https://doi.org/10.18406/2316-1817v16nunico20241830 e-ISSN 2316-1817

Cost defines the type of nitrogen fertilization for coffee trees initial development

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Received in: 25/08/2023
Accepted in: 07/02/2024

Abstract

Several fertilizer-associated technologies are available on the market capable of promoting greater effectiveness in nutrients use and availability to crops. In coffee growing, the classes of nitrogen fertilizers with enhanced efficiency stand out. Hence, this study evaluated the efficiency of different types of nitrogen fertilizers in coffee trees development compared by use cost. We conducted two experiments: one in the field, in Campos Gerais municipality, Minas Gerais, and another in a greenhouse. Aside a control treatment (without nitrogen application), the following nitrogen fertilizer technologies were tested: conventional fertilization, slow-release fertilizer and controlled-release fertilizer, according to manufacturer's recommendations. In the pots, we adjusted the fertilizer dose according to the volume of soil available to the root system. Height, stem diameter, number of primary branches, crown diameter, soil plant analysis development (SPAD) index, leaf nitrogen (N) content, number of plants regrowing after frost, root and shoot dry mass and use costs were assessed. Results showed a difference for crown diameter and SPAD index in the field experiment. Regarding crown diameter, the controlled-release treatment was superior only to control. As for the SPAD index, control was inferior to all other treatments. In the pots, all the analyzed variables were superior to the control, excepting root dry mass, which showed no difference. In terms of cost, conventional fertilization was the least costly.

Keywords: *Coffea arabica* L. Soil fertilization. Gradual release. Profitability.

Introduction

Growing demand for Brazilian coffee has led producers to increase their production using efficient fertilizer and pesticide technologies, resulting in higher yields without increasing the cultivated area. Coffee trees depend on a balanced nutritional status for its development, from the nursery to the field, requiring precise fertilization and avoiding losses during fertilizer application.

Nitrogen (N) stands out as the nutrient most required during crop development. It can be absorbed in both ammoniacal and nitric forms and is responsible for biomass production, participating in the synthesis of products such as amino acids and proteins, as well as being present in the structures of electron transport molecules (CARR et al., 2020). Adequate nitrogen supplementation in coffee trees ensures an increase in the number of primary branches, leaf pairs, nodes per branch and flowers per node, which is directly related to productivity (NAZARENO et al., 2003). In the soil, nitrogen is easily lost by leaching, in the form of nitrate, and by volatilization, in the form of ammonia, generating significant losses and contributing to environmental contamination (GUELFI, 2017).

Aiming to reduce damage and increase the efficiency of nitrogen fertilizers, the industry invests in technologies capable of reducing or even avoiding these losses to the environment. Among these are fertilizers stabilized with some chemical additive, which prevents the action of urease in unfavorable conditions. These are slow-release fertilizers (with nitrogen complexed in carbon chains of different sizes, promoting release over time) and controlled release fertilizers (with an external coating of sulphur and vegetable polymers, where the coating thickness interferes with the moment of release) (TENKEL, 2010). Use of slow- and controlled- release fertilizers in the crop development, maintenance and production phases is a reality in the field due to their agility, easy application, gradual supply of nutrients and reduced operating costs (FREITAS et al., 2023).

Unlike conventional fertilizers, slow-release and controlled-release fertilizers do not need to be spread out, as they promote lower losses by leaching, volatilization and erosion (CHAGAS et al., 2018). In coffee crops, urea, ammonium sulphate and ammonium nitrate are used as conventional N sources; urea formaldehyde, as slow; and urea coated with elemental sulfur and polymers in the controlled class. Currently, the most widely used nitrogen fertilizer in agriculture is urea, due to its price in relation to the amount of nitrogen present; however, it implies major agronomic disadvantage due to high N loss by volatilization (GUELFI, 2017).

