PAB
Pesquisa Agropecuária Brasileira

ISSN 1678-3921

Journal homepage: www.embrapa.br/pab

For manuscript submission and journal contents, access: www.scielo.br/pab

Horticultural Science/ Original Article

Correlations between agronomic characters in garlic

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Received
June 21, 2021

Accepted
October 18, 2021

How to cite
SANTOS, M.A.V.; ANDRADE JÚNIOR, V.C. de; GUIMARÃES, A.G. ; BRITO, O.G.; TAULA, A.J.V.; COSTA, R.A.; ALVES, J.P.R.; SILVA, N.O.; RESENDE, F.V. Correlations between agronomic characters in garlic. **Pesquisa Agropecuária Brasileira**, v.57, e02603, 2022. DOI: https://doi.org/10.1590/S1678-3921.pab2022.v57.02603.

Abstract – The objective of this work was to evaluate the phenotypic correlations between agronomic characters of garlic (*Allium sativum*) and to carry out the path analysis, using commercial bulb yield as the main character. The experiment was conducted under field conditions in two harvests (2018 and 2019) in the municipality of Diamantina, in the state of Minas Gerais, Brazil. A total of 13 garlic genotypes were evaluated, of which 11 were experimental and 2 were commercial cultivars. The experimental design used was randomized complete blocks with four replicates. Characters related to plant biometry and bulb yield were evaluated. The phenotypic correlations and the path analysis of the studied characters were carried out. The phenotypic correlations that showed significant positive effects occurred between commercial bulb yield and plant height, bulb diameter, number of commercial bulbs, mean total bulb mass, mean commercial bulb mass, total bulb yield, and number of bulbils per bulb. However, only number of commercial bulbs and bulb diameter had significant effects (direct and indirect) on commercial bulb yield. Therefore, in genotype genetic breeding programs in the studied region, selection should seek a larger diameter of bulbs and a higher number of commercial bulbs to increase commercial yield.

Index terms: *Allium sativum*, correlations, genetic breeding, path analysis.

Correlações entre características agronômicas em alho

Resumo – O objetivo deste trabalho foi avaliar as correlações fenotípicas entre características agronômicas de alho (*Allium sativum*) e realizar análise de trilha, tendo-se utilizado a produtividade comercial de bulbos como característica principal. O experimento foi conduzido sob condições de campo em duas safras (2018 e 2019), no município de Diamantina, no estado de Minas Gerais, Brasil. Um total de 13 genótipos de alho foram avaliados, sendo 11 experimentais e 2 cultivares comerciais. Utilizou-se o delineamento experimental de blocos ao acaso, com quatro repetições. Foram avaliadas características relacionadas à biometria da planta e à produção de bulbos. Foram realizadas as correlações fenotípicas e a análise de trilha das características estudadas. As correlações fenotípicas que apresentaram efeito positivo significativo ocorreram entre produção comercial de bulbos e altura de planta, diâmetro do bulbo, número de bulbos comerciais, massa média de bulbo total, massa média de bulbo comercial, produtividade total de bulbos e número de bulbilhos por bulbo. No entanto, apenas o número de bulbos comerciais e o diâmetro do bulbo tiveram efeitos significativos (direto e indireto) sobre a produtividade comercial de bulbos. Portanto, em programas de melhoramento de genótipos na região estudada, a seleção deve buscar maior diâmetro de bulbos e maior número de bulbos comerciais para incrementar a produtividade comercial.

Termos para indexação: *Allium sativum*, correlações, melhoramento genético, análise de trilha.

Introduction

Garlic (*Allium sativum* L.) is an important crop for culinary and medicinal purposes, whose high demand (Bacelar et al., 2023) has been increasing, especially in Brazil (Bessa et al., 2021). In the country, bulbils are mainly consumed in their fresh form (Lucena et al., 2016), although, in recent years, they have also been consumed on a large scale as well-accepted industrialized products, such as spices, pastes, and dehydrated garlic (Lima et al., 2019).

