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Article

Nutrition of Shade-Grown Coffee Plantations with Inorganic Fertilizers in Oaxaca, Mexico

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Abstract

Coffee is a very important world commodity because of the countries involved in its production, along with the total cultivated area, production volume, consumption and economic impact. In Mexico, the coffee producing area locates mainly in hilly terrain of southern Mexico under agroforestry systems predominantly owned by smallholders. Low productivity is faced specially in the state of Oaxaca as a result of inadequate management practices such as aged plantations and deficient practices on pruning and plant nutrition. In order to evaluate the effect of N-P-K inorganic fertilizer application an experiment was carried out at three plantations located in the coastal coffee producing region of the state of Oaxaca, Mexico. Three levels of Nitrogen, Phosphorus and Potassium were evaluated using a randomized complete block design with four replications. The experiments initiated on plantations with three and four years since planted with the objective of having at least one harvest for yield evaluation. The results showed that Nitrogen application increased coffee yield on both varieties of Arabica coffee: Typica and Oro Azteca.

Keywords: *Coffea arabica*; agroforestry system; coffee productivity; nitrogen fertilizer

1. Introduction

Coffee is a key internationally traded commodity, with coffee plantations in over 50 countries and about 11 million hectares managed under varied conditions and production systems with productivity levels that range from 44.2 x 60-kg bags per hectare to 0.3 x 60-kg bags per hectare [1]. High productivity, is generally obtained in monoculture intensively managed systems [2] while the medium to low productivity is achieved mainly by smallholder farmers with coffee growing under shade trees and with low external input [3]. Coffee world production in the marketing year (MY) 2024/2025 was 100.2 million bags (60 kg) of *C. arabica* and 75.1 million bags of *C. canephora* with Brazil and Colombia as the main *C. arabica* producers, followed by Ethiopia, Honduras, Peru, Mexico and Guatemala. Mexico's production in this FY was 3.87 million bags with 91 % corresponding to *C. arabica* [4].

Coffee production in Mexico in 2024 was carried out in 701,335 ha mainly in the southern states of Chiapas (34.8 %), Veracruz (20.7%), Oaxaca (18.9%) and Puebla (10.2%). These states comprise the 84.5 % of the total area, 91.4 of the total production and 89.7 % of the production value. The remaining production was carried out in the states of Puebla, Guerrero, Hidalgo, San Luis Potosí, Jalisco, Nayarit, Colima, Tabasco, Estado de Mexico, Queretaro y Morelos. The total land area cultivated with

coffee in the Oaxaca state in 2024 was 132,268 ha with an average yield of 0.8 t ha⁻¹ and a total production volume of 90,257 t of cherry coffee. The lowest cherry coffee yield occurs in the coastal region of Oaxaca with 0.5 t ha⁻¹. [5,6].

The production coffee system in Mexico is managed mostly by smallholder farmers, with coffee plantations growing on hilly areas with forest trees providing shade to the coffee plants. The majority of these farmers lack financial resources to invest on improving yields and, as a consequence, cherry coffee yield ranges between 0.4 and 1.7 t ha⁻¹, while the national average is 1.6 t ha⁻¹[5].

The low productivity of the coffee system in the state of Oaxaca is a result of several factors such as plantations of seven years or older, few pruning activities and inadequate plant nutrition practices. Because of the lack of technical recommendations and limited investment resources, fertilization either mineral or organic is deficient or non-existent. The last technical fertilization recommendation was generated by the Instituto Mexicano del Café (INMECAFE), and consisted in applying 18-12-00 of N-P-K per hectare [7]. This institution was extinct in 1989 and after that, research institutions focused mainly on the evaluation of coffee varieties with resistance to coffee leaf rust that became a major problem for coffee varieties with high susceptibility to this disease.

Proper coffee nutrition is very important in order to obtain adequate bean size and quality both affecting coffee productivity [8]. Nutrients applied replenish those used by the plant to form tissue and fruits altogether with leaching and immobilization [9]. Coffee plants require high Nitrogen and Potassium and less Phosphorus amounts. Harvesting a hectare of a high yield coffee plantation may extract from the soil, annually, about 135, 34 and 145 kg of Nitrogen, Phosphorus and Potassium, respectively [10].

Knowledge of soil nutrient conditions is essential when designing fertilization rates, especially in hilly areas with high slope values where soil organic matter content is very below the upper horizon. Soil properties in a coffee producing area in southern Mexico with slope values higher than 50% showed medium to high content of organic matter and Nitrogen at the surface horizon (0 – 30 cm depth) but at the subsurface horizons the content of these nutrients decreased drastically [11]. Because of the high organic matter and N content at the soil surface, sampling soil only at the surface horizons may lead to inaccurate conclusions about the soil fertility [12,13].

Research on mineral fertilization of coffee plantations is scarce, predominating papers on areas such as pollination, shade management, nanotechnology applications, roasting effects, disease management, and environmental impacts. [14]. Accordingly, this study was carried out to evaluate the effect of varied N, P and K rates, along with the application of dolomitic lime. Three experiments were established in two farms at the coffee producing Coastal Region of Oaxaca State, initiating fertilization treatments in August 2018 and continuing in 2019 and 2020. Fertilizers were applied yearly during the month of July before the start of the rainy season. Coffee plantations with three or four years since planted were selected with the object of having at least one fruit harvest. Plant height data was recorded between 2018 and 2020 and ripe cherry coffee yield was registered in 2022.

Soil profiles at the experimental sites were described and soil samples from the identified horizons were analyzed for chemical and physical properties.

2. Results

2.1. Soil Characterization

Soil samples taken from varied depths in the soil profile from both experimental sites were analyzed for chemical and physical properties. Coarse loamy textures are common as a result of low weathering processes because of the high slope values. According with the texture, bulk density had values of 1.35 g cm⁻³ or higher. pH varied from moderate to strongly acid and, accordingly, Calcium carbonate content is also very low.