Using fertilizers with increased efficiency promotes better performance regarding losses to the environment, generating less environmental and economic impact (SOUZA et al., 2023), also promoting, in some cases, greater agronomic efficiency compared to conventional fertilizers (BACHIÃO et al., 2018). For coffee trees in their initial post-transplant development in the field, the use of slow- and controlled-release fertilizers would provide better nitrogen availability, following the plant's growth and nutrient uptake curves, thus reducing the cost of nitrogen fertilization during the initial crop development. Hence, this study evaluated the morpho-agronomic growth parameters of newly planted trees and the cost-effectiveness of nitrogen fertilization, using three nitrogen fertilizer technologies at the initial stage of Arabica coffee tree development, tested in the field and in a greenhouse.

Material and methods

We conducted two experiments on Arabica coffee plants from the Arara cultivar: one in the field and the other in a greenhouse. Both experiments used the following treatments: control (without nitrogen fertilization) (T1); and three different types of urea: conventional urea (without release technology, T2), formaldehyde urea (slow-release, T3) and urea coated with elemental sulfur + polymers (controlled-release, T4). All treatments were arranged in a randomized block design with five replicates.

Experiment I

Experiment I was conducted in Campos Gerais municipality, Minas Gerais, under field conditions, between December 2020 and October 2021. Spacing of 3.5 m between rows and 0.6 m between plants was used, resulting in a semi-dense system with 4,762 plants ha^{-1}. The trees were distributed in the blocks' planting rows, with plots consisting of six plants and two border plants in-between. Treatments were distributed by lot, always disregarding one planting line as a border between the blocks, totaling 120 plants evaluated. Table 1 shows the main chemical characteristics of the area's clayey soil layer from zero to 20 cm before treatments.

Preparation of the area began with top dressing with dolomitic limestone, which had a relative efficiency (PRNT) of 85 %, 36 % calcium oxide (CaO) and 17 % magnesium at a dosage of two tons per hectare. Subsequently, the soil was plowed with a three-disc plow, leveled with a harrow to reduce the size of the earth clods, and furrowed to a depth of 40 cm.

After opening the furrow, we applied 1 ton ha^{-1} of the same limestone to bring calcium and magnesium into the depths and providing phosphate fertilization, applying simple superphosphate at a 310 g m^{-1} linear dosage at its bottom. The furrow was then scarified with a subsoiler, incorporating and mixing the material. Seedlings were planted in January 2021, in holes dug 20 cm deep and spaced 60 cm apart. Lastly, the treatments were applied.

Table 1. Chemical characterization of the soil in the experimental area (0–20 cm) before treatment application. Campos Gerais, MG, 2020

Specifications	Unit	Values
pH in water – Ratio 1:2.5	-	4.63
P – Mehlich Extractor 1	mg dm^{-3}	4.51
P – Resin	mg dm^{-3}	7.04
K – Mehlich Extractor 1	mg dm^{-3}	67.54
Ca – KCl Extractor (mol L^{-1})	cmolc dm^{-3}	1.57
Mg – KCl Extractor (mol L^{-1})	cmolc dm^{-3}	0.47
S – Aceticacid monocalcium extractor	mg dm^{-3}	10.20
Cu – Mehlich Extractor 1	mg dm^{-3}	0.81
B – Hot water extractor	mg dm^{-3}	0.12
Zn – Mehlich Extractor 1	mg dm^{-3}	3.16
Fe – Mehlich Extractor 1	mg dm^{-3}	37.8
Mn – Mehlich Extractor 1	mg dm^{-3}	13.4
Al – KCl Extractor (mol L^{-1})	cmolc dm^{-3}	0.33
H+Al – SMP	cmolc dm^{-3}	3.47
Effective CTC (t)	cmolc dm^{-3}	2.54
Potential CTC (T)	cmolc dm^{-3}	6.01
Aluminum saturation (m)	%	12.99
Bases saturation (V)	%	36.77
Sum of bases	cmolc dm^{-3}	2.21
Organic matter – Colorimetry	dag kg^{-1}	1.55

Fertilizer dosage for each treatment was adjusted according to manufacturer's recommendations, except for the conventional treatment, which used conventional urea (45 % N) as the nitrogen source, applying 13 g of N per plant, divided into three applications in a 30-day interval (RIBEIRO et al., 1999). For formaldehyde urea, the recommended dosage was 9 g of N per plant and for urea coated with elemental sulfur + polymers, 11 g of N per plant.

