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Productivity and physical properties of corn grains treated with different gypsum doses

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The productivity of corn grains is directly associated with factors related to soil fertility, which are relevant to the application of gypsum (calcium sulphate), in addition to variables inherent to the grain. Thus, the objective of this study was to evaluate the variability of the physical properties of grains (circularity, roundness, bulk density, real density, volume and porosity) and production components (productivity and weight of 1,000 grains) of corn irrigated with increasing doses of gypsum, and evaluate the effects of direct and indirect associations of physical properties of grains and weight of 1,000 grains on grain productivity. The soil of the experiment was a Dystrophic Red Latosol. The experiment was conducted using a random blocks design. An analysis of variance by F test and a univariate regression analysis were performed regarding the relations among culture variables with different doses of gypsum (0.0, 2.5, 5.0, 7.5 and 10 t ha^{-1}). An analysis of variance by t test was also performed together with a multivariate analysis using a path analysis with multicollinearity in order to analyze the direct and indirect effects of the physical properties of grains and weight of 1,000 grains on productivity. The bulk density of the grains had a direct effect on productivity of corn grains. In addition, the decrease in bulk density in function of the increase of gypsum doses is attributed to a greater increase in porosity in relation to weight of 1,000 grains.

Key words: Zea mays L., calcium sulphate, path analysis, bulk density.

INTRODUCTION

Corn (*Zea mays* L.) is regarded as a basic component of the human diet. It is highly demanded in the production of animal feed because of its high energy content (Coradi et al., 2011). In the 2015/2016 harvest, however, the productivity in Brazil was 4% below average with respect to last season (Conab, 2016). Therefore, it is necessary that production systems be improved considering various factors aiming to an increased productivity. In view of the

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various factors that negatively affect the productivity of corn, agricultural gypsum is used to overcome problems related to low productivity because gypsum is considered a soil conditioner providing a greater absorption of water and nutrients by plants mainly at deeper soil layers (Sousa et al., 1996).

Productivity is a complex parameter and depends directly or indirectly on the association between different biotic and abiotic factors and different components of the plant structure itself (Carvalho et al., 1999). Thus, the degree of such associations obtained by correlation studies allows identifying variables that affect productivity. Some physical properties of the grains are important in the cause and effect mechanism related to productivity. Yet, their determination is relevant at various stages of beneficiation, equipment sizing, handling, transportation, drying and storage processes (Gürsoy and Güzel, 2010). Specifically, the shape and size of grains are extremely important for the control and automation of processing equipment and post-harvest equipment (Nunes et al., 2014; Pereira et al., 2014).The unfolding of correlations developed by Wright (1921), called path analysis, allows a better understanding of the causes involved in associations of parameters, where correlations are estimated as direct and indirect effects of explanatory variables on the dependent variable.

For path coefficients to be reliable and generate a biologically correct interpretation, a multicollinearity diagnostic should be made (Cruz and Carneiro, 2003). In the presence of moderate to severe multicollinearity, path coefficients may reach values too high. Therefore, in order to correct this problem, an alternative approach to the least squares, that is, ridge path analysis, should be used (Carvalho, 1995).The objective of this study was to evaluate the variability of the physical properties of grains (circularity, roundness, bulk density, real density, volume and porosity) and production components (productivity and weight of 1,000 grains) of corn irrigated with increasing doses of gypsum, and evaluate the effects of direct and indirect associations of physical properties of grains and weight of 1,000 grains on grain productivity.

MATERIALS AND METHODS

Data were obtained from an experimental research conducted at Brazil, at an experimental area of the Goiano Federal Institute, campus Rio Verde (17°48' S, 50°54' W; altitude 744 m), during the agricultural year 2014/2015.The climate is classified as Aw, tropical with an average annual temperature of 21°C, 1,500-1,800 mm rainfall and relative humidity at 30 to 85% (Sectec, Rio Verde City Hall).The soil of the experimental area is classified as a dystroferric Red Latosol, with a dense, medium texture (Santos et al., 2013). Soil preparation was performed with a disc plow and a leveling tractor. The main chemical characteristics analyzed, according to the methodology described by EMBRAPA (2006), and the physical characteristics are shown in Table 1. Sowing and coverage fertilizations were performed according to soil analysis and the recommendation by Sousa and Lobato (2004). A drip irrigation system was adopted, which was managed by a digital puncture tensiometer with a sensitivity of 1 kPa. Tensiometric rods were installed 20 cm deep and spaced 15 cm from the drip line in three series. Thus, a voltage limit of 50 kPa was considered, keeping 100% of the available water capacity in the soil (AWC).

