

Slow-release fertilizers in arroqueño agave (*Agave* spp.): effects on growth and nutrition

Fertilizantes de liberación lenta en agave arroqueño (*Agave* spp.): efectos sobre el crecimiento y nutrición

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ABSTRACT

Agaves, including wild species such as arroqueño (*Agave* spp.), are essential for mezcal production. However, most species used in its manufacture, except for *Agave angustifolia* Haw., are not widely cultivated. To ensure the sustainability of mezcal production, it is crucial to promote reforestation and the cultivation of wild agaves. This study evaluated the effect of slow-release fertilizers (SRFs) on the growth, foliar nutrition, and sugar content of arroqueño agave. A completely randomized block design was used, with three treatments and four blocks. Within each block, treatments were randomly assigned, including five plants per treatment. Each treatment involved a total of 20 plants distributed across the four blocks. Treatments were evaluated over 10 months and included: T1) control, without fertilization; T2) Osmocote Plus[®]; and T3) Multicote Agri[®]. Compared to control plants, the application of Osmocote Plus[®] increased the number of unfolded leaves by 17.7 %, plant height by 13.7 %, stem circumference by 13.8 %, fresh leaf weight by 52.4 %, fresh stem weight by 48.9 %, and dry leaf weight by 53.4 %. Fertilization with Multicote Agri[®] increased fresh root weight by 36.0 % and foliar NO₃⁻ content by 59.3 %. The results highlight the positive effects of SRFs on the growth and nutrition of arroqueño agave, contributing to more efficient nutrient use, reduced environmental impact associated with conventional fertilization, and the sustainable cultivation and conservation of native agave species.

KEY WORDS: Wild agaves, Plant growth, Fertilization, Mezcal, Plant nutrition.

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RESUMEN

Los agaves, incluidas especies silvestres como el arroqueño (*Agave* spp.), son esenciales para la producción de mezcal. Sin embargo, la mayoría de las especies utilizadas en su elaboración, con excepción de *Agave angustifolia* Haw., no se cultivan ampliamente. Para asegurar la sostenibilidad de la producción mezcalera, es crucial promover la reforestación y el cultivo de agaves silvestres. Este estudio evaluó el efecto de fertilizantes de liberación lenta (SRFs) sobre el crecimiento, nutrición foliar y contenido de azúcares en agave arroqueño. Se empleó un diseño de bloques completamente al azar, con tres tratamientos y cuatro bloques. En cada bloque, los tratamientos se asignaron aleatoriamente, incluyendo cinco plantas por tratamiento. Cada tratamiento contó con un total de 20 plantas distribuidas en los cuatro bloques. Los tratamientos se evaluaron durante 10 meses e incluyeron: T1) control, sin fertilización, T2) Osmocote Plus® y T3) Multicote Agri®. En comparación con las plantas control, la aplicación de Osmocote Plus® incrementó 17.7 % el número de hojas desplegadas, 13.7 % la altura de planta, 13.8 % la circunferencia de tallo, 52.4 % el peso fresco de hojas, 48.9 % el peso fresco de tallo y 53.4 % el peso seco de hojas. La fertilización con Multicote Agri® aumentó 36.0 % el peso fresco de raíces y 59.3 % el contenido foliar de NO₃⁻. Los resultados evidencian el efecto positivo de los SRFs sobre el crecimiento y nutrición del agave arroqueño, lo que contribuye a optimizar la eficiencia en el uso de nutrientes, reducir el impacto ambiental asociado a la fertilización convencional y promover la conservación y el cultivo sustentable de especies nativas de agave.

PALABRAS CLAVE: Agaves silvestres, Crecimiento vegetal, Fertilización, Mezcal, Nutrición vegetal.

Introduction

Mexico is recognized as a center of diversity and domestication of the *Agave* genus, hosting 79 % of its species, most of which are endemic to the country (García-Mendoza, 2011). This remarkable diversity is also attributed to human intervention, traditional selection, and the historical use of agaves, commonly referred to as “magueyes” (Gentry, 1982; Eguiarte *et al.*, 2021). A total of 53 agave species are used in the production of distilled beverages, mainly “mezcal” (Torres *et al.*, 2015). For at least 10,000 years, humans have extensively utilized agave, utilizing nearly all parts of the plant. More than 92 distinct uses have been identified (Colunga-GarcíaMarín *et al.*, 2017; Trejo *et al.*, 2022). These applications include food, human and veterinary medicine, building materials, distilled and fermented beverages, living fences, soil retention, ornamentation, forage, fuel, fiber extraction, paper and soap production, crafts, and ceremonial rituals (Colunga-

GarcíaMarín *et al.*, 2017). The primary uses of agave are closely tied to its most distinctive biological traits: 1) carbohydrate accumulation in the stem, at the base of the leaves, and in the sap of the inflorescences near the end of its reproductive cycle; 2) fibrous leaves rich in saponins; and 3) a rosette structure combined with an extensive and shallow root system (Colunga-GarcíaMarín *et al.*, 2017).

