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ORIGINAL ARTICLE

Chemical composition of potato tubers: the effect of cultivars and growth conditions

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Abstract The aim of the study involved evaluating the chemical composition of tubers of five potato cultivars that were grown under the same cultural practices in soils with low, medium, and high availability of phosphorus. The experimental designs corresponded to a randomized block with four replicates. Tuber samples were analyzed in terms of moisture, ash, protein, lipid, total sugar, fiber, starch, and phosphorus contents. The results suggested that increased availability of phosphorus in soil allowed the production of tubers with higher dry matter content, lower total sugar content, and a higher percentage of starch and protein. Hence, the aforementioned parameters constitute important factors corresponding to the nutritional and industrial quality of potatoes. Increased phosphorus availability in soil can promote significant changes in the composition of potato tubers, and thereby in potential uses of tubers.

Keywords *Solanum tuberosum* · Tuber quality · Nutrients · Soil fertility

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Introduction

Productive efficiency of a potato ensures high use of areas for the production of food, and this is an important feature in a global scenario of constant population growth. A potato is the fourth most important food crop, and it contains a wide variety of phytochemicals compounds (Brown 2008; Marwaha et al. 2010; Ezekiel et al. 2013). In Brazil, a potato is the main horticultural crop in terms of area and food preference (Streck et al. 2007), and the planted area in 2013 corresponded to 127 thousand hectares with an agricultural production of 3.5 million tons (FAO 2016). The potato production in Brazil is concentrated in a limited number of cultivars. The cultivars Agata, Asterix, Atlantic, Markies, and Mondial constitute the most planted cultivars in Brazil and represent the largest portion of the total area planted with potatoes.

The chemical composition of potatoes determines processing quality and is influenced by several factors, including production area, cultivars, soil and climate, agricultural practice, storage, and commercialization conditions (Arvanitoyannis et al. 2008).

Differences in the potato crop between genotypes for shoot growth rate and dry matter production are attributed to differences in phosphorus (P) uptake efficiency and in the use efficiency of phosphorus absorbed (Balemi and Schenk 2009). Potato crops possess a high requirement for soil available P and this indicates a low P uptake efficiency. Low P use efficiency in potato was reported as primarily related to a relatively low root to shoot ratio and especially to a relatively low proportion of root hairs (Dechassa et al. 2003; Westermann 2005; Iwama 2008; Thornton et al. 2014; Hopkins et al. 2014). The phosphorus following absorption by a plant participates in various metabolic processes including energy transfer, synthesis of nucleic acids and starch, respiration, synthesis and stability of membranes, activation and deactivation of enzymes, redox reactions and carbohydrate metabolism (Vance et al. 2003).

Starch is the main carbohydrate of potato tubers and phosphorylation of starch during its biosynthesis process has important effects on technological properties of potato starch (Lu et al. 2011). Leonel et al. (2016) examined the characteristics of starches of different potato cultivars grown in soils with three levels of phosphorus (P) availability and found that higher contents of P in starch were observed when potatoes were grown in soils with higher P availability. Additionally, increased starch phosphorylation promoted significant changes in amylose content as well as thermal and pasting properties.

Potatoes are among most widely cultivated crops in the world, and thus it is extremely important to understand the impact of grown conditions on qualitative parameters of potatoes in terms of the importance of phosphorus in potato plant metabolism. Therefore, an objective of this study involved investigating the impact of three levels of phosphorus availability in soil on the composition of tubers of five potato cultivars that were grown in Brazil.

Materials and methods

Growing of potatoes

The study involved three experiments that were conducted under field conditions in commercial potato production areas. Soil samples consisting of 20 subsamples were collected at a depth corresponding to a 0–0.20 m layer to determine chemical properties of the soil prior to the installation of the experimental tests.

The experiments were conducted in the following soils with different P availabilities: low (14 mg dm^{-3}), medium (36 mg dm^{-3}) and high (70 mg dm^{-3}) P availability soils. The available phosphorus was extracted using ion exchange resin and was determined by atomic absorption spectrophotometry (Van Raij et al. 2001).

The experiments were conducted in a randomized block design with four replications. The treatments consisted of five potato cultivars, and each plot consisted of five rows of 5 m of length. With respect to the evaluations, central rows disregarding 0.5 m were considered at the end of each row of plants and a row on each side of the plot. The species of potato cultivars used in all the experiments included Agata, Asterix, Atlantic, Markies, and Mondial.

