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Growth and dry matter partitioning in potatoes as influenced by paclobutrazol applied to seed tubers

Crecimiento y partición de materia seca de papa influenciada por paclobutrazol aplicado al tubérculo-semilla

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Potato production field.

Photo: F.F. Araújo

ABSTRACT

Under cultivation conditions that favor the growth of plant shoots, the adoption of management practices that reduce the size of potato plants can be an alternative for increasing tuber yield. The objective of this study was to evaluate the effect of paclobutrazol on vegetative growth and dry matter partitioning in the potato plant cv. Markies, cultivated under summer conditions in the state of Minas Gerais. The treatments were 0.1, 1.0, 10 and 100 mg L^{-1} of paclobutrazol (PBZ), applied to sprouted seeds before planting and control with water. PBZ was efficient in reducing plant height. The PBZ treatments with doses of 10 and 100 mg L^{-1} delayed the emergence of shoots and the beginning of plant tuberization. PBZ at 0.1 mg L^{-1} reduced the lengh of the stem by 18% but did not differ from the control for the fresh and dry mass content, total production, specific gravity and starch content of tubers. The treatment with seed potatoes and PBZ at 0.1 mg L^{-1} resulted in smaller, more compact plants, which could be suitable for more densely planted cultivations in order to maximize plant populations and increase economic return per unit of area.

Additional key words: *Solanum tuberosum* L.; gibberellin; plant regulator; tuberization.

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RESUMEN

En condiciones de cultivo que favorezca el crecimiento de la parte aérea de la planta, la adopción de prácticas de manejo que reduzca el tamaño de las plantas puede ser una alternativa para aumentar el rendimiento de los tubérculos. El objetivo de este trabajo fue evaluar el efecto del paclobutrazol sobre el crecimiento vegetativo y la partición de la materia seca de la planta de papa cv. Markies cultivado en verano en el estado de Minas Gerais, Brasil. Los tratamientos fueron 0,1; 1,0; 10 y 100 mg L^{-1} de paclobutrazol (PBZ) aplicado a las semillas germinadas antes de plantar y um control tratado con agua. PBZ fue eficiente em la reducción de la altura de la planta. Los tratamientos con dosis de 10 y 100 mg L^{-1} de PBZ retrasaron la aparición de la parte aérea y el comienzo de la tuberización de la planta. PBZ a 0,1 mg L^{-1} redujo la longitud del tallo en un 18%, pero no difirió con el control en relación al contenido de masa fresca y seca, la producción total, la gravedad específica y el contenido de almidón de los tubérculos. El tratamiento de tubérculos de papa con PBZ a 0,1 mg L^{-1} presentan plantas más pequeñas y compactas, que podrían ser adecuadas para una plantación más densa para maximizar la población de plantas y aumentar el rendimiento económico por unidad de área.

Palabras clave adicionales: *Solanum tuberosum* L.; giberelina; regulador vegetal; tuberización.

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INTRODUCTION

With a high biological protein value, the potato is one of the most nutritious food sources for man, being the fourth most consumed staple food in the world (ABBA, 2019a). Although it is consumed fresh in most of the countries, the potato is also processed as frozen pre-fried or dehydrated products, among other derivatives.

The consumption of industrialized potatoes in Brazil has increased significantly in recent years (Evangelista *et al.*, 2011), especially frozen pre-fried French fries. Good quality tubers are of fundamental importance for the processing industry, which requires a high percentage of dry matter and starch, which favor the frying yield, providing less oil retention, guaranteeing crispness and texture in the final product (Fernandes *et al.,* 2010).

The lack of raw material in adequate quantity and quality has led to the search for new potato cultivars, with high quality for processing adapted to the Brazilian climate conditions (Muller *et al.*, 2009) and providing the characteristics required by the consumer market. Recently, the cultivar Markies, which has tubers with characteristics similar to the frying cultivar Asterix (Fernandes *et al*., 2010; Evangelista *et al.*, 2011), began to be cultivated in Brazil in significant areas and has become one of the top five cultivars of processed potatoes planted in that country (ABBA, 2019b).