According to the horizon description and the soil laboratory results, soils at both sites were classified as Lithic Ustortents [15] with low pedogenic evolution, because of the topographic relief conditions prevailing at the study area. The geologic settings at the study area, correspond to

metamorphic geological material (schist and gneiss) from the medium Proterozoic age (1500 million of years).

The amount of organic matter is high only at the surface horizon and after 25 cm depth, organic matter content is low to very low. Phosphorus content is very low and potassium content varies from low to medium values (Table 1).

Table 1. Chemical and physical soil properties at the experimental sites.

Depth (cm)	BD	Texture	pH	O.M.	N	K	P ₂ O ₅	CaCO ₃
-----La Concordia-----								
0 - 5	1.37	Sandy loam	5.3	4.12	0.17	0.50	1.48	0.23
5 - 21	1.45	Sandy loam	5.3	3.99	0.13	0.23	0.00	0.75
21 - 24	1.52	Sandy loam	5.4	2.83	0.08	0.15	0.00	1.16
-----La Galera-----								
0-25	1.35	Loamy sand	4.8	5.4	0.18	0.6	1.18	0.52
25-55	1.53	Loamy sand	4.7	0.9	0.04	0.39	0.00	1.04
55-83	1.75	Loamy sand	4.7	0.64	0.01	0.25	0.00	1.04
83-95	1.67	Loamy sand	4.6	0.39	0.00	0.25	0.00	1.1
95-115	1.35	Loamy sand	4.2	0.51	0.01	0.26	0.00	0.98

BD=Bulk Density (gr cm⁻³) pH= Hydrogen Potential; O.M.= Organic Matter (%); N=Nitrogen (%); K=Potassium (Cmol(+) Kg⁻¹); P₂O₅=Phosphorus (Mg Kg⁻¹); CaCO₃= Calcium Carbonates (%).

2.2. Plant Height

Plant height data recorded at the beginning and at the end of the experiments are shown in Figures 1–3. The Initial plant height of the Typica variety at Finca La Concordia (four years since planted), averaged 103.3 cm with a variation coefficient of 12.6. The Oro Azteca variety at Finca La Concordia (3 years since planted), had a lower Initial plant height average (90.5 cm) and also a lower variation coefficient (8.8). The Oro Azteca variety at Finca La Galera (2 years since planted) registered the lowest Initial plant height (51.0 cm) and also the lowest variation coefficient (5.6). The Initial plant height difference between the Oro Azteca varieties is that at Concordia, the plantation had one more year since planted. The final plant height at Concordia-Typica, averaged 199.3 cm with a variation coefficient of 12.5. The Oro Azteca variety at Concordia, had a lower final plant height average (136.8 cm) and also a lower variation coefficient (9.4). The Oro Azteca variety at Galera with one year less since planted, averaged practically the same Final plant height (136.5 cm) than the Oro Azteca at Concordia and also slightly lower variation coefficient (8.2).

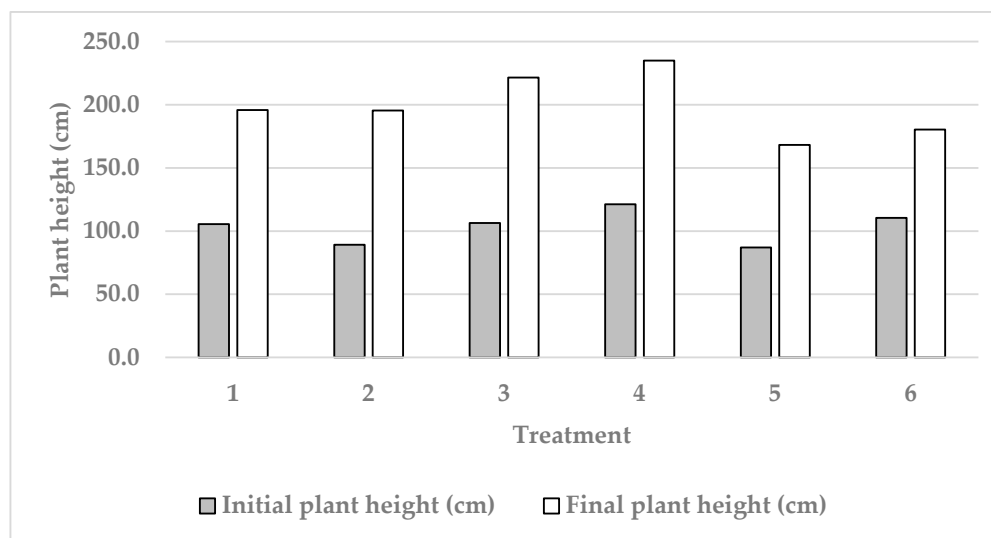


Figure 1. Initial and final plant height of the Typica variety at Finca La Concordia.

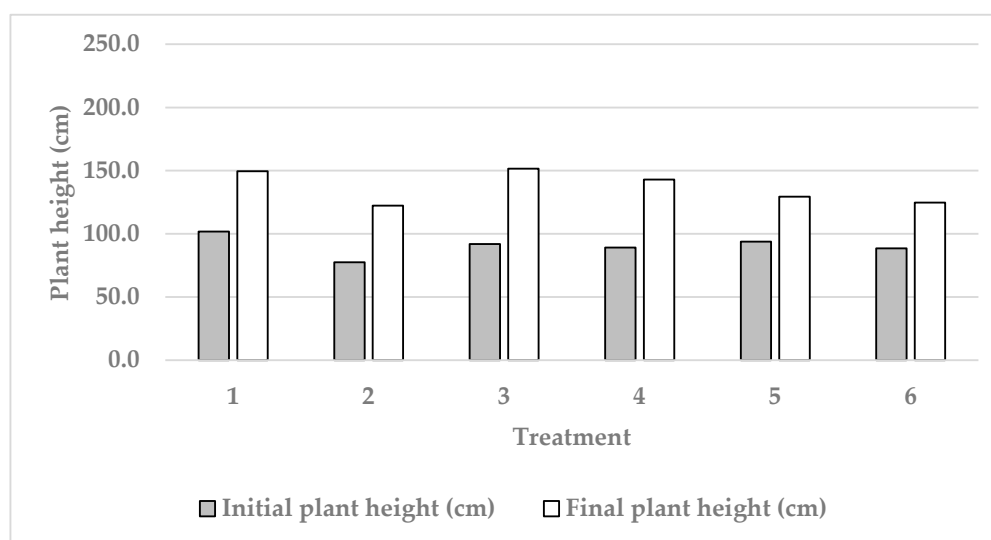


Figure 2. Initial and final plant height of the Oro azteca variety at Finca La Concordia.

