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Programmed pruning cycle for arabica coffee as enhancer of nutrient cycling to maintain soil fertility

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Abstract – The objective of this work was to evaluate the nutrient cycling and biomass input of arabica coffee plants managed with a programmed pruning cycle and potassium fertilization. The experiment was carried out in a split-plot arrangement, with four doses of K in the plot, and nine periods of evaluation in the subplot. A randomized complete block design with four replicates was applied. Significance was observed as a function of days after pruning, reaching 78.5% of the decomposed leaf material at 324 days. The release of nutrients showed a variable behavior. At 360 days of evaluation, the percentages of releases nutrients were: 97.2, 79.1, 73.7, 68.0, 48.6, and 32.5, for K, P, Mg, Mn, N, and Ca, respectively. Potassium fertilization levels do not influence the decomposition rate of the leaves eliminated by the programmed pruning cycle in arabica coffee.

Index terms: *Coffea arabica*, biogeochemistry cycling, coffee cultivation renewal, mineral nutrition.

Poda programada de ciclo em café arábica como potencializador da ciclagem de nutrientes para manutenção da fertilidade do solo

Resumo – O objetivo deste trabalho foi avaliar a ciclagem de nutrientes e o aporte de biomassa em plantas de café arábica manejadas com poda programada de ciclo e adubação potássica. O experimento foi realizado em parcelas subdivididas, com quatro doses de K na parcela e nove épocas de avaliação na subparcela. Um delineamento de blocos ao acaso foi aplicado com quatro repetições. Observou-se significância em função dos dias após a poda, tendo atingido 78,5% de material foliar decomposto aos 324 dias. A liberação de nutrientes apresentou comportamento variável. Aos 360 dias de avaliação, as percentagens de liberação de nutrientes foram: 97,2, 79,1, 73,7, 68,0, 48,6 e 32,5% de K, P, Mg, Mn, N e Ca, respectivamente. Os níveis de adubação potássica não influenciam a taxa de decomposição das folhas eliminadas pela poda programada de ciclo em café arábica.

Termos de indexação: *Coffea arabica*, ciclagem biogeoquímica, renovação da lavoura cafeeira, nutrição mineral.

Introduction

Coffee cultivation is one of the most prominent agricultural activities in Brazil, which is the biggest producer of this grain in the world (Volsi et al., 2019). This activity covers highly technicized areas and mountainous regions, where it is carried out mostly by small farmers (Sanjay J. et al., 2024). Commercial cultivation of coffee relies on two species *Coffea arabica* L. and *Coffea canephora* Pierre ex Froehner (Gokavi et al., 2021; Santos et al., 2021).

A coffee shrub needs high doses of nutrients to achieve a satisfactory productivity, for which potassium is the second most required nutrient. Potassium plays a crucial role in the physiological and biochemical coffee processes, influencing the increase of productivity, enzymatic activity, and the quality of coffee beans (Clemente et al., 2015; Vinecky et al., 2017; Mulindwa et al., 2022).

Strategies that allow the improvement of efficiency of the nutrient use in cultivation is important for a sustainable production. The recommendations for fertilization of arabica coffee take into consideration the soil analysis and the crop productive potential. However, these recommendations are not efficiently accommodated by some management techniques, such as a programmed pruning cycle of arabica coffee tree (PPCA), which is based on the conduction of more than one orthotropic branch from each plant (Baitelle et al., 2019; Verdin Filho et al., 2024).

Pruning is essential for the management of coffee shrubs because it fosters the renovation of the cultivation and production earnings (Verdin Filho et al., 2014). In the decomposition process, the constant production of biomass allows of the release and recycling of part of the nutritional elements present in leaves and branches of the pruned material, maximizing the efficiency of nutrient use (Pinto, 2016; Gokavi et al., 2021).

The decomposition of leaf litter is a dynamic process, in which the physical fragmentation of structures, chemical transformation, and synthesis of new compounds occur simultaneously (Guo et al., 2021). Litter decomposition rates depend essentially on the physical, biological, and chemical conditions of the environment, and on the organic and nutritional quality of the material (Lam et al., 2021).