The treatments were applied as top dressing on January 8th, 2021, shortly after the plants had set seed in the field. In this experiment, Ciclus NS® fertilizer (30 % N) was used as a slow-release nitrogen source and Producote Longer® fertilizer (37 % N) as a controlled-release nitrogen source.

After seedling planting and treatment application, manual weeding was carried out to control weeds that had resisted the soil preparation process, cleaning out clods and organic materials present in the planting row. From then on, the weeds in the planting row were controlled with an oxyfluorfen-based pre-emergent herbicide (480 g a. i. ha^{-1}) and between the rows with a tractor-mounted mechanical brush cutter. Soil analysis showed a low potassium (K) content; thus we applied 30 g of potassium chloride (20 g of K_2O) divided into two applications.

Experiment II

Experiment II was conducted in a greenhouse at the Federal Institute of Education, Science and Technology of Southern Minas Gerais (IFSULDEMINAS) – Machado Campus, under partially controlled conditions between March and September 2022.

We used three pots per plot, with one plant per pot, distributed along a suspended bench. A total of 60 5.3 L-pots were used, with a substrate made up of three parts of soil taken from the C layer of a red/yellow, clay-textured latosol, one part of washed sand, both solarized for a week, ½ part of inert commercial substrate and 2 kg of simple superphosphate per 500 dm^3 of substrate. Irrigation was provided according to the plants' needs.

Treatments were applied in March 2022, using Ciclus NS® fertilizer (31 % N) as a slow-release nitrogen source and Polyblen Montanha® fertilizer (39 % N) as a controlled-release nitrogen source.

The fertilizer amount for each treatment in a pot was determined using Araújo et al.'s methodology (2008), in which the dosage per pot was proportional to the recommended dosage per 0.4 x 0.4 x 0.4 m pit (volume 64 dm^3), the area occupied by the coffee tree roots in the first six months in the field. In T2 treatment, we applied 0.83 g per pot of conventional urea; T3, 2.4 g per pot of formaldehyde urea; and T4, 2.36 g per pot of urea coated with polymer and elemental sulfur.

No weeds, diseases or pests had to be controlled in the greenhouse cultivation. For nutritional management, 2 g of potassium chloride (KCl) was applied as top dressing per pot and a mixed foliar fertilizer was applied with minimum guarantees of 26.4 % zinc (Zn), 16.5 % manganese (Mn), 11.7 % copper (Cu) and 5.6 % molybdenum (Mo), at a concentration of 2 mL per liter of water, plus boric acid diluted to 0.5 %.

Evaluations

Plant height, stem diameter, crown diameter, soil plant analysis development (SPAD) index and number of primary branches were assessed in both experiments, 60 days apart Height and crown diameter were determined using a graduated ruler, measuring from the soil surface to plant's apex and from end to end, respectively. Stem diameter was obtained using a digital caliper, measuring from below the first primary branch. For the chlorophyll content (SPAD index), readings were taken from three leaves per plant, two in the third pair and one in the fourth pair, counted from the apical bud; then the average value of these three readings was determined, corresponding to the SPAD index, using the Minolta® SPAD-502 chlorophyll meter. Root and shoot dry mass was also evaluated in the pot experiment.

Nitrogen plant content was determined by sampling leaf tissue, collecting two leaves from the middle third of each plant, from the six useful plants in each plot at the field experiment. The leaves were washed in running water and wiped dry with paper towels. All the leaves from the greenhouse plants were collected after obtaining the shoot dry mass and sent to the IFSULDEMINAS Soil Laboratory. The leaves, shoots and root system were dried in a forced circulation oven at 65 °C for 72 hours. During the field experiment, a severe frost affected the other scheduled evaluations. It was therefore decided to repot the plants and evaluate the effects of the treatments on sprouting and crop recovery. To determine the number of regrowing plants after frost, the plants were picked up 5 cm from the ground, 30 days after the phenomenon, and a single assessment was performed in October 2021. The number of regrown plants and primary branches was obtained by direct counting.