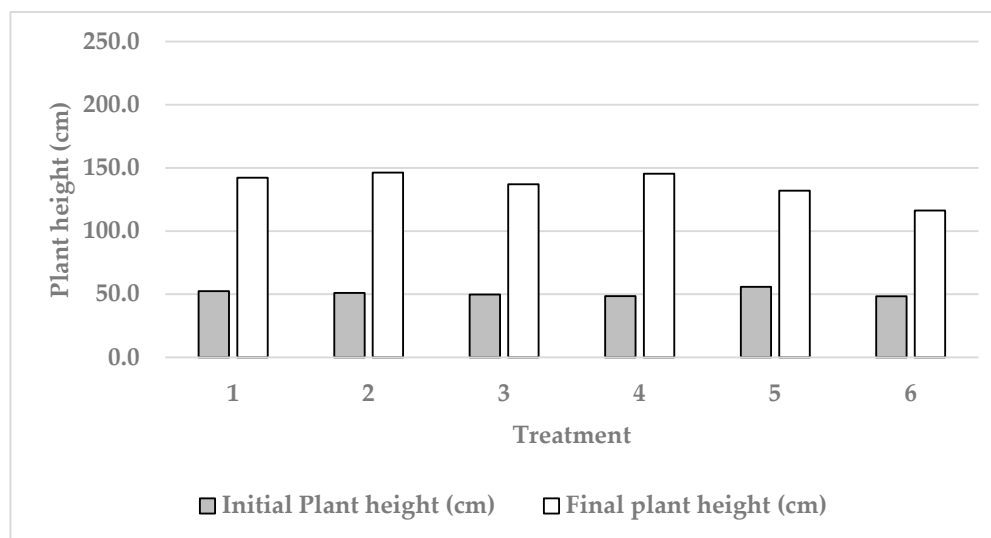


Figure 3. Initial and final plant height of the Oro azteca variety at Finca La Galera.

The plant height increment between the initial and the last recording is shown at Figure 4. The height increment of the Typica variety at Finca La Concordia, averaged 93.4 cm with a variation coefficient of 18.1. The Oro Azteca variety at Finca La Concordia, averaged the lowest height increment with 45.3 cm and a variation coefficient of 19.0. The Oro Azteca variety at Finca La Galera averaged a plant height increment of 85.5 cm and a variation coefficient of 13.2.