The experimental plots were distributed in a randomized blocks design with five doses of gypsum (0, 2.5, 5.0, 7.5 and 10 t ha^{-1}) in five blocks (replications). Each plot was composed of 8 lines 4.0 meters (m) long with a 0.45 m spacing between rows. The use area of the plot consisted of 4 central rows 2.0 m long, totaling 3.6 m^2. The gypsum was manually applied to the surface, keeping a most uniform application, at 45 days after plant emergence. To determine the proper harvest time, the water content was determined using an electric capacitance determiner until the level was suitable for harvesting (the proper level was 14.5% on a wet basis). After the manual harvest of hybrid corn (P 4285 YH) realized in July 6, 2016 totaling 120 days of cultivation, the physical properties of the grains (volume, circularity, roundness, bulk density, real density and porosity), weight of 1,000 grains and grain productivity were analyzed.15 corn grains per treatment were used (Oliveira et al., 2014) to determine the volume in m^3 (Equation 1), circularity in % (Equation 2) and roundness in % (Equation 3) according to Mohsenin (1986). The measurements were taken using a digital caliper with a 0.01 mm resolution, where a = bigger axis of the grain, in mm; b - average axis of the grain, in mm; c - smaller axis of the grain, in mm.

$$V = \frac{\pi(a * b * c)}{6} \tag{1}$$

$$Cir = \frac{b}{a} * 100 \tag{2}$$

$$Esf = \frac{\sqrt[3]{a * b * c})}{6} \tag{3}$$

The bulk density was determined using a Hectoliter Weight (PH) BK 4001 scale, and was expressed in kg m^{-3}. The real density (ρ_r) was determined by the ratio between the mass (kg) and the volume (m^3) of the grain according to Mohsenin (1986).The porosity of the granular corn mass was determined indirectly using an air comparison pycnometer built by the Department of Postharvest of the Goiano Federal Institute, campus Rio Verde, using the average of five replications per gypsum treatment according to the procedure described by Mohsenin (1986).The productivity was obtained from the manual harvest of the four 2 m central rows. After threshed, corn grains (Kg), in known area units, were extrapolated to kg ha^{-1}. At the same time, 1,000 grains were separated per experimental unit and the weight of 1,000 grains was determined. Initially, an analysis of variance ($P < 0.05$) was performed. When there was a significant effect, the polynomial regression linear of the culture variables was adjusted according to gypsum doses. A diagnosis of multicollinearity and the multicollinearity of the singular matrix X'X, based on the condition number (CN), which is the ratio between the highest and lowest eigenvalue of the matrix, were performed. A NC < 100 means a weak multicollinearity and does not constitute a problem for the analysis; 100<NC<1,000 means an average to strong multicollinearity, and NC>1,000 means a severe multicollinearity (Cruz and Carneiro, 2003).Subsequently, a path analysis with multicollinearity was performed according to Wright (1921) in order to adjust the k value and unfold the phenotypic correlations into direct and indirect effects of variables of the physical properties of the grains on productivity. The variance inflation factor (VIF) was also determined. All statistical analyses

Table 1. Chemical and physical characteristics of dystrophic Red Latosol at the layers 0-20 and 20-40 cm, Rio Verde, March 2016.