In December 2020 and January 2021 a detailed survey was conducted on the implementation price of each fertilizer using quotes from the local market in Campos Gerais, Minas Gerais. The cost of each fertilizer was expressed as price per hectare, obtained by the amount applied per plant multiplied by the number of plants in the area, plus the cost of application in man/days, disregarding freight, adapted from Freitas (2017). Man-day rate, for an eight-hour workload, was calculated by the time spent on treatment application according to the price paid in the region, equivalent to R$ 70 reais. Time spent on application was determined by timing application on a neighboring one-hectare area, establishing a time of four working hours per application, equivalent to ½ man-day. The number of man/days required to apply each fertilizer was calculated according to the number of applications for each treatment.

Data were tabulated and underwent analysis of variance. When significant, the means were submitted to Tukey's test at 5 % probability. For the regrowth variable, the data was transformed using the equation $\sqrt{x+1}$. Analyses were performed using Sisvar software (FERREIRA, 2011).

Results

Experiment I

In the field experiment, 100 days after planting, the means for plant height, stem diameter, crown diameter, number of branches and SPAD index were not significant to the F test at 5 % probability (Table 2).

At 160 days after treatment application, the means for height, stem diameter and number of branches presented no changes according to the F test, with 5 % probability. Crown diameter and SPAD index showed a significant effect between treatments (Table 3).

Table 2. Growth in height, stem diameter, crown diameter, number of primary branches and SPAD index after 100 days of field application of different nitrogen fertilizer technologies. Campos Gerais, MG, 2021

Treatment	Height (cm)	Stem diameter (mm)	Crown diameter (mm)	Number of branches	SPAD
Control	26.23	4.80	22.31	5.65	53.30
Conventional	26.60	4.87	23.28	5.75	54.77
Slow-release	25.02	5.03	22.31	5.41	54.15
Controlled-release	25.32	5.04	23.27	5.54	56.47
Overall mean	25.79	4.94	22.79	5.59	54.67
F_{trat}	1.14^{NS}	0.64^{NS}	0.85^{NS}	0.46^{NS}	2.77^{NS}
CV (%)	6.06	6.70	5.93	8.61	3.29

^{NS} F test not significant at 5 % probability.

Table 3. Growth in height, stem diameter, crown diameter, number of primary branches and SPAD index after 160 days of field application of different nitrogen fertilizer technologies. Campos Gerais, MG, 2021

Treatment	Height (cm)	Stem diameter (mm)	Crown diameter (mm)	Number of branches	SPAD
Control	31.29	5.98	30.27 b	8.86	60.79 b
Conventional	33.70	6.48	32.06 ab	9.67	69.18 a
Slow-release	31.40	6.24	31.40 ab	9.17	67.68 a
Controlled-release	31.95	6.47	32.88 a	9.19	70.47 a
Overall mean	32.08	6.29	31.65	9.22	67.03
F_{trat}	1.07^{NS}	1.80^{NS}	5.20*	1.72^{NS}	24.58*
CV (%)	7.53	6.20	3.42	6.15	2.90

^{NS} F test not significant; *Significant F-test at 5 % significance. Means followed by equal letters in the columns do not differ by Tukey's test at 5 % probability.

Regarding crown diameter, the controlled-release treatment performed almost 9 % better than the control, whereas the conventional and slow-release fertilizers were not significant in relation to each other and the other treatments. As for the SPAD index, control had lower values than all other treatments. When compared, SPAD index reduced 12.13 % with the conventional fertilizer, 10.18 % with the slow-release fertilizer and 13.74 % with the controlled-release fertilizer.

No significant differences were observed for leaf nitrogen content and number of regrown plants in the field experiment. In terms of N content, only the control treatment and the slow-release fertilizer resulted in foliar N levels lower than those classified as deficient in adult crops (<2.5 dag Kg^{-1}), except for the controlled-release treatment, which obtained a threshold level (MATIELLO et al., 2016) (Table 4).

During the field experiment, the months of January, February and March had satisfactory rainfall, with a surplus of 63.9, 90.1 and 25.1 mm, respectively. But despite this adequate volume of rainfall (Figure 1), rain was poorly distributed during the period, favoring two drought periods, one in the second half of January and the other in mid-March. April, May, June, July and September had low rainfall volumes, increasing the water deficit in the period. October saw the highest volume of rainfall, with an accumulation of 316.2 mm and a water surplus of 119.7 mm, making it the wettest month with the best rain distribution during the experiment.

