF), measured with a digital scale; pulp yield (PY), determined through the ratio between the fresh mass of fruit without skin and MF.

For chemical analyses, fruit were processed in a Philco PMP1500P Turbo 5 multiprocessor at 1 900W - 220v, until a homogeneous paste was formed. The following parameters were evaluated: total solids content (TS) and total soluble solids content (SS), by direct reading of the homogeneous paste in a refractometer; pH, in 1.0 gram of the homogeneous paste, measured with a pH meter sensor (Zenebon et al., 2008); titratable acidity content (TA), determined by potentiometric volumetry (Zenebon et al., 2008), with results expressed in malic acid percentage; incineration residues (IR), by heating fruit pulp samples at 550°C in a muffle, (Zenebon et al., 2008).

For a better understanding of the response of each pair of traits, the Pearson's correlation test was applied to data from the evaluated 16 traits of the 13 plantain genotypes, as follows: Y, yield (mass of brunches extrapolated to 1 ha); SS, soluble solids content in the fruit; H, plant height; DF, days to flowering; DH, days to harvest; NPL, number of photosynthetically active leaves; PD, pseudostem diameter; NF, number of fruit in the bunch; MF, mass of fruit with skin; PY, pulp yield; ST, skin thickness; FL, fruit length; pH, hydrogenionic potential; TA, titratable acidity content; TS, total solids content; and IR, incineration residue. The significance of correlation coefficients was tested by the t-test at 1% probability.

The evaluated traits were used for clustering genotypes and complementary study on influences of trait correlation and variation on genotypes grouping, using the principal component analysis (PCA). Biplots were constructed from the eigenvalues related to the first two components obtained. In a complementary way to compare the formation of groups obtained by PCA, the genotypes were grouped by the unweighted pair group method (UPGMA) based on the Mahalanobis distance, calculated from the model whose residual matrix was used as source of covariance.

After identifying potentially problematic correlations for simultaneous genetic gains in the selection process, gains were estimated by direct and indirect selection (using selection indices) for the traits Y (positive selection), SS (positive selection), and H (negative selection).

The applied selection intensity was 30.7% (4 genotypes), with selection gains (SG) estimated by the expression: $SG = dH^2$, in which: SG is the selection gain; d is the selection differential – obtained by the difference between the general average and the average of selected genotypes; and H^2 is the coefficient of genotypic determination that expresses the degree of correlation between genotypic and environmental effects acting on the trait expression. Selection gain was then expressed as percentage, taking the general average of the trait for all genotypes as a reference point.

The indices used for simultaneous selection were the classic indices of Smith (1936) and Hazel (1943) , with assignment of weights 10, 4000, and 1000 for Y, SS, and H, respectively; the ranking sum index of Mulamba & Mock (1978), with weights 100, 140, and 100, respectively; the index based on the desired gain proposed by Pešek & Baker (1969), with expected gains of 15%, 2%, and -2%, respectively; and the index based on the distance from the ideotype genotype (Cruz et al., 2014). The weights assigned to each index were determined through trial and error, with the aim of identifying the combination of weights that

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would optimize gains for each trait, while ensuring the desired direction (increase or decrease) for each trait.

Analyses were conducted with the help of the Genes software (Cruz, 2013) and the R software version 4.0.5 (R Core Team, 2021) based on functions available in the basic packages and in the 'corrplot' (Wei & Simko, 2021) and 'factoextra' packages (Kassambara & Mundt, 2020).

Results and Discussion

The linear correlation analysis showed positive and negative linear relations between traits. The FL showed strong positive correlation (> 0.7) with SS, TS, and MF, and strong negative correlation with NF (Figure 2). In addition, the SS displayed strong positive correlation with TS and MF, while there was strong negative correlation with NF. pH showed moderate (-0.7), or strong negative correlation (< -0.7) with TA, Y, and PD. In addition, TA showed moderate positive correlation with PD.

The TS presented strong negative correlation with NF and strong positive correlation with MF. The MF showed negative correlation with NF, and DH showed high positive correlation with NF, Y, and DF. The Y also showed moderate and strong positive correlation with PD and DF, respectively. The H showed moderate positive correlation with PD, while DF showed strong positive correlation with PD. The traits PY, ST, and IR showed lower (≤ 0.6) or absent correlation coefficients with all other traits.