Macronutrients											
Depth	**pH**	**OM**	**$P_{mehlich}$**	**K**	**Ca**	**Mg**	**H+Al**	**BS**	**CEC**	**Al**	**V**
cm	**H_2O**	**g dm^{-3}**	**mg dm^{-3}**		**----------------- mmol$_c$ dm^{-3} --------------------**						**%**
0 - 20	5.2	16	25.3	8.7	9.0	4.3	33	22	55	0.0	40
20 - 40	5.5	17	1.2	6.4	1.2	0.4	24	8.0	41.7	0.0	42.5

Texture			
Depth	**Clay**	**Silt**	**Sand**
cm	**--------------------------------------- g kg^{-1} ---------------------------------------**		
0 - 20	348.6	143.8	507.6
20 - 40	425.1	183.4	391.5

pH = potential hydrogen; OM = organic matter; $P_{mehlich}$= phosphorus determined by Mehlich; K = potassium; Ca = calcium; Mg = magnesium; H+Al = hydrogen + aluminum; SB = base saturation; CEC = cation exchange capacity.Source: Authors.

Table 2. Summary of the analysis of variance of the variables roundness (R), circularity (Cir), bulk density (ρBD), real density (ρRD), volume (Vol) and grain productivity (Prod). Rio Verde, March 2016.

Source of variation	**DF**	**Mean Square**							
		R	**Cir**	**ρBD**	**ρRD**	**Vol**	**P**	**W1000**	**Prod**
Gypsum dose	4	23.3**	14**	1,927.8**	2,285.1**	6,176.3**	2.25**	15,821,861.2**	15,821,861.2**
Blocks	4	0.37	0.67	0.51	24.03	11.98	0.03	44,340.8	44,340.82
Redisues	16	0.61	1.14	3.36	118.01	7.99	0.108	784.5	784.57
CV (%)		1.23	1.35	0.24	0.85	1.19	0.81	0.28	0.28

**Significant at 1% probability by the F test; CV - Coefficient of variation. Source: Authors.

were performed using the software Genes (Cruz, 2013).

RESULTS AND DISCUSSION

There was a significant effect of the variables roundness (R), circularity (Cir), bulk density (ρBD), real density (ρRD), volume (Vol), porosity (P), weigh of 1,000 grains (W1000) and productivity (Prod), which shows a variability among gypsum doses. The coefficients of variation were low: 0.24 to 1.35% (Table 2). Figure 1 shows the linear adjustment of culture variables evaluated in function of gypsum doses. Thus, the positive linear regression was adjusted for roundness, circularity, volume, productivity, porosity and weight of 1,000 grains (Figure 1A, B, E, F, G and H) with an estimated increase of 0.79, 0.46, 3.09, 3.39, 0.41 and 0.29%, respectively, by one-unit dose increase of gypsum. The negative linear regression was adjusted for bulk density and real density (Figure 1C and D), resulting in a reduction of 0.59 and 0.38%, respectively, by unit increase in the gypsum dose. Several studies found a positive effect of the application of gypsum on corn productivity. Some particularities were highlighted by Blum et al. (2013), who found that the positive effects of such application on corn productivity are associated with Ca^{2+} and SO_4^{2-} contents in the soil. Caires et al. (2011) found a significant relation between the productivity of corn and exchangeable Ca^{2+} contents in the soil even after nine years, and concluded that the observed differences in productivity, with respect to gypsum, may be related to the absorption of Ca^{2+} by plant roots due to cation exchange.

Caires et al. (2004), studying soil chemical changes and corn response to liming and the application of gypsum, found that gypsum improved the chemical characteristics of the soil in depth. An increase in Ca^{2+} and SO_4^{2-} in the soil and in N, K and Ca in the leaves of corn was observed, thereby increasing productivity. Importantly, the biological fixation of air nitrogen by *Azospirillum* depends on the concentration of S. Even in the absence of S, there is no N_2 fixation in corn. According to the authors, this is because the source of H_2 results from water vapor from root respiration by the action of ferredoxin containing sulfur (Vitti et al., 2015).Since gypsum provides a greater absorption of nutrients and water by the plant (Souza and Lobato, 2004), the increase in the physical properties of the grains in function of the increase in gypsum doses is attributed to a greater increase in water content in relation to photoassimilates. This is proven by porosity showing an increase (0.41%) higher than the weight of 1,000 grains (0.29%), which is linked to a decrease in the