The PPCA system shows advantages over other forms of pruning. In addition to maintaining productivity in the year following the cut (other prunings have “zero harvest” in the following year), PPCA makes it possible that the biomass resulting from the removal of plagiotropic branches be incorporated into the soil annually after harvest (with 70% or more of its productive capacity) (Verdin Filho et al., 2014). The PPCA may positively alter the level of organic matter in the soil. This way, the search for information on the dynamics of nutrient release – derived from the decomposition of plagiotropic branches eliminated by pruning – is essential to the quantification for the reuse of resources that contribute to the maintenance of soil fertility.

The objective of this work was to evaluate the nutrient cycling and biomass input in arabica coffee plants managed with a programmed pruning cycle and fertilization with increasing K doses.

Materials and Methods

The experiment was carried out at the Centro de Pesquisas Cafeeiras “Eloy Carlos Heringer” (Cepec), in the municipality of Martins Soares (20º14'30"S, 41º50'44"W, at 750 m altitude), in the state of Minas Gerais (MG), Brazil. The genetic material evaluated was the *Coffea arabica* 'Catuaí Vermelho IAC 44' group (intermediate maturation), conducted in 2.5×0.6 m, with a population of 6,666 plants ha^{-1}, occupying an area of 0.2 ha, which is considered a dense cultivation. The climate is Cwa, mesothermal with humid summers, according to the Köppen-Geiger’s classification. The soil of the area was characterized as Latossolo Vermelho-Amarelo distrófico, according to the Brazilian Soil Classification System (Santos et al., 2018) (Table 1).

'Catuaí Vermelho IAC 44' seedlings were planted in 2011 and managed with drastic pruning in 2016. The top of the coffee shrubs was removed and the trunk was maintained at 20 cm height. Then, the emerging shoots were selected to promote the establishment of two orthotropic stems for each plant. From then on, during the reproductive cycle, the plants were managed with a PPCA type pruning (Verdin Filho et al., 2014). The experiments in this work were carried out in the 2019/2020 harvest, starting in August 2019 and ending in July 2020, completing 360 days.

Samples of soil (collected at 0–20 cm depths) and leaves were analyzed to manage the fertilization and liming, aiming at supply the nutritional demand of the coffee plants, according to the recommendations for the cultivation of *C. arabica* (Sakiyama et al., 2015). Phytosanitary treatments were applied according to seasonal occurrences of pests and diseases. This experiment was carried out without using irrigation.

The experiment was performed in a split-plot design, with four doses of K in the plot and nine evaluation periods in the subplot described as follows. Potassium in the plot was applied at 50% (300 kg ha^{-1}), 100% (350 kg ha^{-1}), 150% (400 kg ha^{-1}), and 200% (450 kg ha^{-1}) of the K_2O. In the subplot, the evaluation was performed over nine periods, and assessments occurred at the following number of days after pruning: 30 (August 2019); 60 (September 2019); 90 (October 2019; 120 (November 2019); 150 (December 2019); 180 (January 2020); 210 (February 2020); 240 (March 2020); 270 (April 2020); 300 (May 2020); 330 (June 2020); and 360 (July 2020). The analyzed variables were biomass and nutrient content; and decomposition rate and nutrient release.

The entire pruned material of each treatment from the trimmed plagiotropic branches (composed of leaves and stems) that reached 70% of their productive capacity was collected and weighed in an analytical scale, to obtain the fresh masses of leaves and stems. After weighing, one sample was removed and dried at 60ºC in a forced-air oven, until the constant dry matter was attained. Then, the dry masses of leaves and stems of the plagiotropic branches were measured on an analytical scale and, subsequently, the material was ground in a Wiley-type mill. Total biomass determination of plagiotropic branches deposited per hectare (TBD, kg ha^{-1}) was obtained through a sum of estimates of the total dry mass of leaves of plagiotropic branches per hectare (TDML, kg ha^{-1}) and total dry mass of stems of plagiotropic branches per hectare (TDMS, kg ha^{-1}).

Micro- and macronutrient contents (N, K, P, Ca, Mg, Cu, Fe, Mn, and Zn) of the dry mass of leaves and stems were analyzed as described by Teixeira et al. (2017) with adaptations. Initially, the material was subjected to nitroperchloric digestion, for the determination of P, K, Ca, Mg, Cu, Mn, and Zn. To determine the levels of N, the material was subjected to sulfuric digestion. After digestion, N and P were determined by spectrophotometry. The nutrients K, Cu, Mn, and Zn were determined by flame photometry, and Ca and Mg by atomic absorption spectrophotometry. The nutritional content deposited in the soil with the pruned material was estimated by using the TBD; the level of nutrients in leaves and stems was determined from plagiotropic branches through simple multiplication. The organic carbon content in arabica coffee leaves was determined with the elemental analyzer C-144 carbon analyzer (Leco, St. Joseph, MI, USA).