In an overview, the correlation coefficients show that taller plants tend to be more productive, with less acidic and sweeter fruit. Other correlations also show that investment in strategies to increase FL may contribute to increase the SS, but with reduction of the NF and, consequently, lower Y. The existence of correlations among phenotypic traits may result from genetic correlations (close genes involved in the control of different traits), or even from correlations due to environmental effects (Cruz et al., 2014).

Although data were observed in a single environment, the correlations support the expected thought in the biological sense: larger plants have greater photosynthetic potential for the generation of greater NF with greater MF, which is mainly due to the greater FL and higher SS. The strong correlations (positive or negative) can be a result of gene linkage or pleiotropy (Chebib & Guillaume, 2021). Studies involving molecular markers, which are still poorly applied in plantains, can provide some support about genetic relations between these traits.

The greatest challenge for plantain breeders is, therefore, to reduce H without loss of Y and fruit quality. The positive correlations between H and Y had already been reported by Amoutchi et al. (2020), who evaluated several agronomic traits in nine plantain genotypes under field conditions in Côte d'Ivoire. Ortiz (1997) evaluated 118 segregating plantains with different ploidy levels and reported a correlation of 0.6 between H and Y. Despite the reports on correlations involving plant height and other agronomic traits in plantain, the correlations with the SS have been reported, for the first time, in this work.

In the PCA analyses, the first two principal components were able to explain 71.7% of the total variation among genotypes (Figure 3). Other studies have shown low variance explanation in two principal components involving agronomic traits in plantains (Osuji et al., 1997; Amoutchi et al., 2020); these studies evaluated some traits similar to those of the present study and other traits, and the total variance explained in the two first components was less than 60%. The greater variance explanation observed in the present study may be influenced by correlations between some physicochemical traits and agronomic traits.

The nonrepresentativeness of a high portion of the variance (28.3%) is an expected event in analyses such as this one, where, in addition to the high number of traits, there are negative correlations between groups of traits. The negative correlations between the group of traits SS, FL, TS, and MF (strongly correlated) with the traits pH, NF, DH, Y, and DF was visible in PCA (Figure 3). The trend of strong positive correlations between Y and DF, and between ST, H, and TA were also illustrated in PCA. Besides the strong correlations between ST, H, and TA, the TA showed bigger variation among them. The traits SS, FL, TS, MF, ST, H, TA, and pH showed a better correlation with the first component, which explained the major part of the variance. The traits Y, DF, DH, NPL, and PV showed a bigger correlation with the second component that explained 30.1% of variation. The traits PD, IR, and NF showed similar correlations with two components.

The physicochemical traits (SS and TS) and the agronomic ones (FL and MF) responded with similar variations among the genotypes (Figure 3). Bugaud et al. (2006) established a relationship between SS and other agronomic traits, such as pulp firmness and peel hardness. Additionally, a similar response of SS and pulp firmness was evidenced in bananas subjected to different humidity conditions (Rajkumar et al., 2012). This type of association between trait responses can assist breeders in indirect selection, thereby enhancing efficiency in the breeding process, where physicochemical analysis demands more time and resources.