Besides being consumed as food and medicinally, bulbils are also important for the vegetative propagation of the garlic crop. Because garlic is a predominantly sterile species, it is grown from bulbils removed from the base of the plant or from aerial bulbils found in the inflorescences, i.e., cloning the plants of origin (Ranjitha et al., 2018; Marodin et al., 2020). However, due to the exclusively vegetative propagation of garlic, it is difficult to perform traditional breeding for the development of new cultivars, and the frequency of natural mutations is low (Hassan et al., 2014; Bacelar et al., 2023). Despite this, since the crop has great phenotypic diversity, morphological descriptors are commonly used to identify new genotypes (Chen et al., 2014; Viana et al., 2016).

In breeding programs, during the selection process, the main goal is to improve the desirable trait and simultaneously preserve or improve the expression of other traits (Nogueira et al., 2012). Therefore, the study of the correlations between traits – that is, of the strengths of the associations between different traits – is a prerequisite to guide improvement programs in the desired direction (Chotaliya & Kulkarni, 2017). Correlations allow the indirect selection of a main trait that has low heritability or is difficult to evaluate, enabling faster genetic gains compared with direct selection (Cruz et al., 2012). However, the result of the correlation may be a group of characters, which makes it necessary to use the path analysis technique to determine the direct and indirect effects on the main variable (Alcantara Neto et al., 2011).

Ranjitha et al. (2018) evaluated the correlations between traits and the path analysis in 50 indigenous garlic genotypes. The authors observed that bulb yield was strongly influenced by the yield, physiological, and vegetative characters of the plant, which included number of bulbils per bulb, number of bulbs, total soluble solids, days to maturity, pseudostem height, number of leaves per plant, median leaf width, plant height, and bulbil weight. The knowledge of these associations in breeding programs allows breeders to identify the most relevant characters for production and to optimize their evaluations during selection.

The objective of this work was to evaluate the phenotypic correlations between agronomic characters of garlic and to carry out the path analysis, using bulb commercial yield as the main character.

Materials and Methods

The experiment was carried out in two harvests (2018 and 2019), in the experimental area of the horticulture sector of Universidade Federal dos Vales do Jequitinhonha e Mucuri, located in the municipality of Diamantina, in the state of Minas Gerais, Brazil (43°36'W, 18°15'S, at 1,296 m altitude). The climate of the experimental area is characterized as Aw, according to Köppen-Geiger, tropical, with a dry winter season from April to September. Data on rainfall and maximum and minimum temperatures in the planting years are shown in Figure 1. The soil was classified as a Latossolo Vermelho-Amarelo distrófico with sandy-loam texture (Santos et al., 2013), i.e., as an Oxisol.

Eleven experimental genotypes of the garlic germplasm bank of Embrapa Hortaliças (DDR6024, RAL159, RAL75, RAL751, RAL27, RE5181, DDR6811, RE6820, RE493099, REPSK, and UO73) and two commercial cultivars (Caçador and Quitéria) registered at Ministério da Agricultura, Pecuária e Abastecimento (MAPA) were used as controls. All genotypes tested are from the noble group, considered to have a late cycle of six or more months. The seed garlic used for the two harvests was subjected to the vernalization process in a cold chamber, at 4±1°C and 65–70% relative humidity, for 50 days before planting.

The experimental design was randomized complete blocks with four replicates. Planting was performed in May 2018 and April 2019 in four beds of 0.2×2.0×26 m (height × width × length), with five planting rows spaced 20 cm apart and plants spaced 10 cm apart, for a planting density of 10 bulbils per linear meter, i.e., 100 bulbils per plot. The three central rows of each plot (60 plants) were established as the useful area, and the borders were formed by the two outside rows.