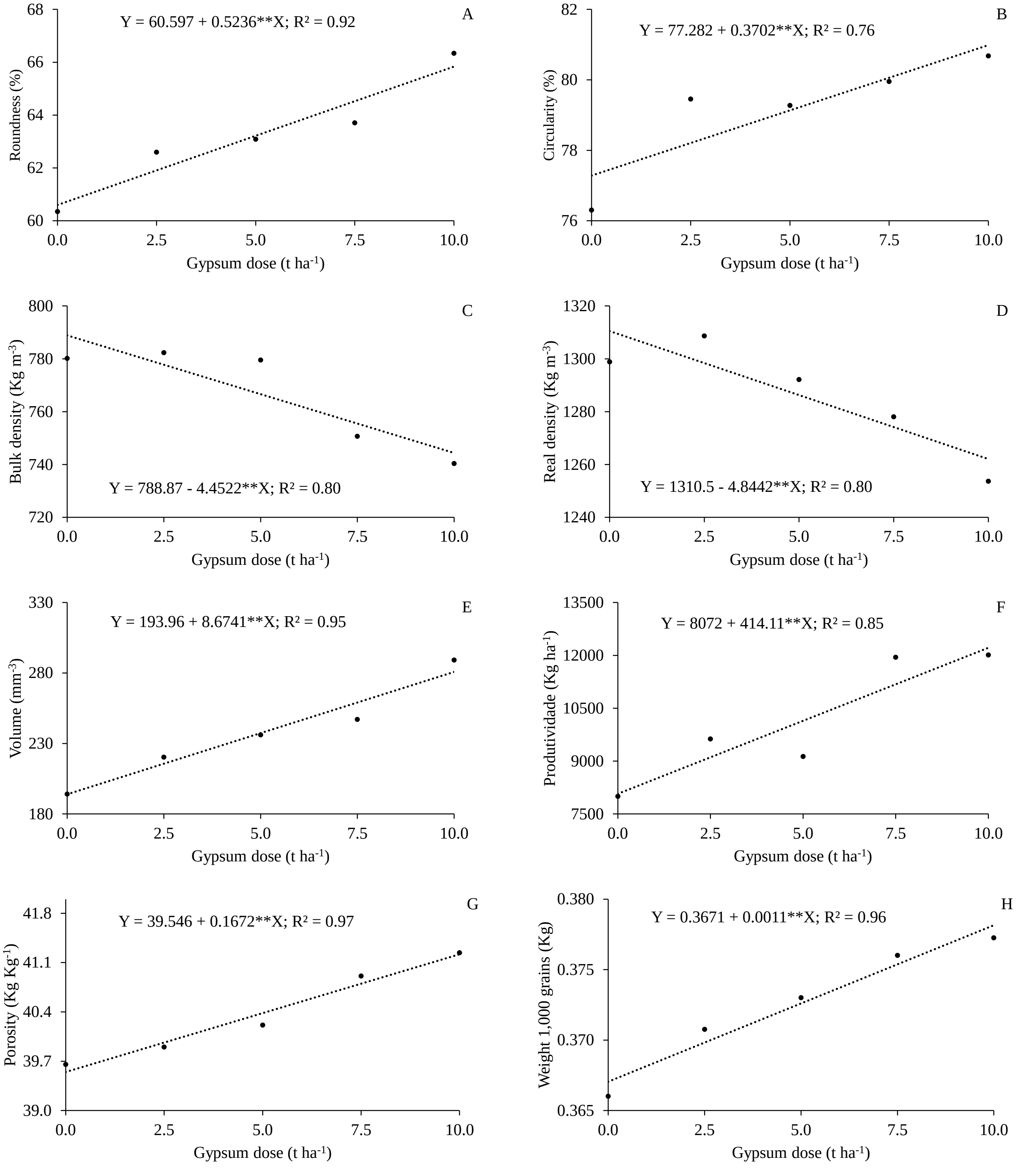

Figure 1. Experimental values and regression analysis for the variables roundness (A), circularity (B), bulk density (C), real density (D), volume (E), productivity (F), porosity (G) and weight 1,000 grains (H) of corn according to gypsum doses. Rio Verde, March 2016. Source: Authors.

