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Characterizing zinc use efficiency in varieties of Arabica coffee

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ABSTRACT. Among micronutrients, zinc (Zn) is important for coffee tree cultivation, especially in the clayey acid soils of Brazil's southeast region, where coffee production is an important activity. This study aimed to evaluate the Zn use efficiency of coffee tree varieties using two zinc concentrations. Seedlings of 11 varieties of coffee trees were grown in a greenhouse in nutrient solution containing either 0.0 or 6.0 μmol L^{-1} of Zn. After eight months, we evaluated the total biomass production, leaf biomass production, concentration of Zn in the plant organs, absorption efficiency, and Zn use efficiency. All characteristics were affected by the Zn concentration. The biomass production of apical leaves was most affected by the Zn treatments, with high variability for the studied varieties. The 'IPR-103' variety had the highest Zn use efficiency, and the 'San Ramon' and 'San Bernardo' varieties had the lowest Zn use efficiency. The 'Rubi' variety had a high and low Zn use efficiency when grown at 0.0 and 6.0 μmol L^{-1} of zinc, respectively. The 'Oeiras' variety had a low Zn use efficiency when cultivated at 6.0 μmol L^{-1} of zinc. The other varieties studied were moderately efficient in their use of zinc.

Keywords: *Coffea arabica* L., micronutrient, zinc content, nutritional efficiency.

Caracterização da eficiência do uso de zinco em variedades de café arábica

RESUMO. Dentre os micronutrientes, o Zn é um dos mais importantes para o cafeeiro, especialmente em solos argilosos e ácidos do sudeste brasileiro, onde seu cultivo é uma importante atividade econômica. Este trabalho objetivou avaliar a eficiência de uso do zinco por variedades de cafeeiro cultivadas em doses contrastantes do elemento. Mudas de 11 variedades foram cultivadas, em casa de vegetação, em solução nutritiva, com duas concentrações de zinco (0,0 e 6,0 μmol L^{-1}). Após oito meses determinaram-se: biomassa seca dos órgãos da planta, concentração de zinco, eficiências de absorção, de produção de biomassa, de produção de biomassa foliar e de utilização de zinco. A concentração de zinco fornecida afetou todas as características avaliadas. A produção de biomassa seca de folhas apicais foi a mais afetada, proporcionando grande variabilidade de resposta entre as variedades. A variedade IPR-103 foi a mais eficiente no uso de zinco, as variedades San Ramon e São Bernardo as menos eficientes. A 'Rubi' apresentou alta e baixa eficiência de utilização de zinco quando cultivada nas doses 0,0 e 6,0 μmol L^{-1}. A variedade Oeiras apresentou baixa eficiência de utilização na dose de 6,0 μmol L^{-1}. As demais variedades estudadas foram moderadamente eficientes no uso do elemento.

Palavras-chave: *Coffea arabica* L., micronutrientes, conteúdo de Zn, eficiência nutricional.

Introduction

Zinc deficiency can impair crop productivity by interfering with the growth and development of plants (EPSTEIN; BLOOM, 2006). Significant differences in micronutrient content among varieties that grow in similar environments are due to genetic variation, the intensity of the demand in sink tissues and interactions among nutrients (MALAVOLTA et al., 2002).

The nutrient use efficiency in plants may be related to their absorption efficiency, translocation efficiency, and nutrient utilization efficiency. A higher efficiency in absorbing nutrients from soil is sometimes related to root structure and function, including morphological features and the biochemical mechanisms responsible for transferring ions through the membranes of root cells (AHMAD et al., 2001).

Under the same cultivation conditions, crop varieties present different behaviors for nutritional characteristics, providing different growth and productivity responses. Such behavior may be due to differences in nutrient use among varieties. Li et al. (1991) defined the nutritional efficiency as a result from product between acquisition efficiency and use efficiency. The acquisition efficiency consists of the absorption mechanism efficiency and the fine root growth, while the use efficiency is a measure of the efficiency of the transport and production of biomass per unit of nutrient absorbed.