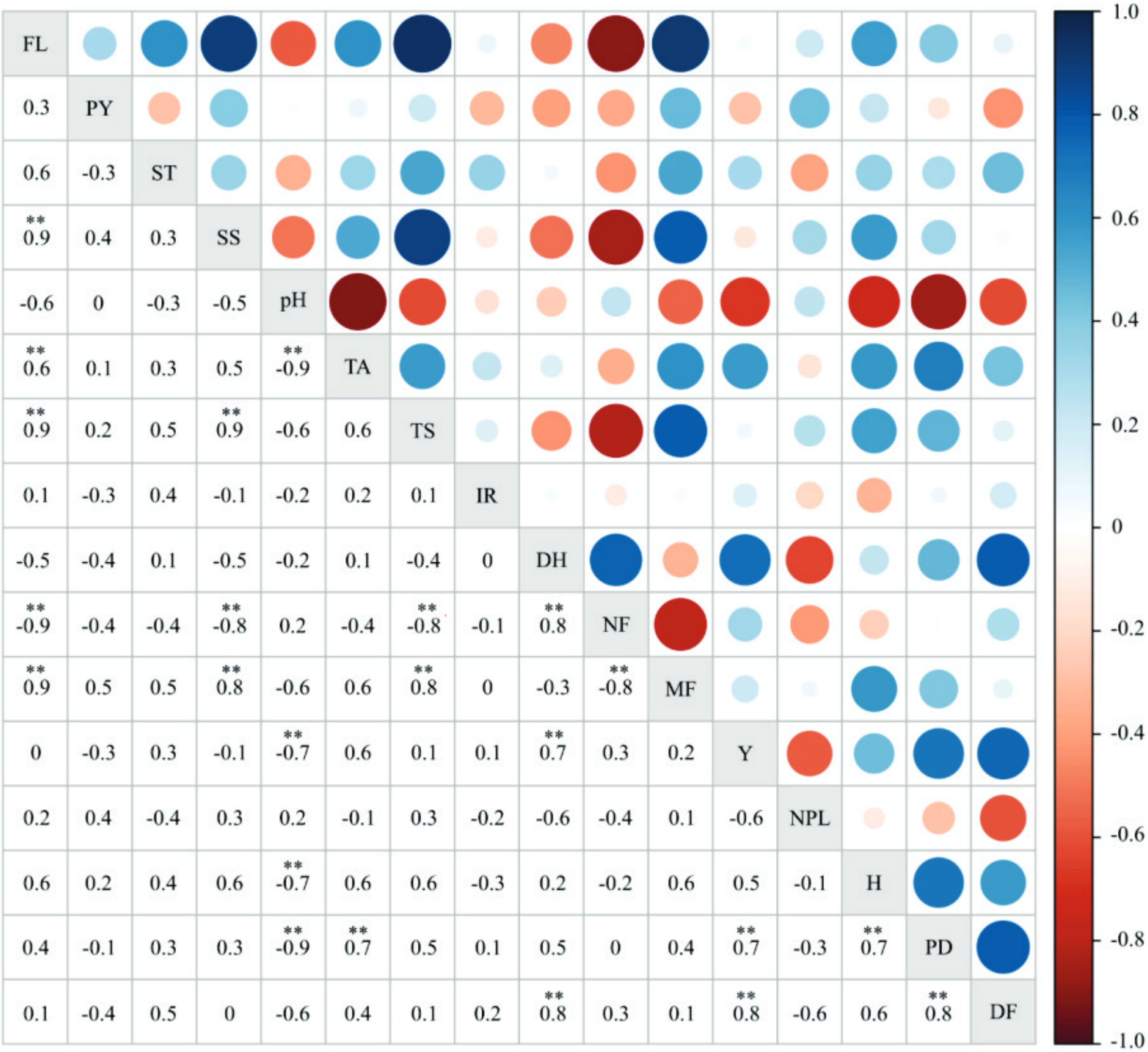

Figure 2. Phenotypic correlations (Pearson's coefficient correlation) among 16 different agronomic and physicochemical traits evaluated in plantain (*Musa paradisíaca*) genotypes: FL, fruit length; PY, pulp yield; ST, skin thickness; SS, content of soluble solids in fruit; pH, hydrogenionic potential; TA, content of titratable acidity; TS, content of total solids; IR, incineration residue; DH, days to harvest; NF, number of fruit in the bunch; MF, mass of fruit with skin; Y, yield (mass of bunches extrapolated to one hectare); NPL, number of photosynthetically active leaves; H, plant height; PD, pseudostem diameter; DF, days to flowering. **Coefficients different from zero, by the t-test, at 1% probability.

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There was no direct correspondence between traits correlation and the nature of them (agronomic aspect in plants or fruit, and chemical traits of fruit). The more correlated agronomic traits were Y, DF, PD, DH, and NF; however, these group showed negative correlation with PY. These results show that later plants tend to bear more fruit and total mass of brunch, but there is a risk for fruit being more acidic and with lesser pulp, which are unappreciated characteristics by consumers (Amah et al., 2021).