The State of Minas Gerais stands out as the main national producer of potatoes, providing 32% of the total amount produced in that country (IBGE, 2019). Highland regions are preferred for potato cultivation since they present mild temperatures and a greater thermal amplitude between day and night. However, in the summer months, stem and leaf mass growth is favored by high temperatures, leading to reduced yield, increased fungal and bacterial diseases and tubers with a low dry matter content. Thus, under cultivation conditions that favor the growth of plant shoots, the adoption of management practices that reduce the size of plants can be an alternative for increasing the yield of tubers. A practice that can be used to achieve a better balance between vegetative growth and tuber growth is the use of plant growth retarding products, which inhibit some steps of the gibberellin biosynthetic pathway (Rademacher, 2000).

The application of plant regulators in propagating organs, such as seeds, bulbs, rhizomes, tubers and cuttings, has numerous benefits over conventional procedures, being simple and low cost and reducing the concentration of the chemical; the content of residues in the products is minimal or nul, with low diffusion into the environment (Magnitskiy *et al*., 2006). Therefore, the application of regulators in seed potatoes would be an alternative for avoiding the risks inherent to the use of these products in commercial potato production fields.

However, the implication of plant development for the use of these products in sprouted tubers, just before planting, is still unknown. Therefore, the objective of the present study was to evaluate the effect of paclobutrazol applied to seed tubers on growth and *dry* matter *partitioning* in cv. Markies, cultivated under summer conditions in the State of Minas Gerais.

MATERIALS AND METHODS

This experiment was carried out with cultivar Markies in Fazenda Água Santa, located in Perdizes, Minas Gerais (19°21'19" S and 47°16'58" W, with an altitude of 1,100 m), during the summer season of the southeast region, between October, 2015 and February, 2016. According to the Köppen classification, the climate of the region is high tropical (Cwb).

Thirty days before planting, the seed potatoes were removed from storage at 4°C and 85% relative humidity and placed at room temperature in the dark to induce spontaneous sprouting of the tubers. The seed potatoes were immersed for 30 min into 0.1, 1.0, 10 and 100 mg L^{-1} of paclobutrazol (PBZ).

The seed planting was done manually with spacing of 0.38 m between plants and 0.8 m between rows, at a planting depth of 0.12 m. The experiment plots were 19.2 m^2, 2.4 m wide and 8 m long, with a longitudinal distance of 4 m between the plots. The experiment was conducted with a split plot design, with the plots comprising the different concentrations of growth regulators and the subplots representing the plant evaluation times, in a completely randomized design with three replicates; each experiment unit consisted of two plants.

The fertilization used 180 kg ha^{-1} of N (MAP and ammonium nitrate), 420 kg ha^{-1} of P_2O_5 (MAP) and 270 kg ha^{-1} of K_2O (potassium chloride). Potassium chloride was applied in the pre-planting, MAP was used at planting, and potassium nitrate used at 35 (ridge) and 65 d after planting. All treatments received micronutrient applications via the central pivot throughout the cycle.

During the growth period, the total precipitation was 1,133 mm, and the average minimum and maximum monthly temperatures were 19 °C (ranging from 15.9 to 23°C) and 29°C (ranging from 19.8 a 37.1°C), respectively. The mean relative humidity was 77%, ranging from 53 to 94%. The solar radiation averaged 206 W m^{-2}.

The evaluations were carried out with 35 (Evaluation I), 50 (Evaluation II), 65 (Evaluation III), 80 (Evaluation IV) and 95 (Evaluation V) days after planting (DAP). Randomly selected plants were harvested from each treatment. The samples were divided into leaves, stems, tubers and roots/stolons. The fresh matter was determined immediately after harvest, and the dry matter of each part of the plant was determined after drying in forced air circulation oven at 70°C for 5 d.