Fageria et al. (2002) observed that different mechanisms can affect the absorption efficiency of micronutrients, including Zn, and that some of these mechanisms are specific to certain elements while others are common to all nutrients. These authors concluded that the response to Zn deficiency depends on the genetic characteristics of the plant and the growing environment. Higher nutrient utilization efficiency correlates with higher efficiency of a variety in producing dry matter per unit of nutrient absorbed. The utilization efficiency results from interactions among the absorption, transport, redistribution, and metabolism of nutrients in a plant.

The absorption, transport and redistribution of nutrients are genetically controlled, allowing improvement or selection (or both) of varieties that are more efficient in nutrient utilization (GALBEMAN; GERLOFF, 1983). Understanding differences in the nutritional needs of varieties will allow us to establish varieties that are less zinc demanding in poorer soils and avoid future problems. Therefore, this work aims to define the zinc use efficiency of the varieties of Arabica coffee cultivated in Brazil.

Material and methods

The experiment was conducted in a greenhouse at the Departamento de Fitotecnia at the Universidade Federal de Viçosa, from February to October 2007. The coffee varieties studied were 'Acaiá Cerrado' MG-1474 (1), 'Caturra Amarelo' IAC-476 (2), 'Catucaí Vermelho' 785-15 (3), 'IPR-102' (4), 'Oeiras' MG-6851 (5), 'Paraíso' MGH-419-1 (6), 'Rubi' MG-1192 (7), 'San Ramon' (8), 'São Bernardo' (9), 'Topazio' MG-1190 (10), and 'Tupi' IAC 1669-33 (11).

Seeds of these coffee varieties were germinated in sand and irrigated with deionized water until emergence. The seeds were then transplanted into trays containing ¼ strength Clark's nutrient solution. After the onset of the first pair of leaves, the plants were transplanted into eight-liter pots with Clark's solution modified according to Martinez and Clemente (2011), with zinc supplied at 0.0 and 6.0 μmol $L^{-1.}$ The experiment consisted of an 11 x 2 factorial (eleven varieties and two zinc concentrations), in a completely randomized design with three replicates.

The ferric chloride and macronutrient stock solutions were purified using the APDC method described by Martinez and Clemente (2011) to avoid contamination with Zn.

The solution was aerated with compressed air, and the pH was adjusted daily to 5.0 ± 0.5. The nutrient solution was exchanged after a 30% depletion of the initial electrical conductivity. At the end of the experiment, eight months after transplantation, the plant material was rinsed in deionized water, and the plant organs were dried separately in an oven at 70°C for 72h. Next, the dried material was weighed and ground in a Wiley mill.

Zinc concentrations in the plant organs were determined by atomic absorption spectrophotometry after nitro-perchloric mineralization according to MALAVOLTA et al. (1997). The zinc content and nutritional efficiency indexes were measured in all organs of the plant and were calculated according to the following formulas:

Zinc content (ZnC);

ZnC (μg) = {Zn concentration (μg g^{-1}) x dry biomass (g)};

Absorption efficiency (AE);

AE ($\mu g\ g^{-1}$) = TZnC / RDB;

Efficiency to produce leaf biomass (EPLB);

EPLB ($g^2\ \mu g^{-1}$) = LDB^2 / LZnC;

Efficiency of biomass production (EBP);

EBP ($g^2\ \mu g^{-1}$) = $ShDB^2$ / CZnSh;

Zinc utilization efficiency (UE);

UE ($g^2\ \mu g^{-1}$) = TDB^2 / TZnC.

where:

TDB = total plant dry biomass (g);

RDB = root dry biomass (g);

ShDB = shoot dry biomass (g);

LDB = leaf dry biomass (g);

TZnC = total zinc content in the plant (μg);

ShZnC = zinc content in shoot (μg);

LZnC = zinc content in plant leaves (μg).

All data were subjected to Lilliefors, Cochran and Bartlet tests prior to being submitted to analyses of variance and F-test. When the data did not fit a normal distribution or the variances were not homogeneous, the analyses of variance were performed with the data transformed into root square of X. The means were compared by Duncan's test at 5% probability. Statistical analyses were performed with the GENES software (CRUZ, 2010).