The decomposition rate of arabica coffee leaves was obtained by the direct method by using polyethylene bags. After drying, 20 g of trimmed plagiotropic branches (composed of leaves and stems) were transferred to polyethylene bags (5×5 mm mesh) measuring 20×20 cm, and the mesh allowed the passage of macro- and mesoinvertebrates. One hundred forty-four polyethylene bags were distributed in the study areas, and collections were carried out at 30, 60, 90, 120, 150, 180, 240, 300, and 360 days after the distribution in the area. The collected leaves were dried in an oven with forced-air circulation at 60ºC, to obtain the percentage of residual mass on an analytical balance (g). After the weighing, the material was crushed in a Wiley mill, and chemical analyses of the nutritional contents of both macro- and micronutrients were carried out, according to the methods described by Teixeira et al. (2017), with adaptations.

The percentage of released nutrients was obtained by a formula described by Guo & Sims (1999), as follows:

$$R = \frac{W0C0 - WtCt}{W0C0} \times 100,$$

Table 1. Soil chemical attributes and organic matter of a Latossolo Vermelho-Amarelo distrófico (Santos et al., 2018), at 0–20 cm soil depths of the experimental area of Centro de Pesquisas Cafeeiras "Eloy Carlos Heringer" (Cepec), in the municipality of Martins Soares, in the state of Minas Gerais, Brazil, 2019.

pH	P	K	H + Al^{+3}	Al^{+3}	Ca^{+2}	Mg^{+2}	SB	CEC	V	SOM
H_2O	(mg dm^{-3})		(cmol$_c$ dm^{-3})						(%)	(dag kg^{-1})
4.39	76.60	230.50	9.80	0.96	2.33	0.31	3.16	4.19	24.26	4.47

H+Al^{+3}: potential acidity; SB, sum of bases; CEC (T), cation exchange capacity at pH 7.0; V, base saturation; SOM, soil organic matter.

where: W0 is the initial dry mass (g) of polyethylene bags; C0 is the initial nutrient content in the polyethylene bags [macronutrients (g kg^{-1}) and micronutrients (mg kg^{-1})]; Wt is the dry mass (g) of leaves remaining in garbage bags, in days (t = 30, 60, ..., 360 days); Ct is the content of nutrients in the remaining leaves in days (t = 30, 60, ..., 360 days) [macronutrients (g kg^{-1}), and micronutrients (mg kg^{-1})].

In order to analyze the biomass input, level and support of nutrients of the plagiotropic branches, the data were subjected to the analysis of variance, and their means were compared by Tukey's test, at 5% probability.

Data referring to the percentage of residual mass and nutrients release rate, according to the doses of fertilization with K and days after pruning, were also subjected to the analysis of variance, at 5% probability, to verify the presence of significant factors, whether as a whole or isolated. In the presence of significant effect to the variation of days after pruning, the regression analysis was employed, to study the percentage of residual mass. For the statistical analysis, the software GENES was used (Cruz, 2013).

Results and discussion

Input data averages for dry biomass deposited in the soil after pruning were calculated as a function of K fertilization (Table 2). The variables TDML and TBD showed smaller averages of doses of 100% K. However, it is possible to observe that a bigger removal of plagiotropic branches by pruning occurred in the other treatments, resulting in a bigger quantity of branches deposited on the soil.

Biomass deposited to cover the soil varied from 739.55 kg ha^{-1} to 919.85 kg ha^{-1} (Table 2). The annual contribution of biomass through PPCA (elimination of depleted plagiotropic branches after harvest) can favor the increase of organic matter, which contributes to higher levels of fertilization, promotes the soil coverage, increases crop yield, and it is a great promise for carbon sequestration (Latifah et al., 2018; Tibasiima et al., 2023). Programmed pruning cycle is an alternative for plant management, and it has the potential to contribute to the sustainability of the productive system, allowing of the possibility to optimize the beneficial effects of annual biomass disposal. The plant layer growth and the biomass disposal on the soil in coffee cultivation are important factors for the preservation of organic matter levels in the system (Vieira et al., 2015). Constant biomass input promotes a raise of the soil pH levels and an increase in the saturation of CEC by Ca, Mg, and K added via vegetable residue (Pan et al., 2021).