bulk density of grains due to an increase in gypsum

doses. The increases in drying air temperatures,

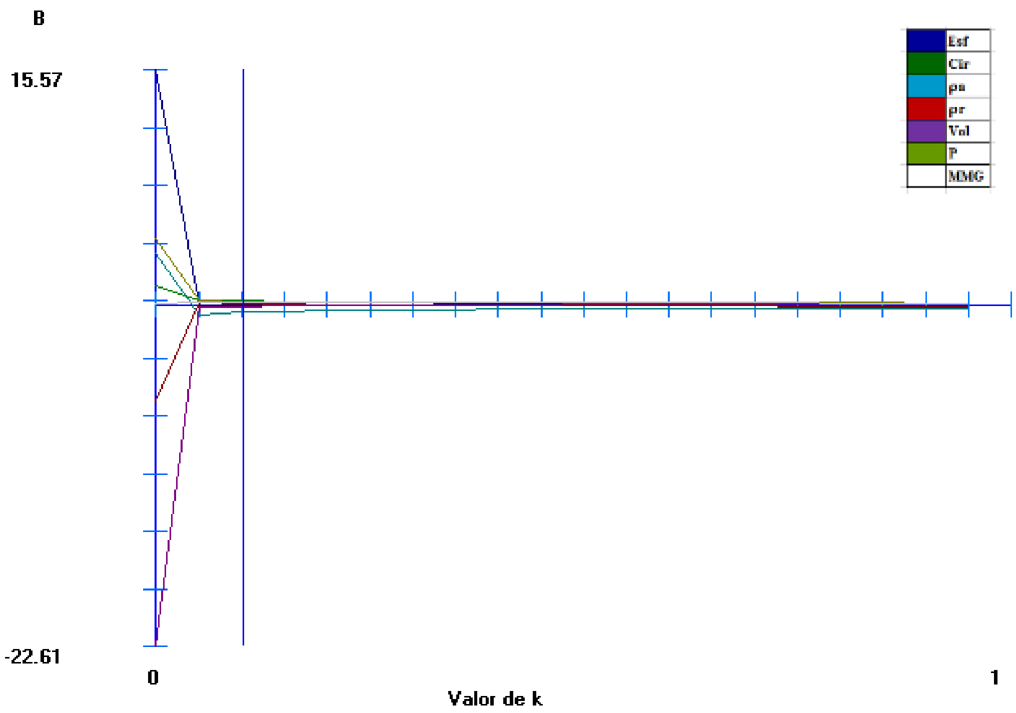

Figure 2. Estimates of path coefficients (θ*) in function of k values obtained from the analysis using the logarithm of the productivity of corn as an independent variable. Rio Verde, March 2016. Source: Authors.

associated with the decrease of water levels, lead to reductions in length, width, thickness, volume, circularity and roundness of corn grains (Coradi et al., 2016).

Since there was variability for gypsum doses, the path analysis revealed a severe multicollinearity for the inverse matrix of independent variables (determinant of the matrix X'X = 1.36 x 10^{-4}, and number of condition (NC) = 184,399.26). According to Montgomery and Peck (1981), the multicollinearity is more intense as the determinant of the correlation matrix between the variables approaches zero. To circumvent the effects of multicollinearity, the path of the K ridge was adjusted in the inverse diagonal matrix and the value (0.1021) was used to decrease the variable inflation factor (VIF) (Figure 2).The estimator in ridge (θ*) is a biased estimator, according to Hoerl and Kennard (1970). For Kalil (1977), the K-value may vary depending on the choice of the researcher being based on subjective criteria. The K-value, according to Carvalho (1995), should also be able to stabilize most path coefficients estimators, and this choice should be based on the lowest value.

The unfolding of estimated correlations into direct and indirect effects of the variables of grains (physical properties) on grain productivity is shown in Table 3.The direct correlation of bulk density with grain productivity is well associated because the simple correlation coefficient (r) (-0.92) and the direct effect (-0.47) are similar in magnitude and equal in signal considering any other combination (Table 3), indicating that the bulk density has the highest direct effect on productivity.