The water balance between January and June, despite the significant water deficit, is not outside the normal range of the municipality's ten-year averages. However, July, August and September have been characterized as the driest and coldest months on record (SISMET COOXUPÉ, 2021).

Experiment II

In the pot experiment, stem diameter and SPAD index increased under the conventional and controlled-release treatments, compared to control, 60 days after treatment application (Table 5).

After 120 days of treatment application, we observed differences in the number of primary branches and SPAD index (Table 6), as well as differences in height, stem diameter, crown diameter, number of primary branches, SPAD index (Table 7) and shoot dry mass (Table 8) 180 days after the treatments were applied. Regarding leaf nitrogen content, control had severe N deficiency, differing from the other treatments, which registered threshold levels (MATIELLO et al., 2016) (Table 8).

Table 4. Leaf nitrogen content and number of regrown plants per plot, in the field, using different nitrogen fertilizer technologies. Campos Gerais, MG, 2021

Treatment	Nitrogen content of field plants (dag kg^{-1})	Regrown plants(1)
Control	2.43	3.40
Conventional	2.50	3.80
Slow-release	2.30	2.60
Controlled-release	2.52	4.00
Overall mean	2.44	3.45
F_{trat}	1.20^{NS}	0.63^{NS}
CV (%)	8.81	22.91

(1) Means of regrown plants within plots with a total of six plants; ^{NS} F test not significant at 5 % probability.

Figure 1. Monthly averages of rainfall, water deficit and water surplus during the field trial period. Campos Gerais, MG, 2021

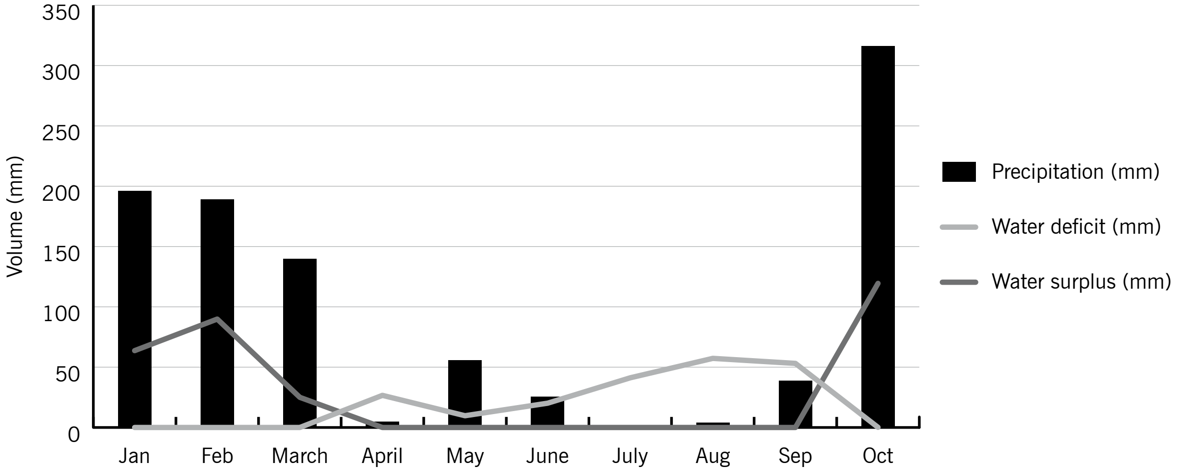

Table 5. Growth in height, stem diameter, crown diameter, number of primary branches and SPAD index after 60 days of pot application of different nitrogen fertilizer technologies. Machado, MG, 2022

Treatment	Height (cm)	Stem diameter (mm)	Crown diameter (mm)	Number of branches	SPAD
Control	29.70	5.23 a	25.23	2.99	69.48 b
Conventional	29.20	4.60 b	26.06	2.00	74.60 a
Slow-release	30.86	5.04 ab	25.93	2.80	73.62 ab
Controlled-release	30.13	5.09 ab	24.96	2.73	75.38 a
Overall mean	29.97	4.99	25.52	2.63	73.27
F_{trat}	0.98^{NS}	3.78*	0.41^{NS}	1.15^{NS}	6.28*
CV (%)	5.31	6.24	7.58	34.67	3.20

^{NS} Not significant; *Significant F test at 5 % significance. Means followed by equal letters in the columns do not differ by Tukey's test at 5 % probability.