In general, about 75% of the total biomass of plagiotropic branches was composed of the biomass of leaves, which is more easily decomposed in the soil than stem materials. According to Momolli et al. (2018), unstable materials, such as foliar biomass, display higher rates of decomposition. This characteristic optimizes the capacity of recycling nutrients present in leaves, allowing it to be made available faster to soil solution than the nutrients present in stems. For comparative purposes, the amount that N, P, and K contributed is enough to supply 5%, 3%, and 15%, respectively, of the coffee crop's needs, when estimating the productivity of 60 bags ha^{-1} (Mesquita et al., 2016). For the micronutrients Cu and Mn, the input contributions are respectively 1.32% and 1.20%, taking into account a soil fertility classification with an adequate level (Ribeiro et al., 1999).

Costa et al. (2010) observed that the amount of nutrients (kg ha^{-1}) supplied via litter varied as follows: for N, from 110 to 170; P, from 4 to 7; K, from 18 to 63; Ca, from 100 to 190; and for Mg, from 25 to 40. These authors concluded that nutrient input was strongly associated with the biomass production. In the present

Table 2. Dry biomass deposited on the soil after the programmed pruning cycle of plagiotropic branches of arabica coffee, according to doses of potassium fertilization in the soil (Martins Soares, MG, at 750 m altitude, 2019)(1).

K dose (%)	TDML	TDMS	TBD
	(kg ha^{-1})		
50	708.81a	211.04ab	919.85a
100	549.23b	190.32b	739.55b
150	679.60a	226.21a	905.81a
200	666.95a	226.71a	893.66a
CV (%)	5.11	6.02	4.57

(1)Means followed by equal lowercase letters, in the columns, do not differ from each other by Tukey's test, at 5% probability. TDML, total dry mass of leaves from plagiotropic branches per hectare; TDMS, total dry mass of stems from plagiotropic branches per hectare; TBD, total biomass of plagiotropic branches deposited per hectare; CV, coefficient of variation.

study, it is possible to infer that the amount of biomass deposited in the soil is strongly associated with the intensity of pruning (the step of eliminating depleted plagiotropic branches in PPCA).

The estimates of nutritional content input by hectare with biomass deposited by pruning (leaves and stems from plagiotropic branches) were described in relation to K doses (Table 3). There was a significant difference in the treatment of contents of N, P, K, Mg, and Fe, in which, in general, the smallest contents anchored by area can be observed in relation to doses of 100% K fertilization, since the amount of total biomass deposited on the soil was also smaller, due to that treatment. Regarding the Ca, Cu, Mn, and Zn contents, no significant differences between treatments were observed.

The levels of C content and the C/N and C/P ratios showed no significant differences in their relation with the K doses. The average level of C observed was 52.85 dag kg^{-1}, whereas this level in relation to C/N and C/P were 29.62 and 541.61, respectively. Similar results to that of the C/N ratio were observed by Santinato et al. (2019), when these authors evaluated the influence of pruning on the coffee trees with nutrient cycling, for which, the C/N ratio varied from 29.4, for selective lateral pruning, to 42, in *recepa* (drastic pruning). This fact shows that the more drastic is the pruning, the bigger will be the relations, which is certainly due to the increase of the quantity of highly arboraceous material (thicker stems). The biomass decomposition depends not only on the climatic and environmental factors, but also on the fertilization management and pruning time. Decomposition can provide mineralization and immobilization of nutrients, depending on the C/N and C/P ratios. When the C/N ratio of organic material is high (above 30), there is a predominance of nutrient immobilization (Libutti et al., 2020; Tessema et al., 2022).

The nutrient mobilization for fruit formation affects the nutrient concentrations considered mobile in the phloem (Libutti et al., 2020). In a study on arabica coffee, the researchers observed that there was an increase in the N and K remobilization activity, during the fruiting phase, in the maturation period of coffee fruit (Reis, 2019). Therefore, it can be inferred that nutrient contents present in the leaf and stem tissues, after pruning, were not remobilized to fruit and to the youngest parts of plants. This way, these unused nutrients can return to the soil through the decomposition of pruned materials and improve the efficiency of the coffee cultivation system.