Soil samples were collected at a depth of 0–20 cm and then analyzed, showing the following results: pH (in water) 6.3, 7.5 mg dm^{-3} P, 42.9 mg dm^{-3} K, 2.6

DOI: 10.1590/S1678-3921.pab2022.v57.02603

$cmol_c$ dm^{-3} Ca^{+2}, 0.6 $cmol_c$ dm^{-3} Mg, 0.0 $cmol_c$ dm^{-3} Al^{+3}, 1.9 $cmol_c$ dm^{-3} H+Al, sum of bases of 3.3 $cmol_c dm^{-3}$, effective cation exchange capacity of 3.3 $cmol_c$ dm^{-3}, cation exchange capacity of 5.2 $cmol_c$ dm^{-3}, base saturation of 63.5%, and aluminum saturation of 0.0%. Fertilizers were applied according to the recommendations of Comissão de Fertilidade do Solo do Estado de Minas Gerais (Ribeiro et al., 1999), in three stages, to provide rates of 80 kg ha^{-1} N, 150 kg ha^{-1} P_2O_5, 80 kg ha^{-1} K_2O, 15 kg ha^{-1} borax, and 30 kg ha^{-1} $ZnSO_4$ during the garlic crop cycle.

Invasive plants were controlled by manual weeding whenever necessary. Garlic plants were irrigated daily using a conventional sprinkler system. Irrigation was suspended 40 days after planting for a period of 10 days to reduce the possible effects of overgrowing and was suspended again 3 days before harvest.

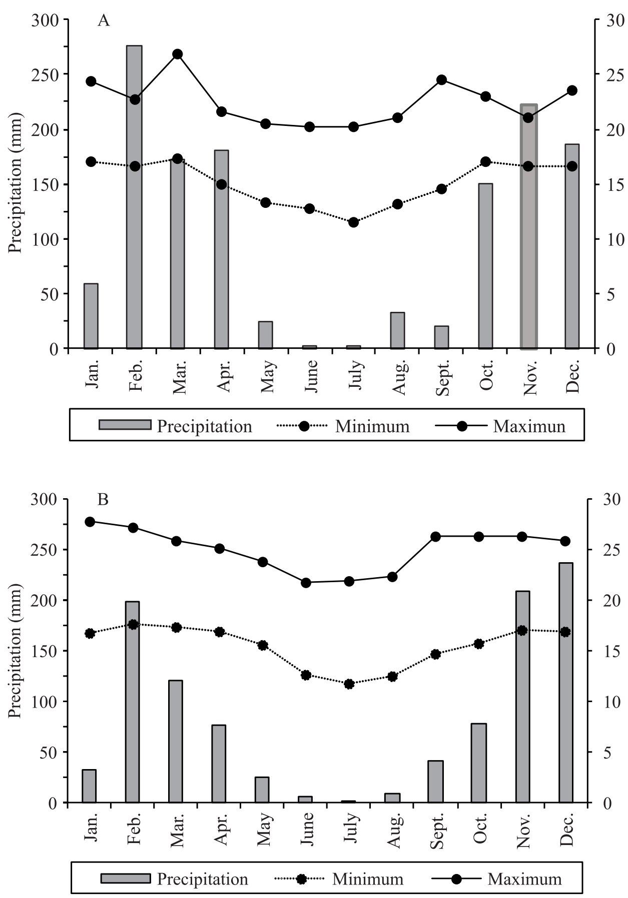

Figure 1. Precipitation and maximum and minimum air temperatures in the 2018 (A) and 2019 (B) harvests in the municipality of Diamantina, in the state of Minas Gerais, Brazil. Source: Inmet (2021).

During plant growth and development and after harvest, the following characters were evaluated: plant emergence (%), by counting the plants that emerged at 7 days after planting; mean plant height (cm), measured from the soil level to the end of the longest leaf of 10 plants of the central rows per plot, at 115 days after planting; mean bulb diameter (mm), measured, using a digital caliper, at the middle part of the bulb in 10 plants of the central rows after 115 days, by removing the soil near the bulb; and pseudostem diameter (mm), measured in 10 plants of the central rows at a height of approximately 5 cm in relation to the soil, also using a digital caliper.