Results and discussion

The zinc content of the plants grown at 6.0 μmol L^{-1} of Zn was significantly higher than the content observed in plants grown at 0.0 μmol L^{-1} in all organs (Tables 1 and 2). The best way to determine the nutritional requirement of a plant is to use the amount of the nutrient accumulated in the dry plant biomass, usually expressed as total nutrient content.

When Zn was omitted from the nutrient solution, the lowest average Zn content was observed in the apical leaves, not the recent mature or lower leaves, which indicates that Zn is an element with low mobility in the phloem, at least in coffee trees (Table 1).

Table 1. Zinc content in apical leaves (ALZnC), recent mature leaves (RMLZnC) and lower leaves (LLZnC) of 11 varieties of coffee trees submited to two zinc doses (0.0 and 6.0 μmol L^{-1}) in nutritive solution.

VAR *	Zinc content (μg)					
	ALZnC		RMLZnC		LLZnC	
	0.0	6.0	0.0	6.0	0.0	6.0
	μmol L^{-1}					
1	17.0 Ba	42.0 Aabc	49.0 Ba	85.0 Abc	23.0 Bab	39.0 Aa
2	7.0 Ba	45.0 Aab	46.0 Ba	109.0 Aab	24.0 Bab	37.0 Aa
3	16.0 Ba	35.0 Acd	51.0 Aa	69.0 Acd	25.0 Aa	31.0 Aab
4	16.0 Ba	46.0 Aa	61.0 Ba	124.0 Aa	19.0 Bab	39.0 Aa
5	10.0 Ba	37.0 Aabcd	41.0 Ba	89.0 Aabc	20.0 Bab	36.0 Aab
6	11.0 Ba	35.0 Abcd	31.0 Ba	72.0 Abcd	18.0 Bab	35.0 Aab
7	15.0 Ba	35.0 Abcd	45.0 Ba	98.0 Aabc	27.0 Ba	37.0 Aab
8	7.0 Ba	21.0 Ae	26.0 Aa	43.0 Ad	15.0 Ab	21.0 Ac
9	12.0 Ba	27.0 Ade	31.0 Ba	67.0 Acd	21.0 Aab	27.0 Abc
10	13.0 Ba	37.0 Aabcd	36.0 Ba	98.0 Aabc	26.0 Ba	36.0 Aab
11	17.0 Ba	38.0 Aabc	61.0 Ba	96.0 Aabc	21.0 Bab	40.0 Aa
Average	13.0	36.0	43.0	86.0	22.0	34.0
CV (%)	22.13		29.73		17.84	

*1 Acaiá Cerrado, 2 Caturra Amarelo, 3 Catucaí Vermelho, 4 IPR-102, 5 Oeiras, 6 Paraíso, 7 Rubi, 8 San Ramon, 9 São Bernardo, 10 Topázio, and 11 Tupi. Means followed by the same letter, horizontal upper case or vertical lower case, do not differ among themselves by Duncan's MRT at 5% of probability. **Variance analyses made with the data transformed into root square of X.

Reis Jr. and Martinez (2002) studied the absorption, translocation, and utilization of Zn and P in coffee trees and observed that the content of Zn in stems, shoots, and roots increased with the zinc supply. Similar results were observed in this study (Tables 1 and 2).

Table 2. Zinc content in stems (SZnC), roots (RZnC) and total (TZnC) of 11 varieties of coffee trees submitted to two zinc doses (0.0 and 6.0 μmol L^{-1}) in nutritive solution.