Potatoes were grown by following traditional potato production technology. Mineral fertilization at the planting phase of all experiments consisted of the application of 62 kg ha^{-1} N and 124 kg ha^{-1} K_2O for all cultivars in the form of ammonium sulfate and potassium chloride, respectively.

Topdressing fertilization in areas with low, medium, and high phosphorus availability was performed 22, 24, and 28 days after planting (DAP), respectively. Specifically, 43, 64, and 41 kg ha^{-1} N of fertilizer was applied in areas with low, medium, and high phosphorus availability, respectively. Pest control was performed in all the experiments based on technical recommendations for the potato crop. The plants in all areas were desiccated with diquat (331 g a.i. ha^{-1}) at approximately 100 DAP, and the tubers were harvested after 21 days for performing evaluations.

Analysis of potato tubers

The samples for qualitative examinations (8–10 kg of potato tubers) were collected from four field replications for each plot by using standard methods. Washed and peeled potato tubers were comminuted, and the following indices were determined with respect to the potato pulp: moisture, ash, total protein, total lipids, total sugar, fibers, starch (AOAC 2012), and phosphorus (Noda et al. 2004).

Statistical analysis

Experimental data were collectively analyzed by considering the potato cultivars and phosphorus availability of the three soil types. The data were subjected to analysis of variance using SAS statistical software. Blocks and all block interactions were considered as random effects. The cultivars and P availability were considered as fixed effects. The means were separated by using Tukey's test at a 0.05 probability level.

Results and discussion

The importance of tuber moisture (or dry matter) in potato processing industries is widely known. Dry matter content of tubers is the most important character that determines the quality and yield of fried and dehydrated products. Increased dry matter or solid content results in the increased recovery of processed products, lower oil absorption, lesser energy consumption, and imparts a crispy texture to a product (Marwaha et al. 2010; Rommens et al. 2010). A dry matter content corresponding to 18–20% is considered as acceptable for chips, French fries, and dehydrated products (Ezekiel et al. 1999).

The results of the present study revealed that the moisture of potato tubers was influenced by the investigated combination of soil P availability and cultivars and corresponded to a range of 78.17 to 88.11 g 100 g^{-1} (11.89–21.83 g 100 g^{-1} of dry matter) (Table 1). Braun et al. (2010) cited 16.54, 16.63, and 21.45% of dry matter content for Agata, Asterix, and Atlantic cultivars,

Table 1 Chemical composition of tubers of potato cultivars cultivated in soil with different P availability

Cultivars	Soil P availability		
	14 mg dm^{-3}	36 mg dm^{-3}	70 mg dm^{-3}
Moisture (g 100 g^{-1})			
Agata	88.11Aa	85.22Ba	85.67Ba
Asterix	85.52Ab	83.39Bb	83.04Cb
Atlantic	82.47Ad	81.43Bc	78.17Cc
Markies	84.00Ac	80.86Bc	78.38Cc
Mondial	85.54Ab	83.37Bb	82.10Cb
Starch (g 100 g^{-1})			
Agata	8.89Bd	11.78Ac	11.33Ac
Asterix	11.47Cc	13.60Bb	14.94Ab
Atlantic	14.53Ca	15.57Ba	18.83Aa
Markies	13.00Cb	16.14Ba	18.62Aa
Mondial	11.46Cc	13.63Bb	14.90Ab
Protein (g 100 g^{-1})			
Agata	1.59ABc	1.71Ac	1.45Bd
Asterix	1.91Ab	1.71Bc	1.65Bc
Atlantic	2.28Aa	1.97Bb	1.91Bb
Markies	2.17Aa	2.35Aa	1.93Bb
Mondial	2.17Aa	1.68Bc	1.50Bd
Fibers (g 100 g^{-1})			
Agata	0.66Ab	0.57Ab	0.60Aa
Asterix	0.74Aa	0.74Aa	0.62Ba
Atlantic	0.71Aa	0.48Bb	0.34Bb
Markies	0.49Ac	0.41ABc	0.39Bb
Mondial	0.80Aa	0.50Bb	0.46Bb
Total sugars (g100 g^{-1})			
Agata	0.72Aa	0.58Ba	0.36Ca
Asterix	0.54Ab	0.65Aa	0.28Ba
Atlantic	0.76Aa	0.19Bc	0.11Bb
Markies	0.20Ac	0.12ABc	0.08Bb
Mondial	0.45Ab	0.44Ab	0.34Aa
Ash (g 100 g^{-1})			
Agata	0.87Ab	0.81Ac	0.81Ad
Asterix	1.07Aa	0.86Bbc	0.99Ac
Atlantic	1.09Ba	1.10Ba	1.38Aa
Markies	1.08 Ba	0.94Cb	1.20Ab
Mondial	0.95Ab	0.92Ab	0.97Ac
Lipids (g 100 g^{-1})			
Agata	0.28Bb	0.94Aa	0.94Aa
Asterix	0.95Aa	0.91Aa	0.88Aa
Atlantic	1.04Aa	0.74Bb	0.60Bb
Markies	0.25Cc	0.43Bc	0.82Aa
Mondial	0.90Aa	0.75ABb	0.66Bb
Phosphorus (mg 100 g^{-1})			
Agata	19.75Aab	25.80Aab	23.32Ab
Asterix	18.70Bab	25.53Aab	22.90ABb
Atlantic	21.27Bab	27.88ABab	29.63Aab
Markies	24.05Ba	30.95Aa	35.27Aa
Mondial	14.10Bb	22.77Ab	24.10Ab