The harvest point was determined by the yellowing and drying of 2/3 of the shoots or by the tipping of the plants. After harvest, the plants were subjected to curing for 20 days in a greenhouse at ~25ºC and 60–70% relative humidity, after which the bulbs were used. To classify the bulbs based on Ordinance No. 242 of 9/17/1992 of MAPA (Brasil, 1992), diameter was measured with a digital caliper, being considered as: class 3, when >32–37 mm; class 4, when >37–42 mm; class 5, when >42–47 mm; class 6, when >47–56 mm; and class 7, when >56 mm.

After the bulbs were classified, the following characters were determined: average total bulb mass (g), calculated as the ratio between the total mass of the bulbs and the total number of the bulbs of all classes; number of commercial bulbs, considered as the number of bulbs produced that showed commercial patterns among the 60 bulbs harvested, classified as class 4 or higher; average commercial bulb mass (g), obtained as the ratio between the total mass of commercial bulbs and the total number of commercial bulbs; total bulb yield (Mg ha^{-1}), considered as the mass of all bulbs from each plot in all treatments; commercial bulb yield (Mg ha^{-1}), obtained as the mass of the bulbs with good phytosanitary conditions and classified as class 4 or higher; number of bulbils per total bulb (bulb/bulb), calculated as the mean number of bulbils out of 10 bulbs randomly selected per plot; and plant dry mass (g), considered the random mass of four plants randomly selected after harvest and dried in a forced-air oven, at 65±2°C, until reaching constant mass.

The phenotypic correlation was based on the averages of the characters in the two studied harvests, since the main character – commercial bulb yield – did not present a significant interaction between genotype

DOI: 10.1590/S1678-3921.pab2022.v57.02603

and crop (data not shown), which is an indicative that the garlic genotype ranking was the same in both years. The equation used to obtain the phenotypic correlation coefficient (rF) was: $rF = COV(X,Y)/ \sqrt{\sigma^2_{FX} \times \sigma^2_{FY}}$, where COV(X,Y) is the estimated phenotypic covariance between characters x and y, σ^2_{FX} is the estimated phenotypic variations of character x, and σ^2_{FY} is the phenotypic variation of character y. The significance of the phenotypic correlation coefficients was assessed by the t-test, at 1 and 5% probability (Cruz et al., 2012).

Before the path analysis was carried out, the degree of multicollinearity of the X′X matrix was estimated based on its number of conditions (NC), which is the ratio between the highest and lowest eigenvalues of the X′X correlation matrix (Montgomery et al., 2012). This criterion considers that multicollinearity will be weak only among the explanatory variables when the relationship between the highest and the lowest values is equal to or below 100. When the value resulting from this division is $100<NC<1,000$, multicollinearity is considered moderate to severe, and when it is $NC\geq1,000$ multicollinearity is considered severe.

For the path analysis, the resolution in the form of a matrix was obtained according to the equation: $X'X\beta = X'Y$, where X′X is a nonsingular matrix of the correlations between the explanatory variables, β is the column vector of the path coefficients, and X′Y is the column vector of the correlations between the explanatory variables and the main variable. The phenotypic correlation was used in the path analysis between the dependent variable (commercial bulb yield) and the explanatory variables (other characters), according to the equation $r_{ix} = P_{ix} + r_j P_{jx}$, where r_{ix} is the correlation between the dependent variable and the i^{th} explanatory variable; P_{ix} is the direct effect of variable i on the dependent variable; and $r_j P_{jx}$ is the indirect effect of variable i, through variable j, on the dependent variable. All analyses were performed in the Genes statistical software (Cruz, 2013).

Results and Discussion

Phenotypic correlations were estimated (Table 1) since field selection was done through the visual observation of the garlic plants, which can be used as an indirect selection criterion (Gomes et al., 2007; Andrade et al., 2010). In addition, selection at the phenotypic level is important for extrapolating the region of interest of the crop and is, therefore, influenced both by the genotype and by the environment (Andrade Júnior et al., 2020).