Table 6. Growth in height, stem diameter, crown diameter, number of primary branches and SPAD index after 120 days of pot application of different nitrogen fertilizer technologies. Machado, MG, 2022

Treatment	Height (cm)	Stem diameter (mm)	Crown diameter (mm)	Number of branches	SPAD
Control	31.40	6.27	26.17	3.40 b	65.68 b
Conventional	33.61	6.10	26.76	4.80 ab	79.42 a
Slow-release	34.83	6.55	27.53	5.73 a	78.00 a
Controlled-release	33.36	6.65	27.13	5.13 a	76.78 a
Overall mean	33.30	6.39	26.89	4.77	74.97
F_{trat}	2.56^{NS}	1.33^{NS}	2.71^{NS}	7.26*	11.88*
CV (%)	5.97	7.73	4.19	16.96	5.44

^{NS} Not significant; *Significant F test at 5 % significance. Means followed by equal letters in the columns do not differ by Tukey's test at 5 % probability.

Table 7. Growth in height, stem diameter, crown diameter, number of primary branches and SPAD index after 180 days of pot application of different nitrogen fertilizer technologies. Machado, MG, 2022

Treatment	Height (cm)	Stem diameter (mm)	Crown diameter (mm)	Number of branches	SPAD
Control	33.2 b	7.35 b	27.06 b	4.53 b	57.82 b
Conventional	39.12 a	7.93 ab	32.41 a	7.91 a	77.54 a
Slow-release	39.60 a	8.34 a	33.06 a	8.33 a	75.02 a
Controlled-release	38.36 a	8.64 a	33.00 a	8.07 a	78.30 a
Overall mean	37.57	8.06	31.38	7.21	72.17
F_{trat}	20.30*	8.60*	11.92*	19.22*	49.42*
CV (%)	3.91	5.28	5.97	12.69	4.26

*Significant F test at 5 % significance. Means followed by equal letters in the columns do not differ by Tukey's test at 5 % probability.

Table 8. Root dry mass, shoot dry mass and leaf nitrogen content after 180 days of pot application of different nitrogen fertilizer technologies. Machado, MG, 2022

Treatment	Root dry mass (g)	Shoot dry mass (g)	Nitrogen content of pot plants (dag kg^{-1})
Control	8.53	11.04 b	1.75 b
Conventional	8.78	21.04 a	2.94 a
Slow-release	9.70	21.52 a	2.59 a
Controlled-release	9.48	21.12 a	2.62 a
Overall mean	9.12	18.68	2.48
F_{trat}	0.77^{NS}	80.25*	23.36*
CV (%)	15.46	6.81	9.46

^{NS} Not significant; *Significant F test at 5 % significance. Means followed by equal letters in the columns do not differ by Tukey's test at 5 % probability.

Regarding the number of branches after 120 days, control remained inferior to the slow- and controlled-release treatments; however, the conventional technology did not differ from the other treatments. As for the SPAD index, all treatments were superior to control and did not differ from each other. In the last evaluation, 180 days after application, control remained last in terms of height, crown diameter, number of primary branches, SPAD index and shoot dry mass compared with all the nitrogen technologies; however, control was equal in stem diameter to the conventional technology. There was no difference between the treatments in terms of root dry mass (Table 8).

Discussion

Results showed that newly transplanted coffee trees, despite favorable climatic conditions, do not cause synergistic effects on the tree's physiological development. Low nutritional demand, correlated with low mineral absorption capacity, the reserve of organic matter in the soil and stress caused by the planting process are directly related to the effect of nitrogen on plant metabolism. The experiment environment, isolated from supposed contamination with other nitrogen sources, proves that one can observe differences in short-term plant nutritional status by means of morphophysiological variables, and that nitrogen should be supplied soon after planting.