VAR *	Zinc content (μg)					
	SZnC**		RZnC**		TZnC	
	0.0	6.0	0.0	6.0	0.0	6.0
	μmol L^{-1}					
1	37.0 Ba	113.0 Ab	43.0 Ba	172.0 Aab	169.0 Ba	452.0 Aab
2	19.0 Ba	142.0 Aab	44.0 Ba	116.0 Aab	139.0 Ba	449.0 Aabc
3	19.0 Ba	139.0 Aab	47.0 Ba	113.0 Aab	159.0 Ba	388.0 Abcd
4	31.0 Ba	241.0 Aa	42.0 Ba	129.0 Aab	171.0 Ba	580.0 Aa
5	19.0 Ba	144.0 Aab	31.0 Ba	218.0 Aa	122.0 Ba	525.0 Aab
6	22.0 Ba	110.0 Ab	38.0 Ba	165.0 Aab	119.0 Ba	417.0 Abc
7	21.0 Ba	109.0 Ab	49.0 Ba	139.0 Aab	156.0 Ba	417.0 Abc
8	11.0 Ba	79.0 Ab	28.0 Aa	67.0 Ab	86.0 Ba	231.0 Ad
9	18.0 Ba	86.0 Ab	34.0 Ba	82.0 Ab	115.0 Ba	288.0 Acd
10	20.0 Ba	144.0 Aab	37.0 Ba	116.0 Aab	132.0 Ba	431.0 Aabc
11	18.0 Ba	177.0 Aab	31.0 Ba	136.0 Aab	148.0 Ba	488.0 Ab
Average	21.0	135.0	38.0	132.0	138.0	424.0
CV (%)	21.71		21.02		29.70	

*1 Acaiá Cerrado, 2 Caturra Amarelo, 3 Catucaí Vermelho, 4 IPR-102, 5 Oeiras, 6 Paraíso, 7 Rubi, 8 San Ramon, 9 São Bernardo, 10 Topázio, and 11 Tupi. Means followed by the same letter, horizontal upper case or vertical lower case, do not differ among themselves by Duncan's MRT at 5 % of probability. **Variance analyses made with the data transformed into root square of X.

The stem accumulated the most Zn (SZnC) when plants were grown at 6.0 μmol L^{-1} Zn, accumulating an average of 135.0 μg, while with no Zn added to the nutrient solution, the average Zn content was 21.0 μg. In the treatment without the addition of Zn, there were no differences between the varieties, but the 'Acaiá Cerrado' variety had the highest average SZnC (37.0 μg), and the 'San Ramon' variety had the lowest average SZnC (11.0 μg). In the treatment with 6.0 μmol L^{-1} Zn, the highest mean SZnC was observed for the 'IPR-102' variety (241.0 μg), which was statistically different from the 'Rubi', 'Acaia Cerrado', 'São Benardo', 'San Ramon' and 'Paraíso' varieties (Table 2).

In the roots, there was an accumulation of 38.0 μg of zinc (RZnC) for the treatment with a zinc concentration of 0.0 μmol L^{-1} and 132.0 μg of zinc for the treatment with a zinc concentration of 6.0 μmol L^{-1} Zn, which indicates that the greater availability of Zn in solution increased the Zn retention by the root system. By omitting zinc, there was a greater RZnC observed for the 'Rubi' variety (49.0 μg), while the varieties with the lowest average RZnC were the 'Oeiras' and 'Tupi' varieties (31.0 μg). However, for the 0.0 μmol L^{-1} Zn treatment, these differences were not significant. Nevertheless, the highest accumulation of Zn was in the roots of the 'Rubi' variety in the low nutrient solution concentration (Table 2).

At a zinc concentration of 6.0 μmol L^{-1}, higher RZnC was observed in the 'Oeiras' variety (218.0 μg); however, measured zinc content was not different from that in the other varieties, except 'San Ramon' and 'São Bernardo', which had the lowest RZnC (67.0 and 82.0 μg, respectively). These results demonstrate that 'Oeiras' has a low Zn absorption efficiency at low Zn concentrations in the cultivation medium. However, at a concentration of 6.0 μmol L^{-1} Zn, this variety was able to accumulate more zinc in roots than the other varieties (Table 2). Reis Jr. and Martinez (2002) compared the 'Catuaí' (*Coffea arabica* L.) and 'Conilon' (*Coffea canephora* Pierre ex Froehner) coffee varieties and observed that high zinc concentrations in the roots of 'Catuaí' were compensated for by higher production of root dry biomass in 'Conilon'. As a result, no significant differences were found in the Zn content in roots of the two varieties.