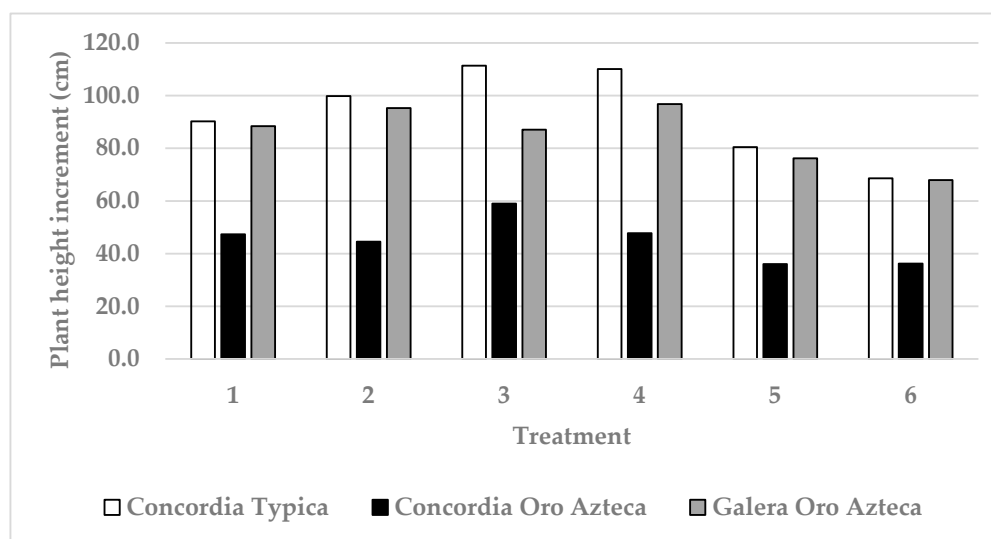


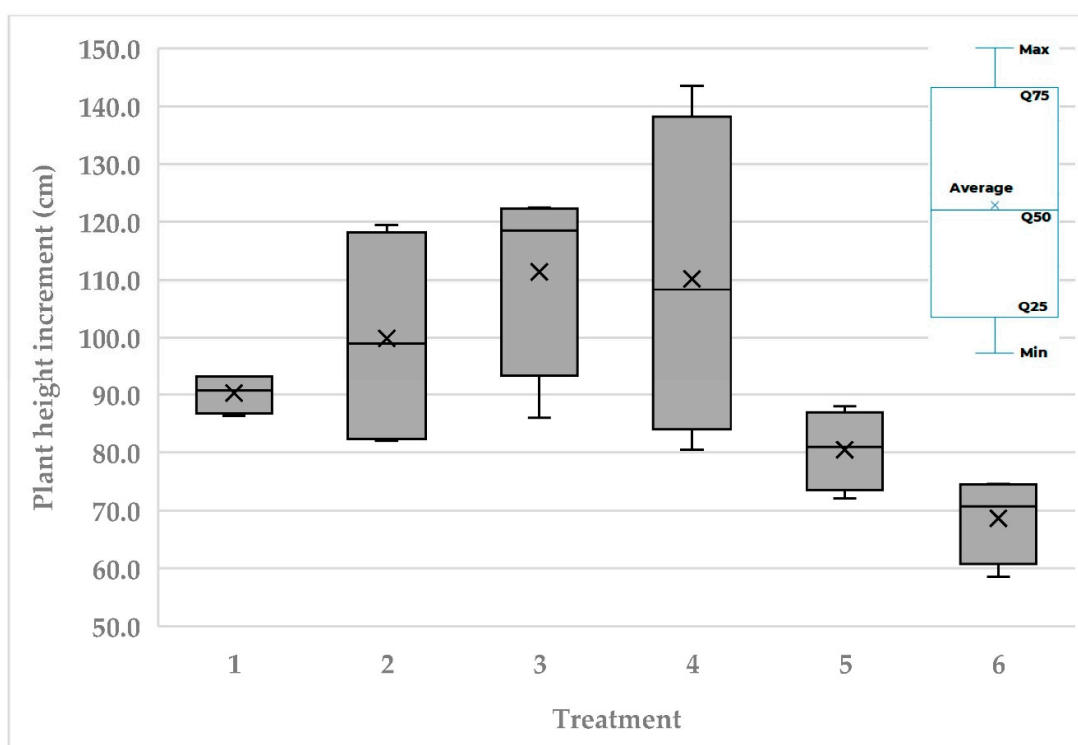
Figure 4. Plant height increment of the Coffee plantations at the study area.

The analysis of variance (ANOVA) performed to the height increment variable, resulted in significant differences among treatments at very low significant values of 0.0022, 0.0034 and 0.0049 for Concordia Typica, Concordia Oro Azteca and Galera Oro Azteca, respectively. Accordingly, the Tukey test for means comparison with an alpha value of 0.05 was practiced (Table 2). Both varieties at Finca la Concordia had similar response with treatment 3 (100-46-60; N-P-K; lime) being statistically different than treatments 5 (18-12-06; N-P-K; no lime) and 6 (00-00-00; N-P-K; no lime) with low NPK levels. ON the other hand, treatments 2 (100-46-120; N-P-K; no lime) and 4 (100-46-60; N-P-K; no lime) were different than treatment 6.

Table 2. Coffee plant height increment (cm) between august 2018 and august 2020.

Treatment	Concordia-typica	Concordia-azteca	Galera-azteca
1	90.2abc	47.4ab	88.4ab
2	99.9ab	44.6ab	95.3a
3	111.4a	59.0a	87.1ab
4	110.2ab	47.8ab	96.8a
5	80.5bc	36.1b	76.2ab
6	68.7c	36.2b	67.9b

The high variability of plants inside the plantations, resulted in high variability for plant height increment with variance coefficient values of 14.3, 15.7 and 11.3 for Concordia-typica, Concordia-azteca and Galera-azteca, respectively. Figures 5–7, show the minimum (min) and maximum (Max) values, 25, 50 and 75 Percentile (Q25, Q50 and Q75) and the average value for each treatment. This values show high variability mainly for treatments 2, 3 and 4 in Concordia-typica; treatment 4 in Concordia-azteca and treatments 1, 3 and 4 in Galera-azteca.

**Figure 5.** Plant height increment variability of the Typica variety at Finca La Concordia.

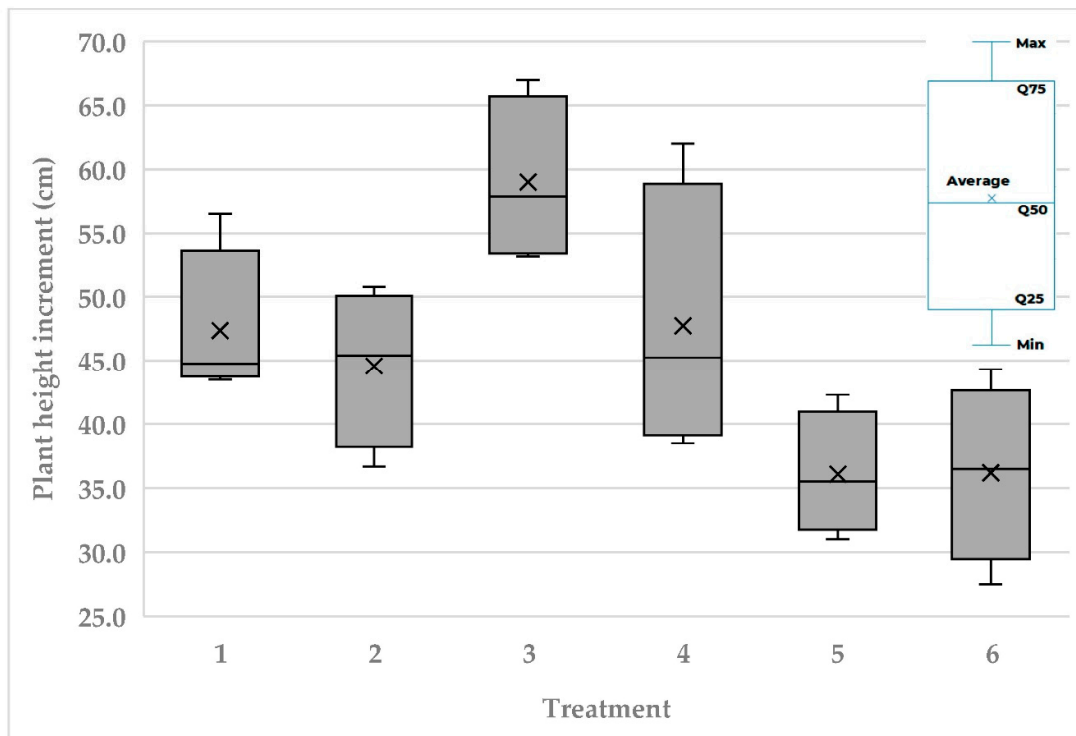


Figure 6. Plant height increment variability of the Oro azteca variety at Finca La Concordia.