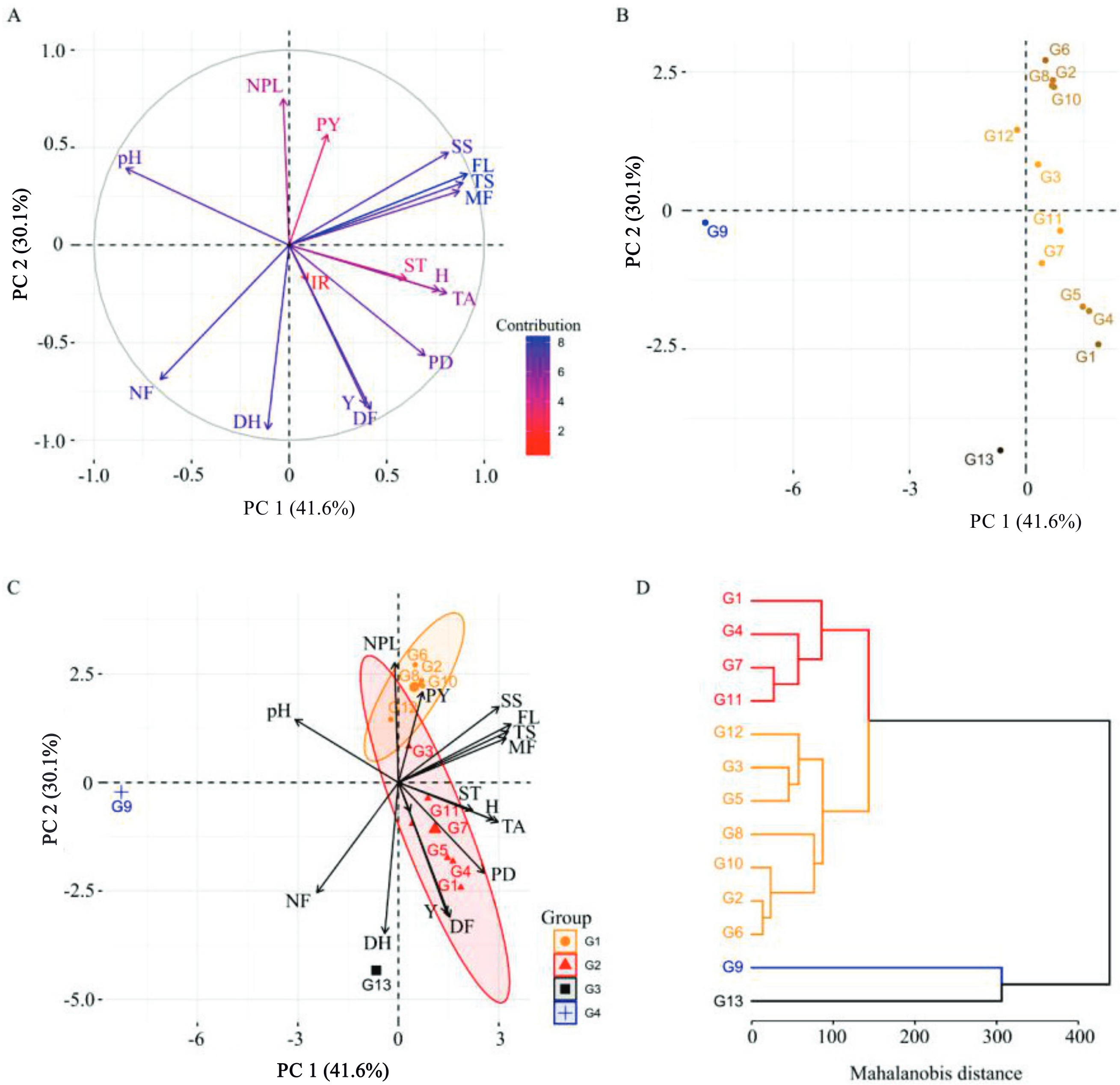

Figure 3. Grouping of plantain (*Musa paradisíaca*) genotypes for 16 quantitative traits, as follows: A, B, and C, via principal components (PC); D, via dissimilarity by the Mahalanobis' distance. Parameters: Y, yield (mass of brunches extrapolated to one hectare); SS, content of soluble solids in fruit; H, plant height; DF, days to flowering; DH, days to harvest; NPL, number of photosynthetically active leaves; PD, pseudostem diameter; NF, number of fruit in the bunch; MF, mass of fruit with skin; PY, pulp yield; ST, skin thickness; FL, fruit length; pH, hydrogenionic potential; TA, content of titratable acidity; TS, content of total solids; IR, incineration residue.