The dry matter partitioniong was determined from the dry mass of each plant part and expressed as a percentage of total dry mass of the plant. The length of the longest stem, number and fresh mass of tubers were determined. The specific gravity was determined with the ratio between the tuber weight in air and the tuber weight in water (Maeda and Dip, 2000), and the dry matter content used the ratio between the dry and fresh mass of the tuber, expressed as a percentage. At 95 DAP, the shoot plants were desiccated with the herbicide Diquat (400 g ha^{-1} a.i.). At 110 DAP, the plants were harvested from the central rows of each plot to determine the total yield.

The quantification of total soluble sugars of leaves and tubers was carried out according to the phenol-sulfuric acid method (Dubois *et al*., 1956). The reducing sugars were quantified according to the dinitrosalicylic acid (DNS) method (Gonçalves *et al*., 2010). The non-reducing sugar content was obtained with the difference between the total soluble sugar content and the reducing sugar content. For the quantification of the starch, the method described by McCready *et al*. (1950) was used.

The data were analyzed with analysis of variance (ANOVA) using the System of Statistical Analysis and Genetics (UFV, 2008). The means were compared with the Dunnett test at 5% probability. The data for stem height and carbohydrate content of tubers were submitted to descriptive analysis.

RESULTS AND DISCUSSION

At 35 DAP, the control plants and seed potato plants treated with the two lowest doses of paclobutrazo (PBZ) had already emerged, while those treated with

10 and 100 mg L^{-1} of PBZ only showed emergence after 65 DAP (Tab. 1). In potato crops, it is desirable to break dormancy before planting the seed tubers. The process of breaking dormancy and initiation of potato sprouting is triggered by the favorable internal balance of plant growth promoting regulators, including auxins, cytokinins and gibberellins, among other factors (Sonnewald and Sonnewald, 2014).

The delay in emergence in the plants treated with 10 and 100 mg L^{-1} of PBZ may have occurred because of a drastic reduction in the content of endogenous gibberellins in the seed tubers, inhibiting sprout growth for a long period. PBZ is a triazole that blocks the biosynthesis of gibberellic acid, reducing its endogenous concentration. The response of plants to PBZ varies according to the concentration, form of application, absorption and phenological stage in which the application is performed (Santos *et al*., 2004; Mabvongwe *et al*., 2016).

Seleguini *et al*. (2013) verified a linear reduction in the germination rate with increased PBZ doses applied to tomato seeds. According to Pill and Gunter (2001), the inhibitory effect of seed germination on PBZ-containing solutions may be associated with the rate of absorption of PBZ, causing toxicity to the embryo, with a reduction in GA levels at values insufficient for germination and for seedling growth. According to Hung *et al*. (1992), the increase of concentration and exposure time of seeds to a growth regulator contributed to an increase in product penetration in seeds and a consequent reduction in germination.

The percentage of dry matter (DM) in the leaves treated with 1.0 mg L^{-1} of PBZ at 35 DAP was significantly higher than the control, accounting for 81% of the total DM of the plant (Tab. 1). At 50 DAP, there was no difference between the treatments in relation to the percentage of DM partition to the leaves. At 65 DAP, the plants treated with 1.0, 10 and 100 mg L^{-1} of PBZ had the highest DM, while the control plants and those treated with PBZ 0.1 mg L^{-1} provided the lowest percentages. In the last evaluation (95 DAP), all treatments showed a decrease in the percentage of DM partitioned to the leaves, except for the two higher rates of PBZ, where the initial growth delay was intense.

The partitioning of DM to the roots at 35 and 50 DAP showed no significant difference between the treatments in the plants that had already emerged (Tab. 1). At 50 DAP, the roots of all treatments represented,

Table 1. **Partitioning of the dry matter (%) for each part of the potato and total dry matter (g), influenced by applications of paclobutrazol (PBZ) in the seed potatoes before planting.**