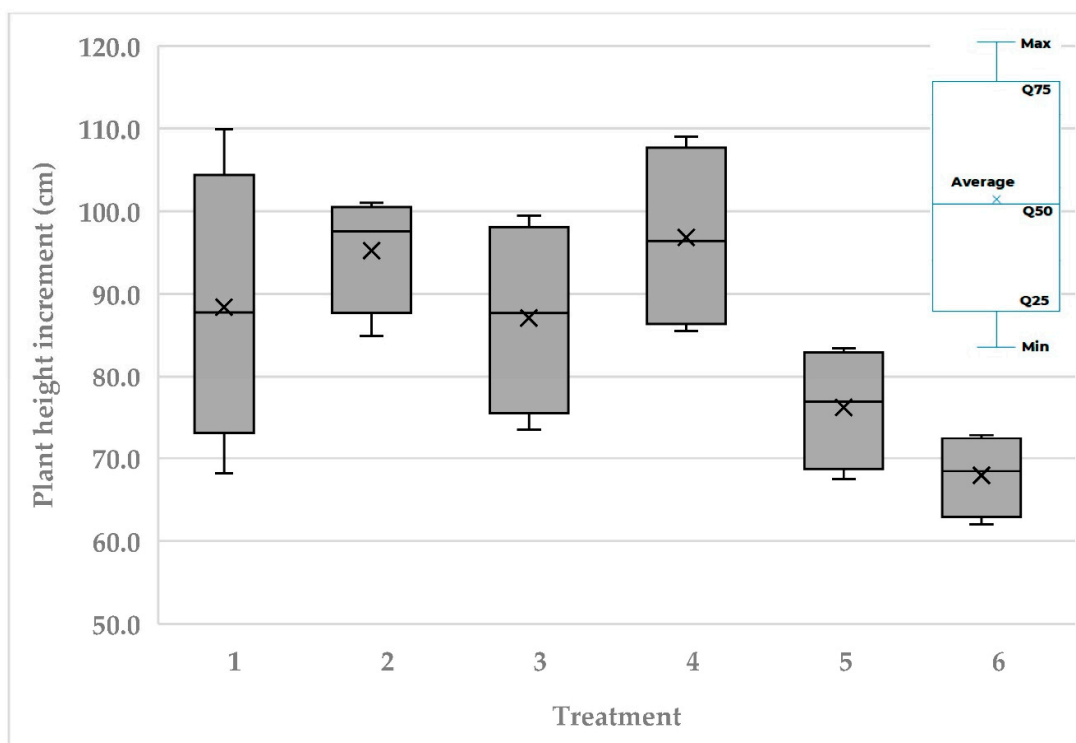


Figure 7. Plant height increment variability of the Oro azteca variety at Finca La Galera.

2.3. Coffee Yield

The experiments were harvested in January 2022, registering the weight of ripe cherry coffee grains for each coffee plant. Figure 8 shows that even when the Typica variety had 8 years since planted at the harvest time, the cherry coffee weight per plant was the lowest with an average of 257.1 g per plant. On the other side, the Oro Azteca at Finca la Galera, resulted in the highest ripe cherry coffee average with 711.1 g per plant although this plantation had 6 years since established when harvested.

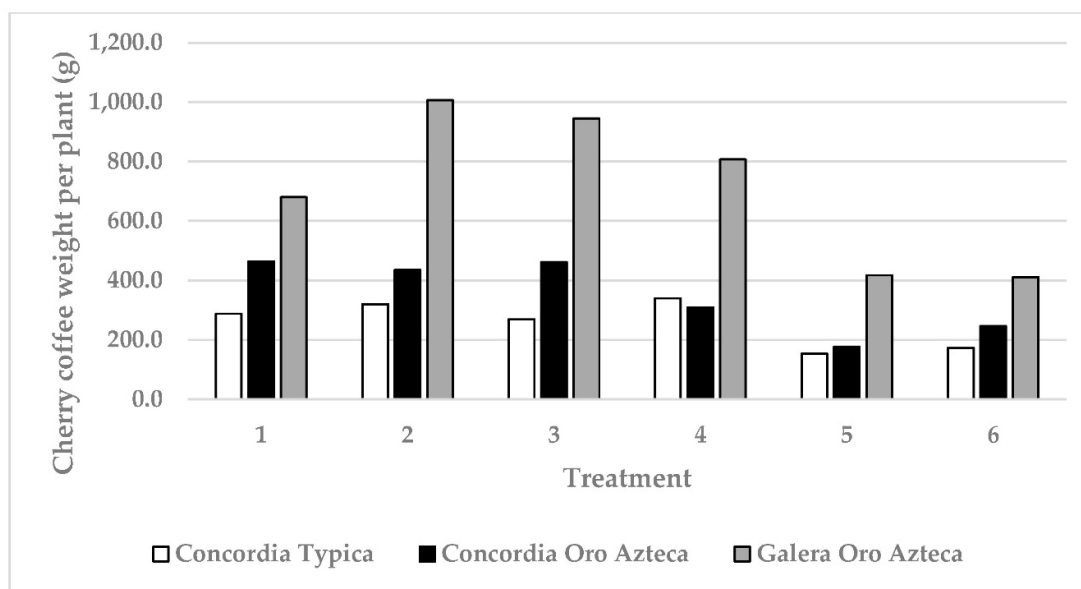


Figure 8. Cherry coffee weight per plant of the coffee plantations at the study area.

The analysis of variance (ANOVA) performed to the Cherry coffee weight variable, resulted in significant differences among treatments at very low significant values of 0.0031, 0.0002 and 0.0001 for Concordia Typica; Concordia Oro Azteca and Galera Oro Azteca, respectively. Accordingly, the Tukey test for means comparison with an alpha value of 0.05 was practiced (Table 3). The three experiments showed that the treatments with low or zero NPK application (treatments 5 and 6) were statistically different than treatment 2 (100-46-120; N-P-K; no lime). On the other side treatment 4 (100-46-60; N-P-K; no lime) was superior to treatments 5 and 6 at the Typica variety in Finca la Concordia and the Oro Azteca variety in Finca la Galera and treatment 3 was superior to treatments 5 and 6 at the Oro Azteca variety for both sites la Concordia and la Galera. Treatment 1 was superior to treatments 5 and 6 only in the Oro Azteca variety at finca la Concordia.