In the genotype clusterings, the thirteen plantain genotypes showed a dispersion pattern that could be characterized as four groups (Figure 3), which is similar to that also indicated by the cluster analysis based on the Mahalanobis distance. Genotypes 13 and 9 were those located at the greatest distance from the others, being also isolated from each other. Genotype 13 is a commercial plantain cultivar, which stood out for its largest PD and highest NF. Genotype 9 is a wild plantain accession, which has still viable seed in its fruit; this genotype stood out for its higher pH values and greater NF, fruit with shorter FL, MF, and low SS. The two largest groups formed by the biplot and by the dendrogram show divergences regarding the composition of the genotypes. However, it is necessary to consider that, when there are smaller intervals of distance between two genotypes, the different mathematical approaches for calculating dissimilarity may present divergences. Despite the inconsistency for the two largest groups, the two analyses were able to show the greatest distance between genotypes 13 and 9 from each other, and their distances from the other genotypes.

The greatest distance of genotype 9 from the other genotypes is an evidence of gains generated by the genetic improvement over years, which allowed of the transformation of fruit with smaller size, lower mass, and lower content of soluble solids, into sweeter fruit, with greater size and higher mass. This result is a direct evidence of the domestication process and crop improvement. provides A deep review reports the domestication process of banana and plantains, showing the impact of breeding on plantain modification from the loss of seed in the fruit (parthenocarpy) to the increase of fruit length and number of bunches (Heslop-Harrison & Schwarzacher, 2007; Brown et al., 2017).

The smaller distance between genotype 13 (commercial cultivar) from the other genotypes, evidenced in the principal component analysis, showed that the other genotypes (under the improvement process) already displayed some advantages in relation to the commercial cultivar. These advantages are associated to Y and higher SS. However, these genotypes also had larger plant than the commercial cultivar, which is an aspect that still needs to be improved by breeders.

The different results observed in the PCA analyses and UPGMA grouping from the Mahalanobis distance are expected, due to the mathematical approach of each method. Despite the standardization of data, PCA is sensitive to strongly correlated traits (multicollinearity), since correlated and representative traits can influence the less contribution of the other traits in genotype groupings (Kyriazos & Poga, 2023). However, the Mahalanobis distance is a robust approach for multicollinearity between traits, in which correlated traits are transformed into uncorrelated standardized variables (McLachlan, 1999). Although the Mahalanobis distance is the most indicated method to infer about genetic similarity between genotypes, the PCA analysis is not disposable, due to other advantages such as the visualization of the specific trait contribution to each group construction.

Regarding the evaluated traits, those of greatest primary interest in the program were Y, SS, and plant H, and the four groups indicated by the cluster analysis – groups 2 and 3 – had individuals with higher Y (Figure 4). Among these two groups, the group 2, despite having individuals with higher Y value, it included also those highest. However, the group 3, despite having individuals with smaller plant size than those of group 2, it included those with lower SS.

The characteristics of groups are evidence of the challenges to obtain simultaneous gains for the three mentioned traits. Group 4, exclusively represented by the wild accession, illustrates well that smaller plants tend to produce fruit with lower weight and lower SS (Figure 4). To obtain an ideotype (ideal genotype) in plantain was reported by Ortiz & Langie (1997), for an evaluation of six plantain genotypes, in which they showed the difficulty to joint yield and growth traits, like plant height. The results of the present study showed that the direct selection for Y would result in an increase of H, and in a reduction of SS (Table 2). Likewise, a positive direct selection for SS, or negative for H would result in the Y loss. In the case of direct selection for H reduction, in addition to the reduction of yield, there would also occur a considerable reduction of SS.

As an alternative to overcome the challenge of obtaining simultaneous gains, the application of selection indices showed advantages over the direct selection (Table 2). The selection indices of Smith and Hazel allowed to obtain the highest gains for Y and SS among all indices, but they were inefficient for reducing H, even when greater weight was applied to

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the latter trait. The Pešek & Baker index allowed of gains in Y, with simultaneous reduction of H, but there was also a reduction of SS, even though a low gain value for SS was expected.

The Mulamba & Mock and the ideotype genotype distance indices showed that it is possible to obtain gains for Y and SS, with the H reduction. Although with smaller gains for Y compared to those of the two Smith & Hazel and Pešek & Baker indices, it was possible to obtain simultaneous gains for the other traits in the desired direction.

Among these indices, the distance of the ideotype index showed a greater efficiency to obtain gains for SS, at the expense of smaller gain of Y and smaller reduction of H, in comparison to the Mulamba & Mock index. The use of this index shows that, despite the selection favors a considerable reduction of the NF, it would be possible to obtain fruit with greater FL (with a consequent increase of bunch diameter) with less TA, and greater Y being justified by the increase of MF, which is a direct reflection on gains of IR.