All significant correlations were positive (Table 1), except the correlation between emergence and pseudostem diameter, which was strongly negative (-0.71). This shows that genotypes presenting a higher emergence percentage at 7 days after planting grew into plants with smaller pseudostem diameters. This result may be related to the increase in the growth-promoting hormones in the bulbils due to vernalization, which accelerates both emergence and vegetative development. Moreover, the short period in which the plants emerged causes a reduction in the development periods of the vegetative stages of the plant, resulting in a decrease in the diameters of the pseudostem and other vegetative structures (Meira et al., 2017).

Bulb diameter showed strongly positive and significant correlations with commercial bulbs (0.88) and commercial yield (0.86), as well as moderate correlations with total yield (0.57) and number of bulbils per bulb (0.55) (Table 1). Therefore, when directly selecting garlic genotypes with larger bulb diameters at 115 days after planting and in good phytosanitary conditions, genotypes with a higher number of commercial bulbs and bulbils will be indirectly selected, resulting in a higher commercial bulb yield. Furthermore, according to Gabriel & Guiñazú (2007), when using bulbs with larger diameters at planting and larger bulbils, there is an increase in garlic yield. Rezende & Silva (2015) also observed a positive correlation between bulb diameter and total bulb yield (0.91) in a study of 89 garlic genotypes in the municipality of Viçosa, also in the state of Minas Gerais, Brazil.

Plant height showed a strong positive correlation with number of bulbils per bulb (0.83) and moderate correlations with average mass of total bulbs (0.62), commercial bulbs (0.61), and commercial bulb yield (0.57). Therefore, taller plants are associated with a higher total and commercial bulb yield because they produce more and heavier bulbs in the Diamantina region, in the state of Minas Gerais. This effect occurs because taller plants have a larger photosynthetically active area, resulting in higher vegetative masses and in a greater accumulation of photoassimilates in the shoots. Therefore, the translocation of the nutrients and reserves present in the leaves and pseudostem during the bulbification period causes larger bulbs (Mathew et al., 2011).

Panthee et al. (2006), when evaluating the genetic variability in garlic from Nepal, based on morphological characters, reported that plant height was positively correlated with bulb mass (0.56), bulb diameter (0.47), number of bulbils per bulb (0.47), and yield (0.65). Zakari et al. (2017) also found significant correlations between these characters, but with different magnitudes. These varying results may be related to the different varieties assessed in each study, as well as to the conditions of the planting sites. In addition, when studying genotypic correlations in garlic, Sable et al. (2020) also observed that plant height showed important and significant genotypic associations with growth and yield characters, highlighting strong associations with pseudostem diameter, number of leaves, bulb diameter, number of bulbs, and bulb yield.

The estimated correlations were significant and positive between mean mass and total yield of bulbs (0.87), mean mass of commercial bulbs (0.84), commercial yield of bulbs (0.71), height of plants (0.62), and number of bulbils per bulb (0.56), indicating that a greater bulb mass influences the height and yield components of garlic. The average mass of the bulbs is an important characteristic for the commercialization of garlic because larger bulbs are valued more highly in consumer markets (Resende et al., 2013). Therefore, to obtain a material with a high commercial standard, this variable must be taken into account in garlic breeding programs.

Regarding the main character of interest, commercial bulb yield showed: very high and positive correlations with number of commercial bulbs (0.95), bulb diameter (0.88), and total bulb yield (0.82); high correlations with total bulb mass (0.71) and number of bulbils per commercial bulb (0.70); and a moderate correlation with plant height (0.57). These results suggest that higher commercial yields are related to taller plants, bulbs of a larger diameter, greater bulb masses, and more bulbils. Andrade Junior et al. (2019), evaluating correlations between garlic characters in the municipalities of Diamantina and Lavras, in the state of Minas Gerais, also obtained high and positive phenotypic correlations between number of bulbils per bulb and commercial yield of bulbs, in alignment with the results found in the present study for both characters.