Similar results to the physiological parameters in the field were obtained by Bernardes (2018), who assessed conventional and controlled-release fertilizers applied as top dressing to young coffee trees in a rainfed system, 90 days after planting. The author proposed that newly planted coffee trees invest their photoassimilates acquired in the nursery in root growth and in emission of the first leaf pairs aiming to fix them in the soil and subsequently capturing light energy, making nutrient absorption a secondary factor in development. Another possible reason for the lack of difference between the treatments at the initial stage of plant development in the field is the effect of low rainfall during this period, favoring ammonia volatilization from the less stable fractions of fertilizers released during the experiment (FREITAS et al., 2023).

Under controlled conditions, however, non-significant results in the SPAD index between control and the slow-release fertilizer can be explained by the low solubility of urea formaldehyde, due to the degree of polymerization of the methylated urea molecules chains, related to the action of soil microorganisms to slowly break down the chain into units that will be readily absorbed by the trees (TRENKEL, 2010; GUELFI, 2017).

Chagas et al. (2018) proposed that, for coffee trees, the best results in terms of production parameters are not achieved with just one technology, but by blending different fertilizer technologies, compensating for each other in adverse climate and soil conditions, reducing the rates of urea hydrolysis and ammonia volatilization. Incorporation of lignified crop remains during soil preparation for crop establishment also affected nitrogen availability, both in the mineralization of organic matter and in the increase of urease activity in the soil, which was favored by incorporation and top dressing (SHARMA et al., 2021). Nitrogen fertilizers applied as top dressing have less of an effect on the initial plant stage compared with incorporation into the pit substrate, due to their greater capacity for loss via volatilization and dispersion in the soil; whereas fertilizers applied and incorporated into the pit at dosages that do not cause toxicity promote release directly into the absorption drain and minimize volatilization losses (PERUZZO et al., 2015; FREITAS et al., 2023).

Santinato, Pereira and Silva (2009), evaluating different nitrogen fertilizers on coffee plants six months after planting under an irrigated system, found no difference between controlled-release fertilizers and the control regarding height and number of branches . In contrast, Ciclus NS® (slow-release) applied at a dose of 20 g per pit resulted in a height 16.8 % higher than control. Crown diameter and number of branches are directly related to the capture of light energy, influencing the production of photoassimilates and reserves that allow for better development and high yields.

The SPAD index, measured by the chlorophyllmeter, reflects the intensity of the leaves' green color. This variable is used in the correlation of chlorophylls, and is characterized by its quickness, simplicity and, above all, its non-destructive evaluation of leaf tissue (RAMOS et al., 2013). The SPAD index can be a parameter for correlating the tree's nutritional status in relation to nitrogen, in which higher values are related to a higher leaf nitrogen content (WICHARUCK et al., 2024). During flowering and fruit expansion (August to October), the possibility of a response to nitrogen fertilization is considered low at units above 81.5. From grain filling to grain setting (November to May), this possibility is 69.5 and from ripening to harvest (June to August), the possibility is low when above 61.7 SPAD units (GODOY et al., 2008). This is because the SPAD index is directly related to the nitrogen supply in the treatments and the evaluation periods, with control having the lowest index due to the lack of nutrient supplementation and low N reserve in the soil, showing chlorosis in the plants.

Low nitrogen content and the similarity between the treatments, concerning the low regrowth rate in the field, can be explained by the water deficit during the period. Rodrigues et al. (2016) detailed that the biomass growth rate is linear as a function of water availability in the soil, noting that lower values of water availability directly influence metabolism, which can reduce the absorption of minerals and lead to low vegetative development. Water deficit in the soil directly interferes with nitrogen absorption and assimilation; consequently, during water stress the enzymes involved in the process (nitrate reductase and nitrite reductase) may have their capacity limited due to the reduction in nutrient absorption by the roots as a result of water deficit (ROCHA et al., 2023).