PBZ doses (mg L^{-1})	Leaves (%)	Roots (%)	Stems (%)	Tubers (%)	Total DM (g/plant)
Evaluation I (35 DAP)					
Control	77.24	11.75	11.01	-	9.78
0.1	79.64^{NS}	12.34^{NS}	8.02*	-	5.71*
1.0	81.18*	12.24^{NS}	6.58*	-	3.94*
10	-	-	-	-	-
100	-	-	-	-	-
CV (%)	8.01	11.30	11.37		11.50
Evaluation II (50 DAP)					
Control	78.29	11.44	10.27	-	33.58
0.1	80.01^{NS}	12.01^{NS}	7.98*	-	18.05*
1.0	80.82^{NS}	12.49^{NS}	6.69*	-	12.60*
10	-	-	-	-	-
100	-	-	-	-	-
CV (%)	7.21	13.7	6.98	-	14.85
Evaluation III (65 DAP)					
Control	57.87	6.40	8.52	27.21	78.85
0.1	63.69^{NS}	6.55^{NS}	6.69^{NS}	23.07^{NS}	62.62*
1.0	79.91*	11.31*	8.78^{NS}	-	35.99*
10	79.38*	12.84*	7.78^{NS}	-	11.99*
100	78.60*	13.12*	8.29^{NS}	-	8.56*
CV (%)	7.94	14.7	19.6	8.97	10.23
Evaluation IV (80 DAP)					
Control	42.42	5.59	6.63	45.36	129.48
0.1	48.59*	5.21^{NS}	6.57^{NS}	39.63*	106.84*
1.0	61.36*	8.25*	6.49^{NS}	23.89*	76.38*
10	80.82*	10.35*	8.83*	-	28.95*
100	81.77*	9.74*	8.49*	-	14.28*
CV (%)	8.32	10.45	22.9	12.68	7.74
Evaluation V (95 DAP)					
Control	34.75	4.26 b	5.96	55.03	151.48
0.1	39.59*	4.54^{NS}	5.57^{NS}	50.29^{NS}	123.84*
1.0	49.03*	8.26*	5.49^{NS}	37.22*	95.38*
10	80.82*	9.69*	9.49*	-	35.61*
100	82.77*	9.07*	8.16*	-	20.28*
CV (%)	7.95	17.11	23.28	5.50	10.92

^{NS} non-significant; * significant ($P \leq 0.05$) with the control by the Dunnett test.

on average, 12% of the total DM of the whole plant. According to Tekalign and Hammes (2005), the root system represents around 4% of the total DM of the potato plant. However, this ratio may vary according to the cultivar and the growing conditions. In. the subsequent evaluations at 65, 80 and 95 DAP, the seed potato plants treated with the 1.0, 10 and 100 mg L^{-1} of PBZ showed a significant difference in relation to the control treatment, obtaining a higher percentage of DM partitioned to the roots. This effect may have been a reflection of the reduction in the growth of the plant shoot, which possibly increased the availability of carbon directed to the root system.

For the accumulation and distribution of DM to the stems, the treatments with PBZ at 0.1 and 1.0 mg L^{-1} presented significant differences in relation to the control in both evaluations at 35 and 50 DAP (Tab. 1). The treatments with 10 and 100 mg L^{-1} of PBZ had the highest indexes of partition for the stems at 80 and 95 DAP when compared to the remaining treatments.

In this experiment, the beginning of the tuberization process started after 50 DAP, except for with 1.0, 10 and 100 mg L^{-1} of PBZ, which did not show any tuber formation. At 80 DAP, the plants treated with PBZ at 1.0 mg L^{-1} already had tubers but had the lowest partition index of DM for the tubers, as compared to the control treatment. At 95 DAP, 55% of the total DM from the control plants was accumulated in the tubers, while, in the treatment with PBZ at 1.0 mg L^{-1} , the accumulation of DM was only 37.2%. The application of the growth regulator PBZ on the seed potatoes before planting did not increase the DM partition to the tubers in the bulking phase.

In the first stages of potato development, the preferential metabolic drains are the leaves and stems, followed by the tubers with fast growth during tuber bulking. Therefore, a high mobilizing capacity in the tubers caused a marked reduction in the accumulation of dry matter begining at 65 DAP for both the leaves and the stems (Tab. 1). In the treatments with 10 and 100 mg L^{-1} of PBZ, this change was not noticed until 95 DAP because of the delay in the tuberization of these plants.