Means followed by the same capital letters in the row do not differ at 5% level by Tukey test. Means followed by the same lowercase letters in the column do not differ at 5% by Tukey test

respectively. Zorzella et al. (2003) analyzed thirteen potato genotypes and reported levels of dry matter ranging from 16.37 to 24.51 g 100 g^{-1}, and observed a content corresponding to 23.51 g 100 g^{-1} of dry matter for the cultivar Atlantic. Similar levels of dry matter in the potato cultivars were observed in the current study with respect to conditions of higher P availability (Table 1).

Data analysis showed that the increase in P soil availability led to an increase in dry matter content of tubers (Table 1). This revealed that the adequate availability of this nutrient in the soil significantly influenced the production and allocation of assimilates in the tubers. The interference of growth conditions on the composition of potato tubers was also observed in other studies.

Specifically, Jenkins and Ali (1999) used different potato cultivars and doses of phosphorus (0–400 kg P_2O_5 ha^{-1}) in their experiments and concluded that P deficiency decreased dry matter production by reducing the radiation intercepted during the crop cycle (RI). However, the sensitivity of RI to phosphorus deficiency potentially varied with the genotype. Daily RI constitutes a product of the daily fraction of radiation intercepted (FRI) by a crop and daily incident solar radiation (Sandaña and Kalazich 2015).

Sandaña (2016) investigated phosphorus uptake and utilization efficiency in response to potato genotype and phosphorus availability and observed that tuber dry matter yield was positively related to total P uptake in two growth conditions corresponding to P fertilization rates of 0 and 130 kg ha^{-1} P.

The potato is considered as a plant with low P use efficiency and with a limited ability to absorb in soils with low phosphorus availability, and this is typically attributed to low density roots of a potato that are concentrated mainly in first 30 cm of depth below the seed tubers (Dechassa et al. 2003; Iwama 2008).

The differences observed between the varieties in the three soils could be due to their mechanisms of adaptation to the growing conditions. Plants growing at low P concentrations develop adaptive mechanisms including changes in morphology and architecture of the root system as well as in physiological characteristics of roots. Root systems with larger root surfaces, lengths, and densities usually exhibit high P uptake efficiency when P availability is low (Hu et al. 2010; López-Bucio et al. 2003; Raghothama and Karthikeyan 2005).

With respect to the starch content in the potato tubers, the results indicated differences among cultivars and also revealed the interference of P in the soil with respect to this component for all cultivars (Table 1).

The starch content ranged from 8.89 to 18.83 g 100 g^{-1}. All cultivars accumulated higher starch content in soil with higher P availability. This result occurred due to P participating in a number of key enzymes that are involved in the regulation of starch synthesis. Additionally, phosphorus is also part of starch composition and is connected to the amylopectin fraction in the form of phosphate ester (Nielsen et al. 1994).

The cultivar Agata did not exhibit an increase in the content of starch with increases in phosphorus availability, and this shows that this cultivar does not require increased P availability in the soil to synthesize and accumulate amounts of starch in tubers (Table 1). This result could be related to an increased development of the root system of the cultivar Agata that resulted in higher P uptake under conditions of medium P availability, and thereby in increased starch accumulation in the tubers.