Notably, the present study also brings contributions regarding correlations involving the physicochemical traits, which, like the SS, are essential for the acceptance of plantain fruit by the consumer market. The strong correlations between traits are indicative of gene linkage (proximity in the chromosome) or pleiotropy (one gene influencing two traits), which are possibilities that need more extensive studies for confirmation (Wang et al., 2010; Schaid et al., 2016). There are some studies on plantain, reporting possibilities of pleiotropic genes influencing bunch

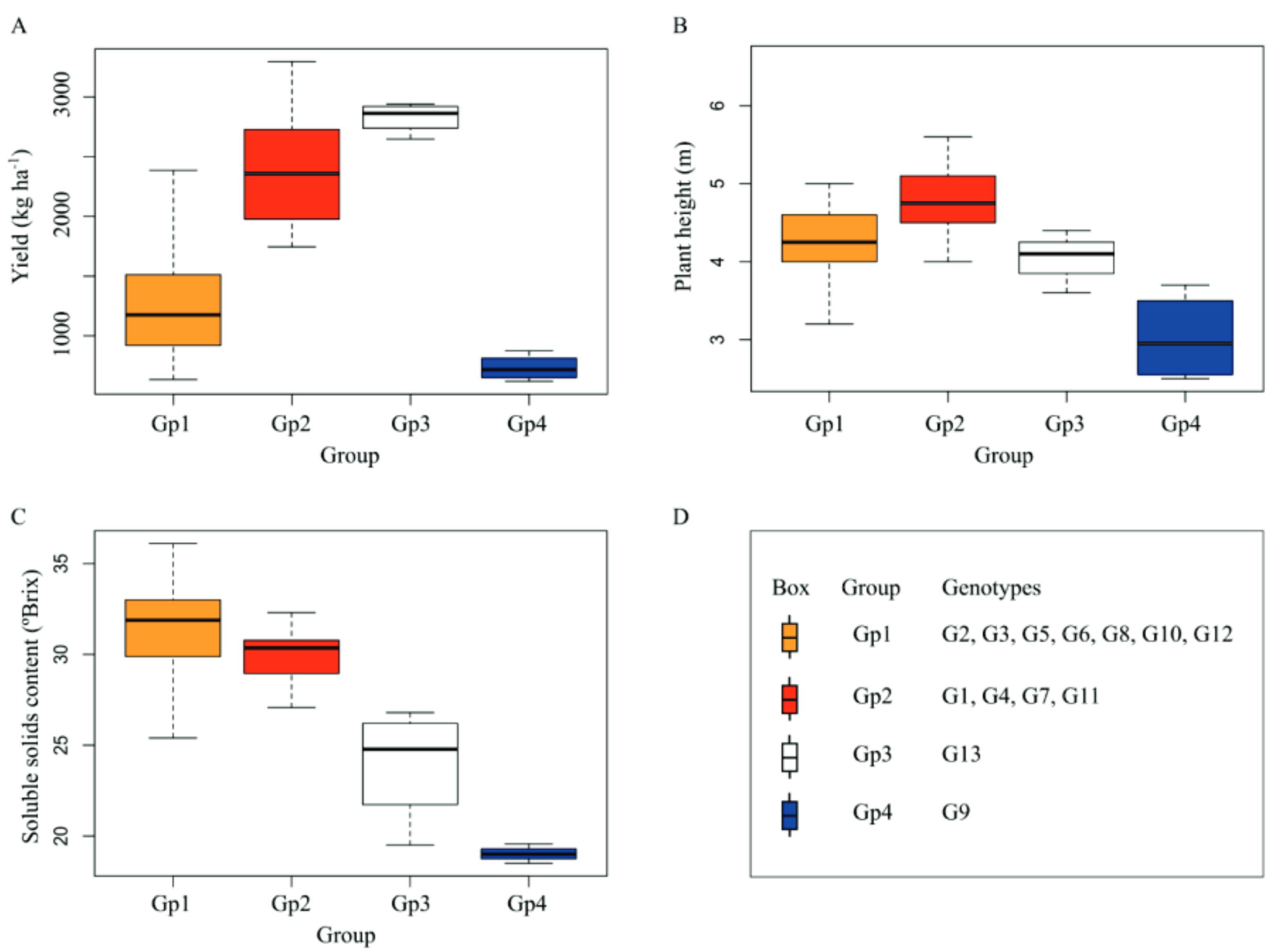

Figure 4. Dispersion of yield values between dissimilarity groups of plantain (*Musa paradisíaca*) genotypes: A, mass of bunches extrapolated to one hectare; B, plant height; C, content of soluble solids in fruit; and D, groups of plantain genotypes.