Table 3. Weight of ripe cherry coffee grains per plant (g).

Treatment	Concordia-typica	Concordia-azteca	Galera-azteca
1	287.7ab	463.5a	680.3ab
2	319.7a	435.1a	1,006.3a
3	269.2ab	461.8a	945.0a
4	339.9a	309.1ab	806.6a
5	153.2b	176.4b	417.5b
6	173.1b	246.3b	411.0b

The high variability of plants inside the plantations, resulted in high variability for cherry coffee yield with variance coefficient values of 24.5, 22.1 and 21.2 for Concordia-typica, Concordia-azteca

and Galera-azteca, respectively. Figures 9–11 show the minimum (Min) and maximum (Max) values, 25, 50 and 75 Percentile (Q25, Q50 and Q75) and the average value for each treatment. This values show high variability mainly for, treatments 2, 3 and 4 at Concordia-typica, treatments 1, 2 and 3 at Concordia-azteca and treatments 1, 2, 3 and 4 at Galera-azteca.

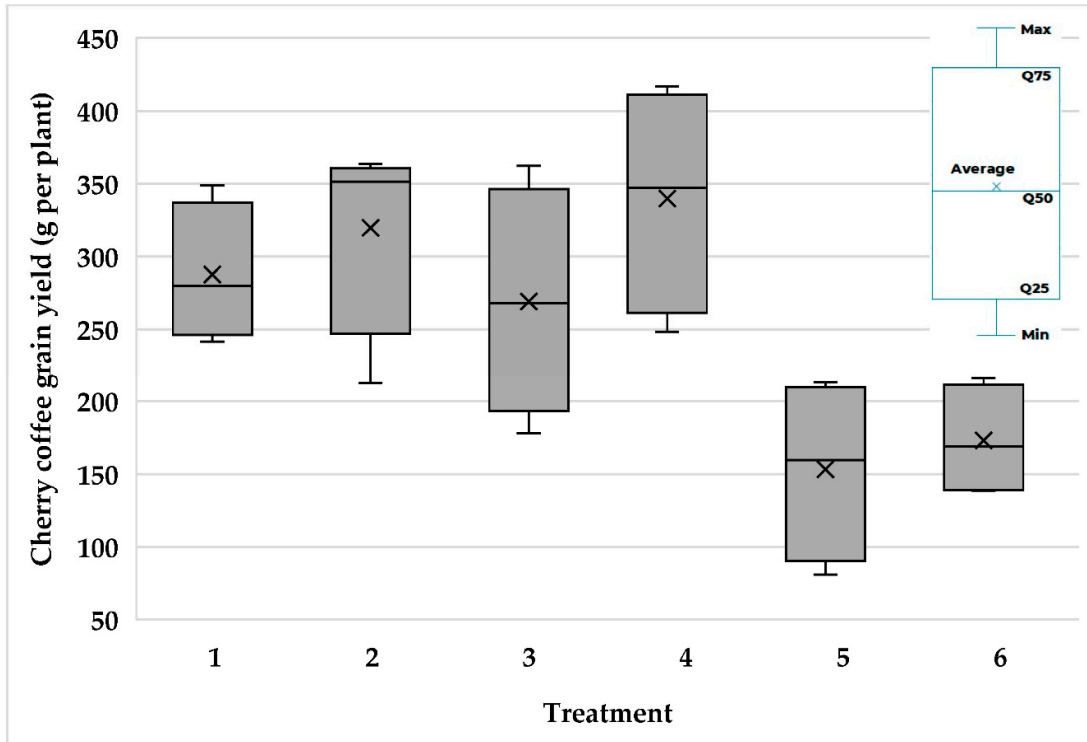


Figure 9. Cherry coffee yield variability of the Typica variety at Finca La Concordia.

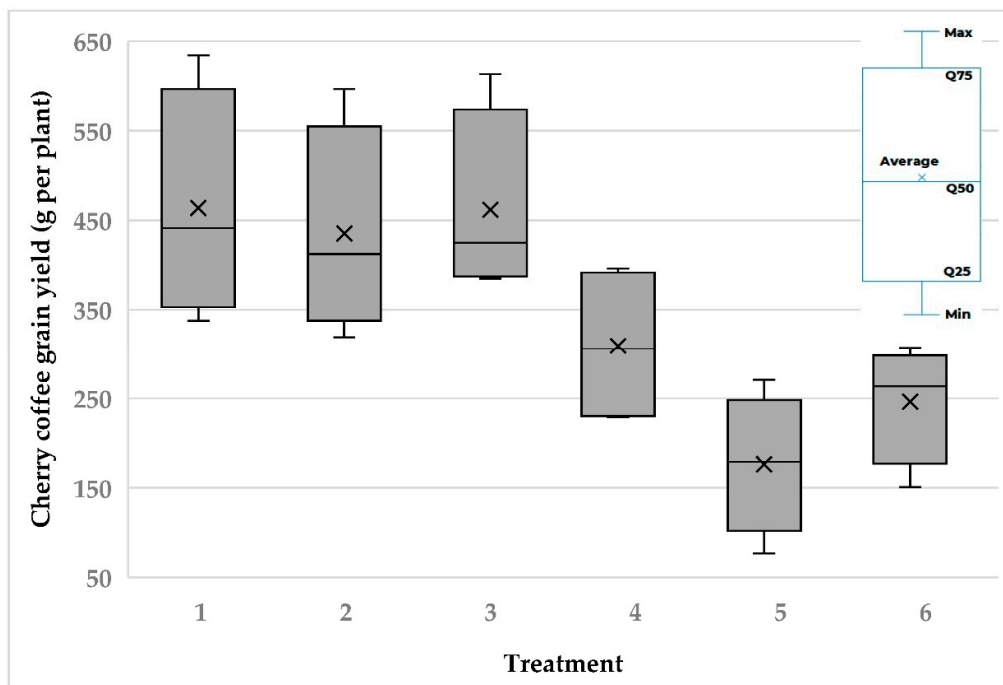


Figure 10. Cherry coffee yield variability of the Oro azteca variety at Finca La Concordia.