Regarding the path analysis, the phenotypic correlation matrix between characters was tested for multicollinearity by the NC proposed by Montgomery et al. (2012). This correlation matrix showed severe multicollinearity (NC = 10,087.75). To overcome this multicollinearity, the method proposed by Carvalho & Cruz (1996) was adopted, which consists of applying a constant k to the diagonal of the matrix X′X of the least squares estimator. The value of k applied was 0.117375, making the results reliable, that is, the NC was 42.11, indicating weak multicollinearity since values of NC<100 are not considered problematic (Montgomery et al., 2012).

The adopted path analysis model explained 96% of the commercial bulb yield ratio, showing that there was a direct effect of the explanatory variables (Table 2). Among the assessed characters that

Table 1. Estimates of the phenotypic correlations between the morphological and agronomic characters evaluated in 13 garlic (*Allium sativum*) genotypes[(1)] in two harvests (2018 and 2019) in the municipality of Diamantina, in the state of Minas Gerais, Brazil.

Character[(2)]	BD	PH	PSD	NCB	TBM	CBM	TY	CY	NbTB	DM
EM	-0.23^{ns}	-0.10^{ns}	-0.71**	-0.07^{ns}	-0.26^{ns}	0.48^{ns}	-0.53^{ns}	-0.20^{ns}	0.17^{ns}	-0.40^{ns}
BD		0.40^{ns}	0.08^{ns}	0.88**	0.32^{ns}	0.22^{ns}	0.56*	0.86**	0.55*	0.59^{ns}
PH			0.30^{ns}	0.44^{ns}	0.62*	0.61*	0.42^{ns}	0.57*	0.83**	0.36^{ns}
PSD				-0.01^{ns}	0.30^{ns}	0.52^{ns}	0.42^{ns}	0.09^{ns}	-0.06^{ns}	0.46^{ns}
NCB					0.52^{ns}	0.44^{ns}	0.67*	0.95**	0.68**	0.53^{ns}
TBM						0.84**	0.87**	0.71**	0.56*	0.11^{ns}
CBM							0.80**	0.59*	0.44^{ns}	0.30^{ns}
TY								0.82**	0.37^{ns}	0.37^{ns}
CY									0.70**	0.48^{ns}
NbTB										0.27^{ns}

[(1)]Eleven experimental genotypes from the germplasm bank of Embrapa Hortaliças: DDR6024, RAL159, RAL75, RAL751, RAL27, RE5181, DDR6811, RE6820, RE493099, REPSK, and UO73; and two commercial cultivars registered at Ministério da Agricultura, Pecuária e Abastecimento: Caçador and Quitéria. [(2)]BD, mean bulb diameter (mm); PH, mean plant height (cm); PSD, pseudostem diameter (mm); NCB, number of commercial bulbs; TBM, mean bulb mass (g); CBM, mean mass of the commercial bulb (g); TY, total bulb yield (Mg ha $^{-1}$); CY, commercial bulb yield (Mg ha $^{-1}$) at a diameter greater than 32 mm; NbTB, number of bulbils per total bulb; DM, dry mass (g); and EM, emergence (%). * and **Significant at 5 and 1% probability, respectively, by the t-test. ^{ns}Nonsignificant.

Table 2. Estimates of the phenotypic correlations, broken down into direct and indirect effects, between the main variable commercial bulb yield and the independent explanatory variables analyzed in 13 garlic (*Allium sativum*) genotypes[(1)] in the 2018 and 2019 harvests, in the municipality of Diamantina, in the state of Minas Gerais, Brazil[(2)].