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Table 2. Selection gain (%) for agronomic and physicochemical traits from direct and indirect selection of 16 traits in 13 plantain (*Musa paradisiaca*) genotypes.

Trait	Direct selection			Simultaneous selection			
	Y	SS	PH	SH	MM	PB	DI
Y (%)	46.62	-36.94	-3.51	22.12	10.55	21.75	7.92
SS (%)	-3.67	11.49	-11.22	5.83	1.62	-1.99	3.02
H (%)	6.17	-0.83	-11.70	10.68	-4.33	-5.95	-4.08
DF (%)	6.96	-7.25	-2.02	4.49	-1.00	-0.07	-0.27
DH (%)	4.44	-5.55	0.72	2.22	-0.58	0.38	0.08
NPL (%)	-3.05	2.67	-0.86	-1.72	-2.22	-1.42	-0.29
PD (%)	9.18	-4.46	-4.19	6.81	3.07	4.12	2.37
NF (%)	42.68	-59.55	46.06	4.60	-2.54	8.03	-16.33
MF (%)	-5.65	11.68	-25.82	10.55	-1.88	-2.45	7.91
PY (%)	-1.62	0.77	-4.65	2.85	-5.37	-3.37	1.65
ST (%)	-1.72	-0.29	-13.87	8.00	-1.77	-2.13	1.97
FL (%)	-4.19	9.00	-14.41	4.44	0.28	-1.61	3.29
pH (%)	-6.32	0.79	4.33	-3.11	-3.32	-1.93	-1.49
TA (%)	13.08	-2.19	-10.74	3.74	7.61	6.59	8.30
TS (%)	-1.59	7.87	-8.11	4.04	1.79	1.43	3.27
IR (%)	-1.09	-4.67	17.32	-24.41	6.39	18.97	24.29

Y, yield (mass of bunches extrapolated to one hectare); SS, content of soluble solids in fruit; H, plant height; DF, days to flowering; DH, days to harvest; NPL, number of photosynthetically active leaves; PD, pseudostem diameter; NF, number of fruit in the bunch; MF, mass of fruit with skin; PY, pulp yield; ST, skin thickness; FL, fruit length; pH, hydrogenionic potential; TA, content of titratable acidity; TS, content of total solids; IR, incineration residue; SH, indices of Smith and Haze; MM, Mulamba & Mock index; PB, Pešek & Baker index; DI, ideotype genotype distance index.

traits and black sigatoka resistance (Ortiz & Vuylsteke, 1995), and between qualitative traits in mutant hybrids (Bermúdez-Caraballoso et al., 2010).

Here, a strong phenotypic correlation was observed between FL and SS, or TS, traits that can be studied in the future to investigate possible pleiotropy or gene linkage. These results corroborate those for the difficulty in plantain breeding, as reported by Ortiz & Langie (1997), and amplify these difficulty, when they showed also undesired correlations among chemical traits and yield, as negative correlations with pH and low correlation with SS (Figure 1). However, the use of selection indices can help breeders to aggregate simultaneous desired characteristics in new plantain cultivars.

The results support the idea that investment to obtain plants with greater efficiency in the use of nutrients, and with more efficient leaf architecture for light capture, in addition to greater resistance to foliar diseases, could be an interesting path for the genetic progress of the plantain cultivation.

The present study should be expanded for the investigation of other genotypes and environments. However, this study indicated interesting paths for decision and/or investigation by plantain breeders. Studies involving molecular tools and physiological data may help to better elucidate the biological events involved in correlations among traits evidenced in the present work.

Conclusions

1. The multitrait selection indices are appropriate to identify shorter plants of plantain (*Musa paradisiaca*) genotypes that are more productive and have higher contents of soluble solids in fruit.

2. In plantain, there are negative correlation between yield and fruit acidity, as well between the contents of soluble solids in the fruit, and positive correlation with plant height and time to flowering.

3. Direct selection on plantain yield provides undesired gains in other agronomic traits generating difficulties in crop managements and low fruit quality.

4. The Mulamba & Mock multi-trait index is efficient to select genotypes with favorable yield, solid soluble contents in the fruit and low plant high in the new plantain cultivars.

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