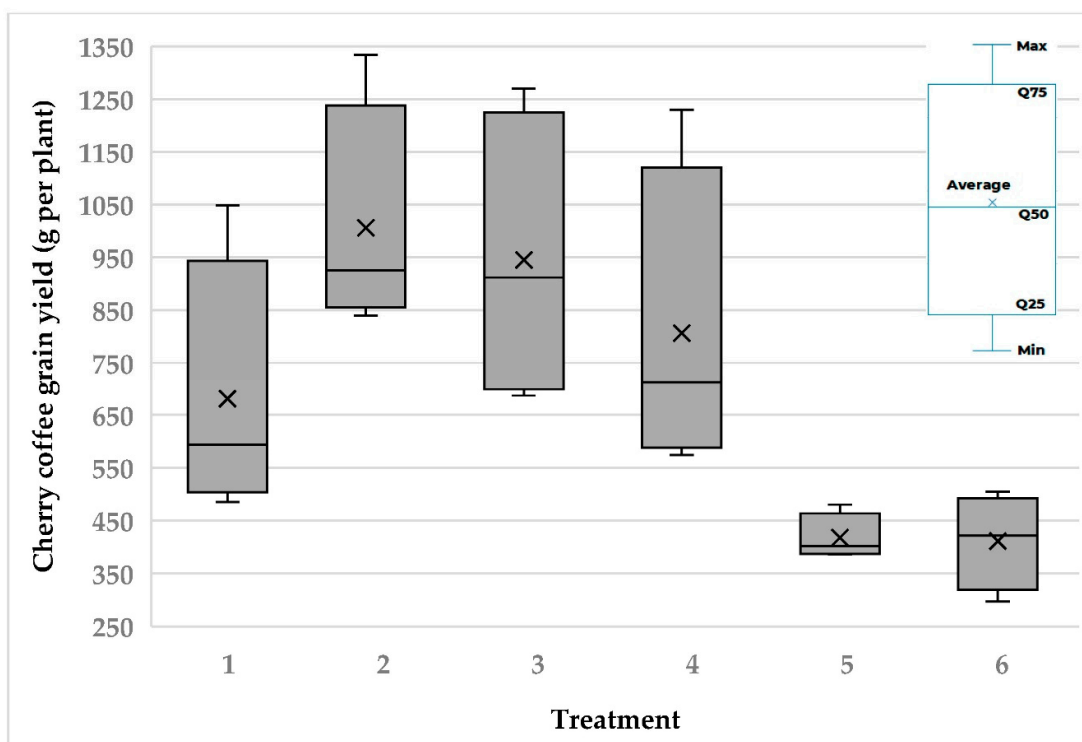


Figure 11. Cherry coffee yield variability of the Oro azteca variety at Finca La Galera.

The cherry coffee yield per plant, was converted to cherry coffee yield per hectare by using a plant density of 3,000 plants per hectare (Table 4). Treatments 4 and 2 are superior than check treatments 5 and 6 for the Typica variety in Finca la Concordia while treatments 1, 2 and 3 at the for the Oro azteca variety in Finca la Concordia and treatments 2, 3 and 4 for the Oro Azteca variety in Finca laGalera overcame the check treatments 5 and 6.

Table 4. Cherry coffee yield per hectare with 3,000 plants per hectare (kg ha^{-1}).

Treatment	Concordia-typica	Concordia-azteca	Galera-azteca
1	863	1,391	2,041
2	959	1,305	3,019
3	808	1,385	2,835
4	1,020	927	2,420
5	460	529	1,253
6	519	739	1,233

3. Discussion

Coffee production in southern Mexico consists predominantly of coffee arabica (*C. arabica* L.) under an agroforestry system with trees intercropped with the coffee plants. Agroforestry systems are very important in hilly areas where the lack of vegetation cover represents a high risk for soil erosion. Beside of providing shade for the coffee plants, the trees in an agroforestry system produce plant residue to the soil surface, protecting the soil from erosion under high slope conditions and increasing the soil organic matter [16–18].

Coffee yields in southern Mexico are low, mainly in the Oaxaca coffee production area where an average yield of 0.77 t ha^{-1} of cherry coffee is reported, compared with 3.4 t ha^{-1} and of cherry coffee at the Mexican state of Puebla [5]. This low yield is product of several factors such as predominance

of plantations older than 15 years, low plant density, use of low productive varieties, lack of pruning practices and deficient fertilization management mainly because of the limited financial resources of the smallholders.

Nitrogen is the most important Coffee nutrient with general recommended rates of 400 kg ha⁻¹ for Brazil and 300 400 kg ha⁻¹ for Colombia [19]. However, it is very important to make proper application taking care of factors such as source, rate, application timing and place because Nitrogen loses by volatilization, denitrification and leaching may reach up to 50% of the applied fertilizer [20]. Nitrogen requirements in shade agroforestry systems are considerably lower than in monoculture system mainly because of low plant densities. Beside the economic situation of the smallholders, few research on fertilization has been done under the Oaxaca coffee production area conditions. Considering the conditions of the study region, in this experiments, relatively low amounts of Nitrogen were applied and the effect on coffee yield was evident.

The Typica variety evaluated at finca la Concordia, reached a yield of 1,020 kg ha⁻¹ with the application of 100-46-60 kg ha⁻¹ of N-P-K (treatment 4), compared with 519 kg ha⁻¹ with the check treatment and 460 kg ha⁻¹ with the low dose of 18-12-02 kg ha⁻¹ of N-P-K.

The Oro Azteca variety also had a good response to treatment 4 yielding 927 kg ha⁻¹ at finca la Concordia and 2,420 927 kg ha⁻¹ at finca la Galera. Some factors for the great yield difference between these two sites is mainly that the Galera plantation has had a better management than the Concordia one. Besides, the soil condition at finca la Galera is better as can be seen at Table 1.