The highest total zinc content, TZnC, in the 6.0 μmol L^{-1} Zn treatment was observed in the 'IPR-102' variety (580.0 μg), which did not differ from measurements in the 'Acaiá Cerrado', 'Caturra Amarelo', 'Oeiras', 'Topazio', and 'Tupi' varieties. For this treatment, the lowest average TZnC was found in the 'San Ramon' variety (231.0 μg), which has a lower zinc requirement (Table 2). This decreased zinc requirement may be due to a lower growth rate or greater efficiency in using the element. As observed by Martinez et al. (2011), the progeny UFV 4066-5 had low total zinc content due to its low zinc requirement but also showed low efficiency in producing biomass, which demonstrates that a low zinc requirement does not necessarily imply a greater nutritional efficiency.

Regarding the zinc supply, the varieties behaved very differently for the nutritional efficiency variables studied. The absorption efficiency (AE) was higher in all varieties when grown with a zinc concentration of 6.0 μmol L^{-1} compared to 0.0 μmol L^{-1} (Table 3). These results demonstrate that the plants were able to absorb more zinc per unit of root dry matter when Zn was provided at a higher concentration in the nutrient solution. Differences in nutrient efficiency between the genotypes may be related to the demand of the nutrient at the cellular level, the affinity of the absorption system, compartmentalization in roots or other plant organs, the mobility in the xylem and phloem vessels, and changes in the rhizosphere during growth (MARSCHNER, 1995). Baligar and Fageria (1999) summarize the features related to plant nutritional efficiency as absorption, translocation, and nutrient utilization efficiencies. However, the usage efficiency of a particular nutrient reflects not only the content of the nutrient placed in different organs at a given nutritional condition but also the amount of dry matter produced per unit of nutrient acquired.

Table 3. Absorption efficiency (AE) and efficiency of biomass production (BPE) of 11 varieties of coffee tree submitted to two zinc doses (0.0 and 6.0 μmol L^{-1}) in nutritive solution.

VAR*	Nutritional efficiencies							
	AE (μg g^{-1})				BPE** (g^2 μg^{-1})			
	0.0		6.0		0.0		6.0	
	μmol L^{-1}							
1	44.91	Ba	136.83	Aab	1.865	Aabc	0.924	Aa
2	30.26	Ba	102.33	Acd	2.089	Aab	1.001	Aa
3	34.32	Ba	121.80	Abcd	1.601	Aabc	0.877	Aa
4	38.76	Ba	110.49	Abcd	2.722	Aa	1.115	Ba
5	33.79	Ba	162.76	Aa	1.687	Aabcd	0.639	Ba
6	30.27	Ba	93.09	Ad	1.079	Abcd	0.748	Aa
7	33.13	Ba	137.63	Aab	2.543	Aab	0.583	Ba
8	29.97	Ba	97.60	Ad	0.677	Ad	0.409	Aa
9	36.39	Ba	105.06	Abcd	0.938	Acd	0.618	Aa
10	36.17	Ba	132.56	Aabc	1.739	Aabcd	0.868	Aa
11	42.92	Ba	136.42	Aab	1.972	Aabc	0.945	Aa
Average	35.54		121.51		1.72		0.79	
CV (%)	21.35				23.78			

1 Acaiá Cerrado, 2 Caturra Amarelo, 3 Catucaí Vermelho, 4 IPR-102, 5 Oeiras, 6 Paraíso, 7 Rubi, 8 San Ramon, 9 São Bernardo, 10 Topázio, and 11 Tupi. Means followed by the same letter, horizontal upper case or vertical lower case, do not differ among themselves by Duncan's MRT at 5% of probability. **Variance analyses made with the data transformed into root square of X.