Because bulk density has a greater importance in the association with productivity, it is attributed to smaller increases of weight of 1,000 grains and to larger increases in porosity due to the increase of gypsum doses, as shown by the univariate analysis.For the variables roundness and volume, it was found that the correlation is caused by indirect effects because the RD is positive and the direct effect is near zero or negative. Thus, these variables associate indirectly with a greater grain productivity by bulk density. These are the situations that presented the highest correlation estimates (Table 3). In all correlations, VIFs presented values below 10, which indicates that the equations of the diagonal of the inverse matrix are well estimated by multicollinearity. All regression models in the multivariate analysis expressed a high reliability because the coefficient of determination for the variables was 92.2%.

Conclusions

The bulk density of the grains had a direct effect on the productivity of corn grains. In addition, the decrease in bulk density in function of the increase in gypsum doses is attributed to a greater increase in porosity in relation to

Table 3. Estimates of the direct and indirect effects and variance inflation factor (VIF) that were related to the main independent variable grain productivity (Prod) and related dependent variables roundness (R), circularity (Cir), bulk density (ρBD), real density (ρRD) and volume (Vol) obtained by path analysis with a diagnosis of multicollinearity.

Variable	Effects of Association	Estimate	VIF
R	Direct on Prod	-0.02	8.02
	Indirect by Cir	0.25	4.21
	Indirect by ρBD	0.39	3.30
	Indirect by ρRD	-0.10	3.93
	Indirect by Vol	-0.09	7.05
	Indirect by P	0.23	6.40
	Indirect by W1000	0.20	5.96
	Total	0.87	
Cir	Direct on Prod	0.27	6.18
	Indirect by R	-0.02	5.46
	Indirect by ρBD	0.31	2.03
	Indirect by ρRD	-0.07	1.91
	Indirect by Vol	-0.08	5.41
	Indirect by P	0.21	4.93
	Indirect by W1000	0.20	6.01
	Total	0.85	
ρBD	Direct on Prod	-0.47	5.86
	Indirect by R	0.02	4.52
	Indirect by Cir	-0.18	2.14
	Indirect by ρRD	0.11	4.86
	Indirect by Vol	0.08	5.34
	Indirect by P	-0.24	6.90
	Indirect by W1000	-0.18	4.59
	Total	-0.92	
ρRD	Direct on Prod	0.11	6.61
	Indirect by R	0.02	4.77
	Indirect by Cir	-0.16	1.79
	Indirect by ρBD	-0.45	4.31
	Indirect by Vol	0.08	5.79
	Indirect by P	-0.24	6.47
	Indirect by W1000	-0.17	4.19
	Total	-0.79	
Vol	Direct on Prod	-0.09	8.68
	Indirect by R	-0.02	6.52
	Indirect by Cir	0.24	3.85
	Indirect by ρBD	0.41	3.60
	Indirect by ρRD	-0.10	4.41
	Indirect by P	0.24	6.75
	Indirect by W1000	0.20	5.96
	Total	0.87	
P	Direct on Prod	0.25	9.13
	Indirect by R	-0.02	5.62
	Indirect by Cir	0.22	3.34

Table 3. Contd.

	Indirect by ρBD	0.45	4.43
	Indirect by ρRD	-0.10	4.69
	Indirect by Vol	-0.08	6.42
	Indirect by W1000	0.20	6.10
	Total	0.95	
W1000	Direct on Prod	0.21	8.15
	Indirect by R	-0.02	5.87
	Indirect by Cir	0.26	4.56
	Indirect by ρBD	0.39	3.30
	Indirect by ρRD	-0.09	3.40
	Indirect by Vol	-0.08	6.35
	Indirect by P	0.24	6.84
	Total	0.93	
Coefficient of determination		0.922	
k value used in the analysis		0.102	
Effect of the residual variable		0.278	

Source: Authors.

the weight of 1,000 grains.

Conflict of interests

The authors have not declared any conflict of interests.

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