Based on the accumulation of DM in the entire plant, in the first evaluation, the control treatment plants had the highest DM contents, followed by the treatment with the lowest dose of PBZ and the treatment with PBZ at 1.0 mg L^{-1} (Tab. 1). In evaluation III (65 DAP), a slow initial growth was observed in the plants treated with PBZ at 10 and 100 mg L^{-1}, presenting a lower percentage of total DM in relation to the other treatments. In the last partition evaluation, the lowest percentage of DM accumulation in the entire plant was obtained in the treatment with the highest dose of PBZ (100 mg L^{-1}).

The control plants had a longer main stem length, as compared to the PBZ treated seed potatoes, throughout the plant cycle (Fig. 1). The immersion of the sprouted seeds before planting in the solution containing 0.1; 1.0; 10 and 100 mg L^{-1} of PBZ reduced the length of the stem by about 18; 25; 51 and 55%, in comparison to the control, respectively. The treatments of seed potato with PBZ resulted in smaller, more compact plants, which could be suitable for more densely planted cultivations in order to maximize plant population and increase economic return per unit of land. Several studies, however, have indicated disadvantages of PBZ seed treatments, which include delay and reduce the shoot emergence rate (Pasian and Bennett, 2001).

In tomatoes, the application of PBZ to seedlings influenced the stems lenght up to 15 d after transplanting, showing that the effect of the regulator can be limited during the culture cycle (Ferreira *et al*., 2017). PBZ at 0.250 L ha^{-1}, applied via spraying at 35 d after planting, was efficient at reducing the potato plant height by 20%, as compared to the control plants (Araújo *et al*., 2019).

According to Fletcher *et al*. (2000), the reduction in plant height induced by PBZ is linked to the inhibition of the conversion of ent-kaurene to ent-kaurenoic acid, resulting in a reduction in gibberellic acid levels, with a consequent decrease in the elongation rate and cell division. López *et al*. (2011) observed that spraying the growth regulators paclobutrazol and uniconazole on potato leaves was more effective in reducing the shoot growth of the potato plants that the cycocell growth regulator. Fagan *et al*. (2019) attributed the effects to the different modes of action of the compounds in gibberellin biosynthesis. Trinexapac-ethyl is an acylcyclohexanoedione, which in poaceae species, such as wheat and rye, causes a reduction in the length of internodes and, consequently, in plant height. However, in dicotyledons, this inhibition is not so strong, showing the selectivity to trinexapac-ethyl in species of the Poaceae family (Rademacher, 2000).

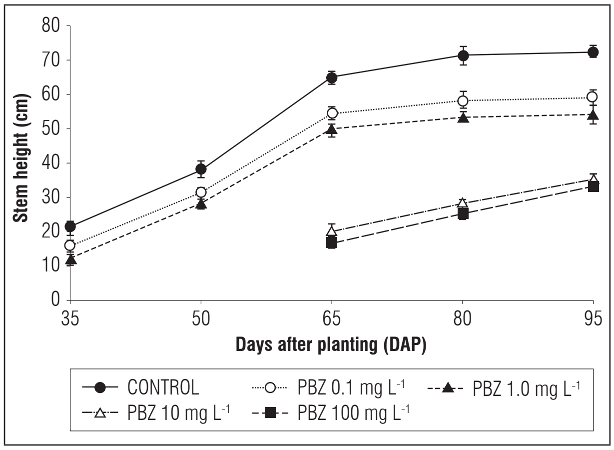

Figure 1. Length of longest stem of plants from potato seeds treated with paclobutrazol (PBZ) in the days following planting. The vertical bars represent the standard error of the mean.