The results indicate that the P availability in soil can affect the starch content of tubers and could thereby interfere in the quality of potatoes with respect to the industry. Kita (2002) correlated texture of potatoes with their starch content as intended for the chips industry and found that levels exceeding 15 g 100 g^{-1} (wet basis) of starch provided greater crispness in terms of the slices.

Following carbohydrates, proteins constitute the second major components of dry matter in potato tubers with content ranging between 2.7 and 14.6 g 100 g^{-1} of dry matter. (Bárta and Bártová 2008; Bártová and Bárta 2009; Bárta et al. 2012; Bártová et al. 2012).

The results showed a variation of 1.45–2.35 g 100 g^{-1} with respect to the protein content in potato tubers (Table 1). The data analysis revealed that lower protein levels were observed in soils with high P availability, and this behavior was not observed for the cultivar Agata.

The fiber content of potatoes is relatively low when compared with that of other commonly used vegetables. Results with respect to the potato tubers showed variations ranging from 0.34 to 0.80 g 100 g^{-1} (wet basis). The effects of cultivars and soil on this component were observed as listed in Table 1. With the exception of the Agata cultivar, potatoes cultivated in soil with increased P availability exhibited less fiber in the composition. The cultivar Markies displayed a lower content of fiber in soil with low and medium P availabilities.

Reistad and Hagen (1986) examined dietary fiber in potato and observed 3.5 g 100 g^{-1} of soluble fiber, 4.0 g 100 g^{-1} of insoluble fiber, and 7.5 g 100 g^{-1} of total fiber (dry weight). A study by Mulling and Smith (1991) revealed values of 2.5 g 100 g^{-1} with respect to soluble fiber, 4.3 g 100 g^{-1} with respect to insoluble fiber, and 6.8 g 100 g^{-1} with respect to total fiber in peeled potatoes, and the aforementioned contents exceeded those for potato cultivars grown in the three soils examined in the current study.

Conversely, the fiber content for potato cultivars in the experiment in the present study are close to those observed by Garcia et al. (2015) in their study with eight potato cultivars planted in Brazil that presented a variation of 0.31–0.66 g 100 g^{-1} of total fiber.

The potato sugar content is an important quality parameter. Non-enzymatic browning or Maillard reaction that occurs in tubers with high levels of reducing sugars constitutes a serious problem in potato products including flakes, chips and French fries. This is the largest contributor to the dark color of foodstuffs in which the pigments melanoidins correspond to end products (Marwaha et al. 2008).

Total sugars in potato tubers ranged from 0.11 to 0.76 g 100 g^{-1} (Table 1). With the exception of the cultivar Mondial, the total sugar content was lower in potatoes cultivated in soil with higher P availability. The limit established as the sugar content was almost consensual and was in the range corresponding to 0.2 and 0.3 g 100 g^{-1} for tubers intended for frying. Thus, only Agata and Mondial cultivars exceeded this limit in the soil with higher P availability.

Low sugar levels in tubers cultivated in soil with high availability of P constitutes very interesting information for potato cultivars destined for the production of chips or French fries. Thus, in these cultivation conditions, cultivars such as Atlantic, Asterix, and Markies are considered as more valuable in the market because they result in products with better quality.

The ash contents of potato tubers ranged from 0.81 to 1.38 g 100 g^{-1}. The results showed differences between cultivars grown in the same soil as well with respect to the same cultivar grown in different soils (Table 1). Lower values for this component were observed with respect to the Agata cultivar and did not differ from those observed for the Mondial cultivar in soils with low P availability.

The lipid content ranged from 0.25 to 1.04 g 100 g^{-1} for potato tubers (Table 1). Statistical analysis of the data showed that differences between cultivars in the same soil as well as with respect to cultivation of the same cultivar in different soils. A significant increase in this component in tubers of cultivar Markies was observed when the P availability in soil was higher.

The absorption of phosphorus by the roots resulted from interactions between the morphological and physiological characteristics of the roots as well as the rhizosphere surrounding the root system and the soil characteristics that determine the movement of P to the soil-root interface. Differences exist between potato cultivars in terms of the length and surface area of roots and the uptake kinetic parameters that affect the P uptake from soil (Fernandes et al. 2014).