In Oaxaca (Mexico), approximately nine agave species are predominantly used for mezcal production. Among them, *Agave angustifolia* Haw., commonly known as “agave espadín,” is the most in demand and the only species widely cultivated in semi-arid areas. The other eight species, including the agave known as “arroqueño” (*Agave* spp.), are either harvested from wild populations or grown in semi-intensive systems, typically as living fences with little to no agronomic management (Bautista-Cruz & Martínez-Gallegos, 2020). In the last decade, mezcal production has increased from less than one million liters in 2011 to nearly eight million liters. This substantial growth has placed considerable pressure on resources, particularly the raw material, as a significant portion of mezcal depends on wild-harvested agaves (Arellano-Plaza *et al.*, 2022).

Agave plants require several years to grow and reach maturity, generally between 5 and 15 years depending on the species (García-Mendoza *et al.*, 2017). *Agave tequilana* plantations typically contain between 2,500 and 5,000 plants per hectare (INEGI, 1997). However, this is not the case for agaves used in mezcal production, where, except for *A. angustifolia*, large-scale cultivation is virtually nonexistent. To ensure a sustainable supply of raw materials for mezcal production year after year, it is crucial to promote both the reforestation of wild populations and the cultivation of the most utilized species, considering the long period agaves require to reach maturity (Arellano-Plaza *et al.*, 2022).

Most conventional synthetic fertilizers contain macronutrients such as nitrogen (N), phosphorus (P), and potassium (K), but their use efficiency is relatively low. Only between 50 and 60 % of N and K, and between 10 and 25 % of P, are effectively absorbed by crops (Rashid *et al.*, 2021), while the remainder is lost through volatilization, runoff, or leaching, contributing to environmental pollution (Motamedi *et al.*, 2023). Therefore, it is essential to optimize fertilization management to improve soil fertility, meet the nutritional needs of crops, enhance yield and quality, support rural economies, and promote sustainable agriculture. In addition, this approach seeks to encourage environmentally friendly farming practices (Wang *et al.*, 2021). In recent decades, the high demand for fertilizers and the urgent need for more efficient usage have driven the development of several types of fertilizers, including slow-release fertilizers (SRFs). These fertilizers are specifically formulated to release nutrients gradually into the soil over an extended period, compared to conventional synthetic fertilizers, thereby ensuring a sustained nutrient supply to plants (Yamamoto *et al.*, 2016). The main limitation to the widespread adoption of SRFs is their high cost, which can be 2.5 to 8 times greater than that of conventional synthetic fertilizers (Rashid *et al.*, 2021). However, SRFs may offset these costs by reducing the need for multiple applications, thereby lowering overall production expenses (Guertal, 2009). Moreover, SRFs improve nutrient use efficiency in crops, which not only minimizes environmental pollution but also mitigates negative effects on human and animal health. Consequently, the use of SRFs aligns with the principles of sustainable agriculture, supporting long-term ecological balance and food security

(Li *et al.*, 2005). In this context, this study aimed to evaluate the response of arroqueño agave to SRFs application under field conditions, focusing on plant growth, foliar nutrient concentrations, and total soluble solids (sugar) content in the stem.

Material and Methods

The experiment was conducted under rainfed conditions in San Jacinto Chilateca (16°50'27.667"N, 96°41'00.673"W), Ocotlán de Morelos, Oaxaca (Mexico), at an average elevation of 1,505 masl (INEGI, 2025). Some of the physical and chemical properties of the soil at the experimental site were as follows: bulk density 1.23 g cm⁻³, organic matter content 2.4 %, pH (soil:water ratio 1:2) 8.3, NO₃⁻-N 4.85 mg kg⁻¹, available phosphorus 24.5 mg kg⁻¹, exchangeable Ca²⁺ 6,354 cmol(+) kg⁻¹, Mg²⁺ 241 cmol(+) kg⁻¹, Na⁺ 24.5 cmol(+) kg⁻¹, and K⁺ 264 cmol(+) kg⁻¹. Micronutrient levels included: Cu 0.81 mg kg⁻¹, Mn 1.65 mg kg⁻¹, Fe 2.82 mg kg⁻¹, Zn 0.15 mg kg⁻¹, and B 0.45 mg kg⁻¹.