Young coffee trees tend to be more vulnerable to the effects of frost due to their smaller crown volume and low resistance to weather damage. In young crops, the underside of the stem becomes more susceptible to frost damage due to exposure to lower temperatures, leading to tissue necrosis, interrupting the conducting vessels and causing plant death. Such an effect is called black frost or ''killing frost" (CARAMORI et al., 2007). Similar results were reported in young coffee trees by Santinato and Santinato (2021), who observed that less than 15-month old coffee trees had a low regeneration capacity due to low carbohydrate reserve content in their tissues. In this case, replanting is recommended. Despite the different forms of N release, the plant tissues formed no reserves and no effect on the crop's ability to regenerate was observed.

Costs

Fertilizer costs were obtained from local market prices in Campos Gerais, Minas Gerais, between December 2020 and January 2021, considering the free price of each input, the number of applications, the cost of each application in man/days and the quantity of each fertilizer based on manufacturer's recommendations. Costs related to energy, storage, transportation and other disbursements involved were not included in the calculations. Table 9 shows the amount of nitrogen applied in each treatment, the price per nitrogen kilogram for each treatment and the price per hectare (obtained by multiplying the amount used by the price of N).

The fertilizer with the highest price per kilogram of nitrogen in its formulation was the slow-release (R$ 21.07 kg^{-1}), followed by controlled-release (R$ 15.46 kg^{-1}) and conventional (R$ 5.33 kg^{-1}). Regarding the amount of nitrogen used, it is inverse to the price of N, with the conventional treatment having the highest amount applied (64.29 kg) followed by controlled-release (52.87 kg) and slow-release (42.87 kg). However, the cost per hectare

Table 9. Price per kilogram of N, amount of nitrogen used per hectare and price per hectare of different nitrogen fertilizer technologies

Treatment	N price (R$ kg^{-1}) (1)	Amount of N (kg ha^{-1}) (2)	Price (R$ ha^{-1})
Control	-	-	-
Conventional	5.33	64.29	342.67
Slow-release	21.07	42.87	903.27
Controlled-release	15.46	52.87	817.37

(1) Average price from three retailers between December 2020 and January 2021 of a kilogram of nitrogen for each technology in the Campos Gerais region, MG; (2) Amount of nitrogen applied per hectare in each treatment, based on manufacturer's recommendations.

remained parallel to the price per kilogram of N. Slow-release fertilizer was the most expensive (R$ 903.27), followed by controlled-release fertilizer (R$ 817.37), a 9.51 % less costly than the slow-release. Conventional treatment had the lowest price (R$ 342.67), being 62.06 % cheaper than the slow-release treatment and 58.08 % cheaper than the controlled-release treatment.

Freitas (2017) found that the use of urea coated with elemental sulfur + polymer (controlled-release) represented a 40.76 % lower price per kilogram of N compared to formaldehyde urea (slow-release), and conventional urea cost 75.36 % less, which can be explained by the complexity of manufacturing each fertilizer, as well as the lower dosages compared to conventional fertilization due to its lower loss in the soil. Guelfi (2017) stated that the prices of conventional and enhanced efficiency fertilizers vary between raw materials, production technology and distance from the consumer market, following an upward trend: conventional < blends ≤ slow-release < controlled-release. As the controlled-release and slow-release treatments were applied in a single dose, cost was calculated based on the number of treatment applications and on the number of man/days, plus the price of the fertilizers (Table 10).

Conventional treatment maintained the lowest cost; however, it required two more applications than the other treatments and consequently more manpower. Slow-release and controlled-release fertilizers kept the same difference, and application did not affect their costs.

Table 10. Cost based on the number of applications, price of applications and final cost per hectare of different nitrogen fertilizer technologies (January/2020)

Treatment	Number of applications	Price of applications (R$)	Final cost (R$ ha^{-1})[1]
Control	-	-	-
Conventional	3	105.00	447.67
Slow-release	1	35.00	938.27
Controlled-release	1	35.00	852.37

(1) Cost referring to the price of each fertilizer on the hectare plus the price of applications.

Conclusions

All nitrogen fertilizer technologies tested had similar morphophysiological performance in coffee trees. We found no correlation between the treatments and leaf nitrogen content, nor between the number of regrowing plants after frost in the field experiment. Conventional (urea) fertilizer showed the best cost-benefit, followed by controlled-release fertilizer and slow-release. Thus, cost has the greatest impact on fertilizer choice.

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