The treatments with PBZ doses significantly decreased the number of tubers per plant when compared to the control (Tab. 2). The average of the PBZ 10 and 100 mg L^{-1} treatments was 5 tubers per plant, while, for the control, it was 7.33. Results obtained by other authors also verified that PBZ, when applied in the form of foliar spraying, reduced the number of tubers of plants (Kianmehr *et al*., 2012; Mabvongwe *et al*., 2016).

The treatments with 1.0, 10 and 100 mg L^{-1} of PBZ significantly reduced the fresh and dry mass of the tubers per plant, and the total production of the tubers was 39.2, 73.2 and 79.0% when compared to the control, respectively (Tab. 2). There was a significant reduction in the specific gravity in the tubers with 10 and 100 mg L^{-1} of PBZ, as compared to the control and the remaining treatments (Tab. 2). The PBZ treatments also delayed the emergence of plants and the beginning of tuberization. At the final harvest, at 110 DAP, the tubers with 0 and 100 mg L^{-1} of PBZ were still in the initial filling stage, which led to a reduction in the specific gravity, as compared to the other treatments.

Regardless of the treatment, the predominant soluble sugars present in the tubers was non-reducing. In all treatments, there was a decrease in the non-reducing sugars (NRS) content over time (Fig. 3C). At the end of the experiment (110 DAP), the treatments with the two lower doses of PBZ did not differ from the control.

The reducing sugars (RS) content decreased during the evaluation period for all treatments, except for PBZ 0.1 mg L^{-1}, where, at 85 DAP, an increase was observed, followed by a subsequent decrease (Figure 3B). The two higher PBZ doses presented higher levels of RS at 95 and 110 DAP, which can be explained by the delay in tuberization and consequent maturation of the tubers. In the final harvest (110 DAP), the tubers in the treatments with 10 and 100 mg L^{-1} of PBZ presented a high content of reducing sugars, with 0.2 and 0.18%, respectively (Fig. 3C).

A high accumulation of reducing sugars leads to a reaction with free amino acids, called the Maillard reaction or non-enzymatic browning (Low *et al*., 1989), resulting in products with brown coloration. After frying for 3 min at 180°C, the French fries developed an excessive brown color (data not shown) when the seed tubers were treated with 10 and 100 mg L^{-1} of PBZ.

The tuber starch content at 80 DAP decreased when treated with 0.1 and 1.0 mg L^{-1} of PBZ, followed by an increase until the end of the experiment (Fig. 3D). This decline may have occurred because of a

Table 2. Number of tubers, fresh matter mass, dry matter mass, total yield and specific gravity of potato tubers as influenced by applications of paclobutrazol (PBZ).

PBZ doses	Tubers number	Tuber fresh mass (g/plant)	Tuber dry mass (g/plant)	Total yield (Mg ha^{-1})	Specific gravity (g cm^{-3})
Control	7.33	654.16	104.40	23.54	1.0581
0.1	6.00*	622.93^{NS}	90.83^{NS}	22.42^{NS}	1.0564^{NS}
1.0	5.67*	397.94*	58.01*	14.32*	1.0560^{NS}
10	5.00*	175.62*	25.33*	6.32*	1.0540*
100	5.00*	137.44*	19.61*	4.95*	1.0534*
CV (%)	9.5	8.5	9.2	13.6	0.9

^{NS} non-significant; * significant ($P \leq 0.05$) with the control by the Dunnett test.