The highest average absorption efficiency (AE) at a zinc concentration of 0.0 μmol L^{-1} was presented by the 'Acaiá Cerrado' variety (44.91 μg g^{-1}), and when grown with a zinc concentration of 6.0 μmol L^{-1}, this variety had an AE of 136.83 μg g^{-1}. This variety showed intermediate values for the efficiency of biomass production (BPE) (1.865 and 0.924 g^2 g^{-1}), leaf biomass production (LBPE) (1.169 and 0.674 g^2 g^{-1}), and zinc utilization (UE) (2.143 and 0.846 g^2 g^{-1}) when grown at 0.0 and 6.0 μmol L^{-1} of Zn. These results indicate that, although this variety has a high zinc absorption efficiency, it has a moderate ability to use the element because of its lower fitness in producing biomass per unit of absorbed Zn in both the zinc concentrations studied (Tables 3 and 4).

The 'Caturra Amarelo' variety showed low AE when grown at 0.0 and 6.0 μmol L^{-1} Zn (Table 3 and 4). However, it presented intermediate BPE (2.089 and 1.001 g^2 g^{-1}), LBPE (1.323 and 0.941 g^2 g^{-1}) and UE (2.497 and 1.151 g^2 g^{-1}) when compared to the other varieties studied. These results show that despite its low absorption efficiency, this variety has a moderate capacity for zinc utilization for the two zinc concentrations assessed.

The 'IPR-102' variety when grown in the zinc concentration of 0.0 or 6.0 μmol L^{-1}, showed the highest BPE (2.722 and 1.115 g^2 g^{-1}), LBPE (1.742 and 1.279 g^2 g^{-1}), and UE of zinc (3.175 and 1.325 g^2 g^{-1}). However, in these same situations, this variety had an AE of 38.76 and 110.49 μg g^{-1} (Table 3 and 4). These results indicate that 'IPR-102' has high zinc capacity utilization because of the greater ability to use the absorbed zinc for biomass production, even with a moderate zinc absorption efficiency in the two zinc concentrations tested.

Table 4. Efficiency of leaf biomass production (LBPE), and utilization efficiency of zinc (UE) of 11 varieties of coffee tree submitted to two zinc doses (0.0 and 6.0 μmol L^{-1}) in nutritive solution.

VAR*	Nutritional efficiencies							
	LBPE (g^2 μg^{-1})				UE** (g^2 μg^{-1})			
	0.0		6.0		0.0		6.0	
	μmol L^{-1}							
1	1.169	Abcd	0.674	Bbc	2.143	Aabc	0.846	Bab
2	1.323	Aabc	0.941	Aabc	2.497	Aab	1.151	Aab
3	1.374	Aab	0.869	Babc	2.149	Aabc	0.925	Bab
4	1.742	Aa	1.279	Ba	3.175	Aa	1.325	Ba
5	1.149	Abcd	0.649	Bbc	2.122	Aabcd	0.566	Bab
6	0.822	Acde	0.745	Aabc	1.501	Abcd	0.831	Aab
7	1.187	Abcd	0.606	Bbc	2.909	Aab	0.614	Bab
8	0.552	Ae	0.530	Ac	0.971	Ad	0.481	Ab
9	0.708	Ade	0.633	Abc	1.224	Acd	0.694	Aab
10	1.215	Aabcd	0.860	Aabc	2.118	Aabcd	0.925	Bab
11	1.354	Aabc	1.083	Aab	2.266	Aabcd	1.005	Aab
Average	1.14		0.81		2.09		0.85	
CV (%)	28.31				23.65			

1 Acaiá Cerrado, 2 Caturra Amarelo, 3 Catucaí Vermelho, 4 IPR-102, 5 Oeiras, 6 Paraíso, 7 Rubi, 8 San Ramon, 9 São Bernardo, 10 Topázio, and 11 Tupi. Means followed by the same letter, horizontal upper case or vertical lower case, do not differ among themselves by Duncan's MRT at 5% of probability. **Variance analyses made with the data transformed into root square of X.