On the days after the PPCA, significant effects were observed when the isolated effect of the variant source on the residual mass was analyzed (Figure 1). However, no significant effect was observed on the interaction between K fertilization doses in the days after pruning and the residual foliar mass during the decomposition process. Doses of K fertilization showed no influence on the decomposition rates of pruned materials, which is certainly due to a variation in the nutritional constitution of leaves related to K doses. Hence, differences were evident only for the amount of deposited foliar biomass (Table 2). The lack of answers in relation to K doses is mostly justified by the fact that the K doses in the soil are already adequate for the cultivation of arabica coffee trees.

A decrease of the residual mass was observed 30 days after pruning as reaching 78.5% of decomposed foliar matter after 324 days, with a tendency to

Table 3. Contribution of macro- and micronutrients contained in plagiotropic branches of arabica coffee eliminated by the programmed pruning cycle ,in relation to doses of potassium fertilization of the soil (Martins Soares, MG, at 750 m altitude, 2019)[(1)].

K dose (%)	N	P	K	Ca	Mg	Fe	Cu	Mn	Zn
	($kg\ ha^{-1}$)					($g\ ha^{-1}$)			
50	14.48a	0.81a	15.95a	19.52a	3.43a	148.38a	12.77a	63.72a	10.11a
100	11.22b	0.65b	12.30b	14.93a	2.50b	111.28b	10.45a	46.55a	7.78a
150	14.16a	0.74ab	14.94ab	17.04a	3.07ab	154.99a	11.16a	54.07a	9.72a
200	13.91ab	0.71ab	15.76a	17.63a	2.91ab	154.72a	9.15a	48.20a	11.28a
CV (%)	9.50	7.39	9.70	20.43	12.41	9.63	17.38	21.31	35.51

[(1)]Means followed by equal lowercase letters, in the columns, do not differ from each other by Tukey's test, at 5% probability. CV, coefficient of variation.

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stabilize itself after that mark (Figure 1). After staying on the soil for 30 days, about 9.5% of the foliar matter was decomposed. Subsequently, after 150 days, 54.4% of the foliar matter had been decomposed. After this period, the speed of decomposition of foliar matter became less intensive.

Our study results for the decomposition rate corroborate those by Pinto (2016), who reported foliar mass loss of coffee trees when accelerated decomposition occurred in up to 180 days, stabilizing itself in 240 days and reaching 64% of decomposition in 360 days. Time associated with microclimatic factors and microorganisms actions promotes a regular and continuous decomposition (Holanda et al., 2015).

No significant effect was observed for the interaction between K fertilization doses, in the days after pruning, and the release rates of N, P, K, Ca, Mg, Zn, Cu, and Mn of leaves. Significances for the days after pruning and all studied nutrients were observed. The distribution average of release rates in relation to days were analyzed for expressed fluctuations of leaves' nutrients release of leaves over the course of days (Figure 2).

Nutrients release showed a variable behavior during the period of foliar biomass decomposition (Figure 2). Nitrogen fluctuated from immobilization to mineralization by 150 days and, from this period on, it was possible to observe the rising of release rates of the element. The behaviors of P, K, Mg, and Mn were similar, as the release of all these elements was observed throughout the evaluation period. As for Ca, the behavior observed was similar to that of N; however, immobilization levels up until 180 days were observed; slight releases happened after 180 days. Significant variations for Cu and Zn immobilization occurred throughout the period of study, tending to reach mineralization in longer periods than the maximum studied (360 days). Nonetheless, there seems to be a decrease of the immobilization rate starting after 240 days of decomposition, in an even higher manner for Zn.

After 360 days in decomposition, the order of coffee tree foliar nutrients released, proportional to the initial amount of nutrients, was: K (97.2%) > P (79.1%) > Mg (73.7%) > Mn (68%) > N (48.6%) > Ca (32.5%). It is worth mentioning that the order of release of coffee trees is an intrinsic characteristic of its cultivation.