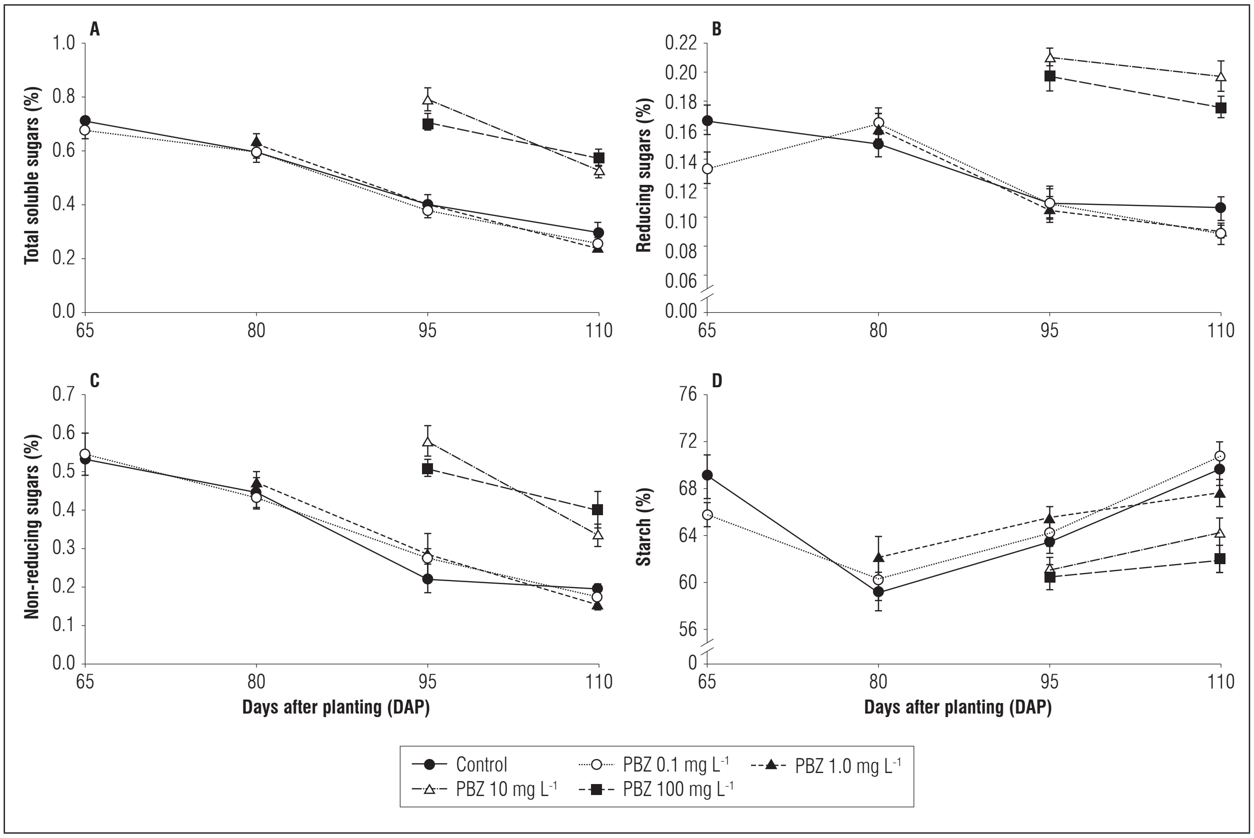

Figure 3. The content of total soluble sugars, reducing sugars, non-reducing sugars and starch in tubers of potato seed plants treated with paclobutrazol (PBZ) (A, B, C and D), respectively, according to the days after planting. The vertical bars represent the standard error of the mean.

momentary dilution of the starch content as the result of the increase in the water content of the tubers since, on the date of this evaluation, a high volume of water was reported in the soil because of heavy rains.

At the final harvest, the two higher PBZ doses had a lower starch content (Fig. 3C), indicating delayed tuber development caused by 10 and 100 mg L^{-1} of PBZ. The reduction in the total soluble carbohydrate content during the cycle coincided with the increase in the starch content, indicating the beginning of tuber maturation. Lewis *et al*. (1994) also observed reduction in total sugar levels in developing tubers, indicating an increase in the rate of starch synthesis.

CONCLUSIONS

The two higher doses (100 and 10 mg L^{-1}) of PBZ delayed shoot emergence and the beginning of tuberization. The treatments of seed potatoes with PBZ at 0.1 mg L^{-1} resulted in smaller, more compact plants, which could be suitable for more densely planted cultivation in order to maximize plant population and increase economic return per unit of land.

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Conflict of interest: this manuscript was prepared and reviewed with the participation of all authors, who declare that there exists no conflict of interest that that puts in risk the validity of the presented results.

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