Commercial yield									
EM		PH		PSD		BD		NCB	
Direct effect on CY	0.01	Direct effect on CY	0.04	Direct effect on CY	-0.12	Direct effect on CY	0.29	Direct effect on CY	0.29
Indirect effect via PH	-0.01	Indirect effect via EM	-0.01	Indirect effect via EM	-0.01	Indirect effect via EM	-0.01	Indirect effect via EM	-0.01
Indirect effect via PSD	0.09	Indirect effect via PSD	-0.03	Indirect effect via PH	0.01	Indirect effect via PH	0.02	Indirect effect via PH	0.02
Indirect effect via BD	-0.06	Indirect effect via BD	0.12	Indirect effect via BD	0.02	Indirect effect via PSD	-0.01	Indirect effect via PSD	0.01
Indirect effect via NCB	-0.02	Indirect effect via NCB	0.13	Indirect effect via NCB	-0.04	Indirect effect via NCB	0.26	Indirect effect via BD	0.26
Indirect effect via TBM	-0.04	Indirect effect via TBM	0.08	Indirect effect via TBM	0.04	Indirect effect via TBM	0.04	Indirect effect via TBM	0.07
Indirect effect via CBM	-0.03	Indirect effect via CBM	0.04	Indirect effect via CBM	0.10	Indirect effect via CBM	0.01	Indirect effect via CBM	0.03
Indirect effect via TY	-0.13	Indirect effect via TY	0.10	Indirect effect via PT	0.12	Indirect effect via TY	0.13	Indirect effect via TY	0.16
Indirect effect via NbTB	0.01	Indirect effect via NbTB	0.06	Indirect effect via NbTB	-0.01	Indirect effect via NbTB	0.03	Indirect effect via NbTB	0.04
Indirect effect via DM	-0.01	Indirect effect via DM	0.02	Indirect effect via DM	0.02	Indirect effect via DM	0.02	Indirect effect via DM	0.02
Total	-0.21	Total	0.57	Total	0.09	Total	0.86	Total	0.95
TBM		CBM		TY		NbTB		DM	
Direct effect on CY	0.14	Direct effect on CY	0.07	Direct effect on CY	0.24	Direct effect on CY	0.07	Direct effect on CY	0.04
Indirect effect via EM	-0.01	Indirect effect via EM	-0.01	Indirect effect via EM	-0.01	Indirect effect via EM	0.01	Indirect effect via EM	-0.01
Indirect effect via PH	0.03	Indirect effect via PH	0.02	Indirect effect via PH	0.02	Indirect effect via PH	0.04	Indirect effect via PH	0.01
Indirect effect via PSD	-0.03	Indirect effect via PSD	-0.06	Indirect effect via PSD	-0.05	Indirect effect via PSD	0.01	Indirect effect via PSD	-0.05
Indirect effect via BD	0.10	Indirect effect via BD	0.06	Indirect effect via BD	0.17	Indirect effect via BD	0.16	Indirect effect via BD	0.17
Indirect effect via NCB	0.15	Indirect effect via NCB	0.13	Indirect effect via NCB	0.20	Indirect effect via NCB	0.20	Indirect effect via NCB	0.15
Indirect effect via CBM	0.06	Indirect effect via TBM	0.12	Indirect effect via TBM	0.12	Indirect effect via TBM	0.08	Indirect effect via TBM	0.01
Indirect effect via TY	0.21	Indirect effect via PT	0.20	Indirect effect via CBM	0.06	Indirect effect via CBM	0.03	Indirect effect via CBM	0.21
Indirect effect via NbTB	0.04	Indirect effect via NbTB	0.03	Indirect effect via NbTB	0.03	Indirect effect via TY	0.09	Indirect effect via TY	0.09
Indirect effect via DM	0.01	Indirect effect via DM	0.01	Indirect effect via DM	0.02	Indirect effect via DM	0.01	Indirect effect via NbTB	0.02
Total	0.71	Total	0.60	Total	0.82	Total	0.70	Total	0.48

[(1)]Eleven experimental genotypes from the germplasm bank of Embrapa Hortaliças: DDR6024, RAL159, RAL75, RAL751, RAL27, RE5181, DDR6811, RE6820, RE493099, REPSK, and UO73; and two commercial cultivars registered at Ministério da Agricultura, Pecuária e Abastecimento: Caçador and Quitéria. [(2)]EM, emergence (%); PH, mean plant height; PSD, pseudostem diameter; BD, mean diameter of the bulb; NCB, number of commercial bulbs; TBM, mean mass of total bulbs; CBM, mean mass of commercial bulbs; TY, total bulb yield; NbTB, total number of bulbils per bulb; DM, dry mass; and CY, commercial bulb yield at a diameter greater than 32 mm. Coefficient of determination = 0.96; and residual effect = 0.19.