The lowest AE at the zinc concentration of 0.0 μmol L^{-1} was presented by the 'San Ramon' variety (29.97 μg g^{-1}). However, this result is not significantly different from the other varieties, and when grown with a zinc concentration of 6.0 μmol L^{-1}, this same variety, along with the 'Paraíso' variety showed low AE (97.60 and 93.09 μg g^{-1}). 'San Ramon' presented the lowest BEP (0.677 and 0.409 g^2 g^{-1}), LBPE (0.552 and 0.530 g^2 g^{-1}), and UE of zinc (0.971 and 0.481 g^2 g^{-1}) when grown at 0.0 and 6.0 μmol L^{-1} Zn. These results show that this variety presents a low zinc absorption efficiency as well as a low zinc utilization, as a result of the decreased ability to produce biomass per unit of absorbed Zn, in both zinc concentrations studied (Tables 3 and 4).

The 'Paraíso' variety had the lowest AE (93.09 μg g^{-1}) when grown with a zinc concentration of 6.0 μmol L^{-1}. Furthermore, when grown with a zinc concentration of 0.0 μmol L^{-1}, this variety showed a low AE (30.27 μg g^{-1}). However, when grown at 0.0 and 6.0 μmol L^{-1} Zn, this variety exhibited moderate BPE (1.079 and 0.748 g^2 g^{-1}), LBPE (0.822 and 0.745 g^2 g^{-1}), and UE of zinc (1.501 and 0.831 g^2 g^{-1}). These results show the low efficiency of the 'Paraíso' variety in absorbing zinc, when compared with other varieties in both studied concentrations of zinc. These results also demonstrate that 'Paraíso' could use zinc more or less efficiently, since it could achieve good biomass production per unit of absorbed Zn, though it had a lower efficiency in absorbing the element (Table 3 and 4).

The 'Oeiras' variety had the highest AE at a zinc concentration of 6.0 μmol L^{-1} (162.76 μg g^{-1}). However, under the same conditions, this variety showed low BPE (0.639 g^2 g^{-1}), low LBPE (0.649 g^2 g^{-1}), and low UE of zinc (0.566 g^2 g^{-1}). These results demonstrate that under these conditions, this variety, despite its high efficiency to absorb zinc, has a low zinc utilization efficiency due to the reduced ability to produce biomass per unit of Zn absorbed (Table 3 and 4).

For efficiency of biomass production (BPE), differences between treatments for the 'Catucaí Vermelho', 'Paraíso', 'San Ramon', and 'São Bernardo' varieties were not observed. The other varieties studied showed differences between treatments, and all these varieties exhibited higher BPE when they were grown with a zinc concentration of 0.0 μmol L^{-1}. However, differences between treatments were observed for LBPE only in the 'Acaiá Cerrado', 'Catucaí Vermelho', 'IPR-102', 'Oeiras', and 'Rubi' varieties, with best LBPE attained at a zinc concentration of 6.0 μmol L^{-1} (Tables 3 and 4).

Several varieties had higher UE of zinc when grown with a zinc concentration of 0.0 μmol L^{-1}. Only the 'Caturra Amarelo', 'Paraíso', 'San Ramon', 'São Bernardo' and 'Tupi' varieties showed no differences between treatments (Table 4).

In this study, the increase in the zinc concentration from 0.0 to 6.0 μmol L^{-1} reduced the BPE, LBPE, and UE of zinc for several varieties (Tables 3 and 4). However, the 'Rubi' variety was the most negatively affected by the zinc concentration of 6.0 μmol L^{-1}, causing low BPE, LBPE, and UE. These results show that this zinc concentration was excessive for the variety. Variations in zinc concentration affect the absorption efficiency of coffee trees. Thus, the zinc content in all plant parts studied, especially in leaves, indicates the zinc use efficiency of the plants.

Conclusion

The 'IPR-102' variety was highly efficient in using zinc. The 'Rubi' variety had high Zn utilization efficiency when grown with a zinc concentration of 0.0 μmol L^{-1} and low utilization efficiency when cultivated with a zinc concentration of 6.0 μmol L^{-1}, which is excessive for such a variety. The 'San Ramon' and 'São Bernardo' varieties showed low zinc utilization efficiency. The 'Oeiras' variety had low zinc utilization efficiency when grown with a zinc concentration of 6.0 μmol L^{-1}. The other varieties studied are moderately efficient in the use of zinc.

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