Even though the Oro Azteca variety produced yields higher than 1,300 kg ha⁻¹ with treatments 1, 2 and 3, the high variability of both plant height increment and cherry coffee yield did no allowed these treatments to be statistically different than treatment 4 and for that reason and because represents less costs, treatment 4 is preferred. Similar situation appeared for the Oro Azteca variety at finca la Galera where treatments 2 (3,019 kg ha⁻¹) and 3 (2,835 kg ha⁻¹) had higher yields of cherry coffee than treatment 4.

4. Materials and Methods

4.1. The Study Area

The study was carried out at the coffee farms identified as “*La Concordia*” and “*La Galera*” in the municipalities of Candelaria Loxicha and San Pedro Pochutla, respectively. These municipalities are located in the state of Oaxaca at southern Mexico very close to the Pacific Ocean (Figure 12) and are characterized by having a warm subhumid climate, with summer rains (800 to 3,500 mm) and a temperature range between 18° and 28°C. Geographic location and altitude characteristics are shown in Table 3. Both sites are located on hilly terrain as can be seen in Figure 12 with soil slope mostly higher than 50% and with the presence of trees that provide shade to the coffee trees.



Figure 12. Location of the experimental sites.

A soil profile was described [21] on each of the farms and soil samples were taken from each identified horizon for the determination of physical and chemical properties in accordance with the Mexican standard NOM-021-RECNAT-2000 [22]. Soil analyses were carried out based on the methodology established by Van Reeuwijk, [23] considering the following physical properties: bulk density ($\text{g}\cdot\text{cm}^{-3}$); wet soil color and granulometric analysis; The chemical properties were pH; Organic Carbon (%); Organic Matter (%); Nitrogen (%); Calcium Carbonates (%); Phosphorus ($\text{Mg}\ \text{Kg}^{-1}$); Sodium ($\text{Cmol}(+) \text{Kg}^{-1}$); Potassium ($\text{Cmol}(+) \text{Kg}^{-1}$); Calcium ($\text{Cmol}(+) \text{Kg}^{-1}$) and Magnesium ($\text{Cmol}(+) \text{Kg}^{-1}$).

4.2. Description of the Experiments

Two experiments were carried out at the site identified as “Finca la Concordia” with the coffee variety known as “Typica” in one experiment and the “Oro azteca” variety at the other experiment. When the experiments were established in august 2018, the “Oro Azteca” variety had three years since planted and the Typica variety had four years of being planted. Another experiment was established at the site identified as “Finca la Galera” where the Oro Azteca variety had two years since planted when the experiment was established.

The Typica variety, evolved from the original coffee variety introduced in Oaxaca in the XIX century in response to the local environmental conditions, and is highly appreciated because of its good cup quality [24] but is highly susceptible to the coffee leaf rust. The Oro Azteca variety was released in Mexico as a product of breeding activities between the hybrid timor with leaf rust resistance and the variety caturra rojo with good yield and quality characteristics [25]. The Oro azteca variety has a lower height than the Typica variety, allowing plantation higher densities and, as a consequence, higher yields [26].

The experimental design was a randomized complete block design with six treatments (Table 6) and four replications. The treatments were selected according to varied amounts of N, P, K and lime. Five treatments had at least N and K applications and the sixth treatment had no application of N-P-K, acting as a check treatment (Table 5). The amount of N-P-K treatments per plant was adjusted to a plant density of 3,000 plants per hectare. The experimental unit consisted of six plants of the Typica variety at Finca la Concordia and four plants of the Oro Azteca variety at both Finca la Concordia and Finca la Galera. At the beginning (august 2018) and at the end (august 2019) of the experiment, height plant from the soil surface to the plant apex was registered. With this data, plant height increment between the beginning and the end of the experiment was obtained. Harvest of the experiments was carried out in January 2022 and data about coffee cherry grain weight per harvested plant was registered for the evaluation of the treatments effect.

Table 5. Geographic location of the experimental sites.

Farm	Longitude (West)	Latitude (North)	Altitude (masl)	Municipality
La Concordia	-96.42527	15.87399	741	San Pedro Pochutla
La Galera	-96.47062	15.96836	1,160	Candelaria Loxicha

Table 6. Characteristics of the evaluated treatments.

Trat.	N	P ₂ O ₅	K ₂	Lime
	----- kg ha ⁻¹ -----			(Yes/No)
1	100	46	120	Yes
2	100	46	120	No
3	100	46	60	Yes
4	100	46	60	No
5	18	12	06	No
6 (Check)	0	0	0	No

Data on plant height increment and cherry coffee grain yield were subjected to analyses of variance with the Statistical Analysis System (SAS) [27], and when significant difference among treatments appeared, Tukey means comparison at 5 % probability was practiced.

5. Conclusions

Agroforestry coffee production systems, are very complex because of the combination of trees providing shade and organic matter to the coffee plants and its productivity is lower than monoculture coffee production systems.

The low productivity of agroforestry coffee production systems is the result of the combination of factors such as aged plantations, low plant density, lack of pruning practices, use of low productive varieties and deficient fertilization management.

Under good management practices, one of the factors that influences coffee productivity the most adequate plant nutrition, both organic and inorganic. However, research specific to the effect of inorganic nutrition on coffee yield is scarce.

With the yearly application of N-P-K rates of 100-46-60 kg ha⁻¹ in agroforestry coffee plantations in the Oaxaca's Coastal coffee producing region, a yield of 1,000 kg ha⁻¹ for the Typica variety and 1,500 kg ha⁻¹ for the Oro Azteca variety is expected.

Proper application of Nitrogen fertilizers must consider time of application and covering the fertilizer with soil in order to avoid volatilization loss. In order for the plant nutrition to be effective good management practices such as pruning and weed control must be ensured. Organic nutrition

practices must be implemented along with the inorganic materials in order to obtain medium and long term soil fertility.

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