According to our results, at 360 days after PPCA, the highest nutrient release rates were observed for K, P, and Mg. These results corroborate the findings by other authors. For K, a simple leaching process is enough for the transfer of plant residue of this element to the soil to happen effectively. It is not necessary to carry out prior mineralization of the material mainly due to the ionic characteristic found in this element. A similar behavior was reported in a section of Alluvial Dense Ombrophilous Atlantic Forest undergoing natural regeneration (Scheer, 2008). After 90 days, approximately 80% of K had already been released from the litter material, thus acting constantly until the end of the evaluation.

Phosphorus release at 50% was also observed in legumes, in the first 120 days of the dry period (Espindola et al., 2006). However, initial P accumulation

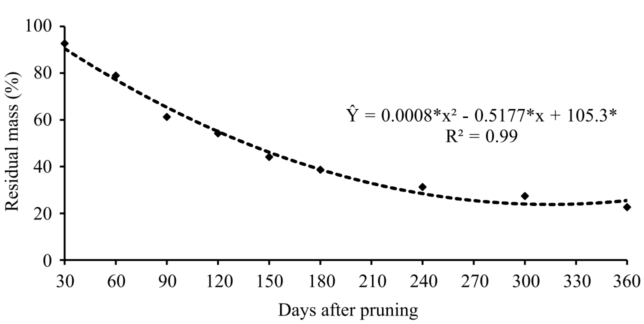

Figure 1. Percentage of residual foliar mass in the days after programmed pruning cycle of plagiotropic branches of arabica coffee trees (Martins Soares, MG, Brazil, at 750 m altitude, 2019). *Angular coefficient of significant regression determined by the t-test, at 5% probability.

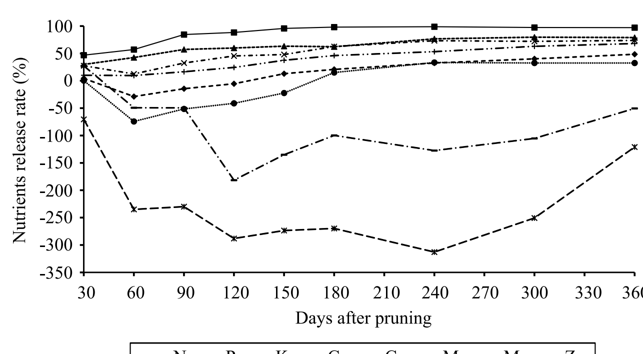

Figure 2. Release or immobilization of foliar macro- and micronutrients in relation to days after the programmed pruning cycle of plagiotropic branches of arabica coffee trees (Martins Soares, MG, Brazil, at 750 m altitude, 2019).

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was reported for *Eucalyptus urophylla* x *Eucalyptus globulus* population, with 20% P immobilization occurring in the first 12 months (Vieira et al., 2015). In other study observed P release at 50% occurred in coffee leaves, showing the potential of this material in the P cycling (Pinto, 2016).

Magnesium release from 50% to 67% was also reported as returning to the soil after 360 days (Momolli et al., 2018). When this residue was associated with that of legume, an initial immobilization occurred, reinforcing that the characteristics of the plant matter influence the ability to cycle nutrients (Pinto, 2016). The PPCA has shown interesting results for increasing productivity in *C. arabica* cultivation (Vedin Filho et al., 2014). Furthermore, residue from the PPCA management can act as interesting allies for maintaining the soil microbial community and assisting in the nutrient cycling processes (Libutti et al., 2020). The reuse of residue generated by PPCA can promote a circular economy approach where the production system is less dependent on fertilizers, by both reducing the environmental damage and achieving certifications for a more sustainable and regenerative agriculture.

Conclusions

1. Annual programmed pruning cycle of arabica coffee tree (PPCA) allows of the continuous supply of plant matter deposited in the soil, as well as plant decomposition and release of nutrients from the flowering period until the granulation of arabica coffee fruit.
2. Significant amounts of nutrients are found in the pruned materials, reaching 78.5% decomposition at 324 days after pruning.
3. At 360 days after the leaves are deposited on the soil, the following behavior of the nutrients contained in them was observed: release of 48.6% N, 79.1% P, 97.2% K, 32.5 % Ca, 73.7% Mg and 68.0% Mn, as well as immobilization of 50.4% Cu and 120.9% Zn.
4. Potassium fertilization levels do not influence the decomposition rate of leaves eliminated with PPCA.

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