The availability of phosphorus in the soil interfered in the content of the P uptake from the soil component in potato tubers, and this effect was not observed for the cultivar Agata (Table 1). With respect to the other evaluated cultivars, an increase in the available phosphorus in the soil led to an increase in this mineral in the composition of the tubers. This result is important because phosphorus in root and tubers is covalently linked to starch in the form of phosphorus esters and the degree of starch phosphorylation influences the qualitative properties of this polymer (Noda et al. 2007).

Conversely, the variation observed for the potato cultivars indicates differences in the absorption efficiency, and this is very important since the use of genotypes with high P efficiency is an option for sustainable production in low-P soils.

Balemi and Schenk (2009) examined genotypic variation for phosphorus efficiency related to the simulation of P uptake and revealed that the processes involved in P transport and morphological root characteristic affect the P uptake.

Significant differences exist in terms of the root mass (dry weight and length) in the plow layer between potato cultivars, breeding lines, and wild relatives. The differences are generally stable across different environmental

Table 2 Pearson correlation coefficients for tuber composition

	1	2	3	4	5	6	7	8
Soil ($p = 14$ mg dm^{-3})								
1-Fiber	1	0.88***	Ns	Ns	−0.65**	Ns	Ns	Ns
2-Total sugar		1	−0.59*	Ns	−0.81***	Ns	0.72**	−0.54*
3-Protein			1	Ns	0.72**	0.85***	−0.89***	0.66***
4-Lipids				1	Ns	Ns	Ns	Ns
5-Starch					1	0.87***	−0.95***	Ns
6-Ash						1	−0.95***	Ns
7-Moisture							1	Ns
8-Phosphorus								1
Soil ($p = 36$ mg dm^{-3})								
1-Fiber	1	0.52*	0.54*	Ns	Ns	Ns	−0.52*	−0.59*
2-Total sugar		1	Ns	0.83***	Ns	Ns	Ns	Ns
3-Protein			1	Ns	0.66***	0.85***	−0.93***	Ns
4-Lipids				1	−0.56*	Ns	Ns	Ns
5-Starch					1	Ns	−0.84***	Ns
6-Ash						1	−0.70**	Ns
7-Moisture							1	Ns
8-Phosphorus								1
Soil ($p = 70$ mg dm^{-3})								
1-Fiber	1	0.65**	−0.60*	0.68***	Ns	−0.71***	0.61*	−0.56*
2-Total sugar		1	−0.89***	0.56*	−0.94***	−0.90***	0.95***	−0.74***
3-Protein			1	Ns	0.89***	0.73**	−0.86***	0.80***
4-Lipids				1	Ns	−0.81***	0.62*	Ns
5-Starch					1	0.84***	−0.95***	0.68**
6-Ash						1	−0.96***	0.57*
7-Moisture							1	−0.65***
8-Phosphorus								1

Ns = not significant ($p > 0.05$), * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

conditions including locations with different soil types, fertilizer rates, and planting densities. Under favorable environmental conditions without severe water and nutrient shortages, root mass differences between genotypes are related to maturity class wherein late genotypes continue root growth for longer periods and attain larger root mass and deeper rooting when compared with those of early genotypes (Iwama 2008).

Results of the Pearson correlation indicated that when the average values of all potatoes were considered it is possible to observe more significant correlations between the components in the tubers cultivated in soils with high availability of phosphorus (Table 2). Typically, the fiber content was positively correlated with total sugar content and negatively correlated with starch, ash and phosphorus contents. The moisture displayed a negative correlation with protein, starch, ash, and phosphorus contents in soils with the increased availability of phosphorus (Table 2).

Conclusion

The results of the present study indicated that the main potato cultivars planted in Brazil differ in terms of nutritional composition. The P availability in the soil plays an important role in the composition of potato tubers. Soils with higher phosphorus concentrations allow the production of tubers with increased dry matter content, decreased total sugar content, and increased percentages of starch and protein, which constitute important parameters influencing the nutritional and industrial qualities of potatoes. The cultivar Agata exhibited distinct behavior that differed from those of other cultivars, thereby indicating possible differences in the absorption system and use of available phosphorus in the soil. The Pearson analysis indicated that moisture content displays a primarily negative correlation with the levels of starch, ash, and protein and is independent of the type of cultivar and soil. Starch and protein were positively correlated in addition to fiber and total sugar.

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