resulted in a greater direct effect on the commercial yield of bulbs, bulb diameter (0.29) and number of commercial bulbs (0.29) had values higher than that of the residual effect (0.19). These data suggest that those two characters have a more significant effect on commercial bulb yield. In a path analysis, Ranjitha et al. (2018) evaluated garlic bulb weight, which is an important variable in yield composition and also has significant indirect effects on bulb diameter, number of bulbils, bulbil length, and pseudostem height. However, the characters emergence (0.01), plant height (0.04), pseudostem diameter (-0.12), mean total bulb mass (0.14), commercial bulb mass (0.07), number of bulbils per bulb (0.07), and dry mass (0.04) had a direct effect that was weaker than the residual effect (0.19). Therefore, their correlations may not be relevant for commercial bulb yield (Cruz et al., 2012). This shows that the significant correlations of most of the characters presented are explained by the indirect effects of the other characters. Bulb diameter and number of commercial bulbs indirectly contributed the most to the majority of the correlations between the studied characters and the main variable (commercial bulb yield).

The aforementioned results show how the estimates obtained in character correlation studies can lead to error, reinforcing the importance of breaking down the correlations into direct and indirect effects. According to Cruz et al. (2012), simultaneous selection is the most appropriate strategy for characters that have significant correlations but with low direct effects, highlighting those in which the indirect effects are significant.

Although pseudostem diameter was used to estimate bulb yield, it showed the lowest direct effect on the commercial yield of bulbs (-0.12) and a nonsignificant indirect effect on the other characters. This suggests that pseudostem diameter should not be considered in the path analysis when the most important character of selection is commercial bulb yield.

The high correlation between number of commercial bulbs and commercial yield of bulbs (0.95) can be explained by the strong direct effect of number of commercial bulbs (0.29) and by the indirect effect of bulb diameter (0.26). Likewise, there was a total correlation between bulb diameter and commercial bulb yield (0.86), in which the indirect effect of number of commercial bulbs was significant (0.26). This response differs from that reported by Andrade Júnior et al. (2019), who concluded that the number of bulbils per bulb was responsible for significant indirect effects on other traits that were significantly correlated with commercial yield.

Based on the results obtained in the present study and in the other mentioned ones, it is fundamental to identify whether a character is associated with the commercial yield of bulbs, that is, to target the selection of characters that have high correlations with the main character of interest and that have greater direct effects in the desired direction, as well as significant indirect effects on the other characters. Bulb diameter and number of commercial bulbs were the only traits that met these criteria in this study, as they showed relevant direct and indirect effects on the other characters and on commercial bulb yield. Therefore, for garlic selection criteria, the genotypes that produce bulbs with larger diameters should be considered if the goal is to increase the commercial yield of the bulb, since this is the main character determining whether the bulb will be commercially valuable.

Conclusions

1. High commercial yields of garlic (*Allium sativum*) are associated with taller plants, larger diameter bulbs, larger bulb masses, and higher numbers of bulbils.
2. Bulb diameter and number of commercial bulbs are the characters that show the most significant direct effects on commercial bulb yield, as well as significant indirect effects on the other studied characters associated with commercial bulb yield.
3. In breeding programs that use the evaluated genotypes to increase garlic commercial yield in the Diamantina region, in the state of Minas Gerais, Brazil, the criteria for genotype selection should be a larger bulb diameter and more commercial bulbs.

Acknowledgments

To Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (Capes), for financing, in part, this study (Finance Code 001); to Universidade Federal dos Vales do Jequitinhonha e Mucuri (UFVJM), for providing the infrastructure needed to conduct the research; and to Universidade Federal de Lavras (Ufla), for funding the translation of the article.

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