Rhizomatous offshoots of arroqueño agave aged 7 to 8 months were used, obtained from three-year-old mother plants. These offshoots averaged 33.5 cm in height and were visually inspected to ensure they showed no signs of lesions, rot, or insect damage. Roots were trimmed to encourage the development of a new root system following field transplantation. Subsequently, the offshoots were disinfected by immersion in a 0.624 % sodium hypochlorite solution for 5 min (Sánchez-Mendoza *et al.*, 2020). Transplanting took place on October 22nd, 2020, with 1.5 m spacing between plants and 3 m between rows, resulting in a planting density of 2,178 plants per hectare. Fertilization was carried out two months after transplanting. The SRFs used were: 1) Osmocote Plus® (15-09-12) (15 % N, 9 % P₂O₅, 12 % K₂O, 6.0 % SO₄, 0.02 % B, 0.05 % Cu, 0.46 % Fe, 0.06 % Mn, 0.02 % Mo, 0.05 % Zn) with a release period of 5-6 months; and 2) Multicote Agri® (18-06-12) (18 % N, 6 % P₂O₅, 12 % K₂O, 2 % CaO, 3.5 % MgO, 2.1 %) with a release period of 8 months. According to Sánchez-Mendoza *et al.* (2020), 100 g of SRF was manually applied around each plant at a depth of 5 cm and a distance of 5 cm from the stem. The experiment was established using a completely randomized block design with three treatments and four blocks. Within each block, treatments were randomly assigned, including five plants per treatment. Thus, each treatment consisted of 20 plants distributed across the four blocks. Each plant was considered an experimental unit. The treatments evaluated were: T1) control, without fertilization (NSRF); T2) Osmocote Plus®; and T3) Multicote Agri®. The evaluation period lasted 10 months. At the end of the experiment, plant height (PH) was measured in all plants using a measuring tape, and the unfolded leaves number (ULN) was determined through visual counting. Half of the plants in each treatment were randomly selected for harvest, resulting in 10 plants per treatment and 40 plants in total. In these harvested plants, stem circumference (SC) was measured with a measuring tape; root volume (RV) was determined by submerging the roots in a 1,000 mL graduated cylinder containing a known volume of water and measuring the volume displaced; root density (RD) was calculated as the mass-to-volume ratio. Fresh weights of leaves (FWL), stem (FWS), and roots (FWR), as well as dry weights of leaves (DWL), stem (DWS), and roots (DWR), were recorded after drying plant material in a solar dryer until constant weight. Sugar content, expressed as total soluble solids (TSS) in the stem, was measured using a handheld refractometer. To quantify foliar

concentrations of Ca^{2+} , Na^+ , NO_3^- , and K^+ , a composite sap sample was collected from the middle portion of all leaves from each plant. Concentrations of these elements were determined using a LAQUAtwin ion meter.

Throughout the experiment, soil temperature and moisture in the agave rhizosphere were monitored in situ using a digital meter (Nennimber GmbH). The average soil temperature was 31°C , and average soil moisture was 61.1 %.

Statistical analysis

Plant height (PH) and unfolded leaves number (ULN) data were tested for normality using the Kolmogorov-Smirnov test, while the Shapiro-Wilk test was applied to all other variables. Variables that did not meet the assumptions of normality (PH, FWS, FWL, FWR, TSS, and foliar Ca^{2+} content) were transformed using base-10 logarithms ($\log_{10}(x)$) or square root transformation. Homogeneity of variance was verified using Bartlett's test. Analysis of variance (ANOVA) was then performed, followed by Duncan's multiple range test for mean comparison ($p \leq 0.05$). All statistical analyses were conducted using SAS software, version 9.1 (SAS Institute, 2004).

Results and Discussion

Of the 16 variables evaluated, 8 showed a significant response to the application of SRFs. Compared to control plants, Osmocote application increased ULN by 17.7 %, PH by 13.7 %, SC by 13.8 %, FWL by 52.4 %, FWS by 48.9 %, and DWL by 53.4 % (Tables 1 and 2). Fertilization with Multicote increased FWR by 36.0 % (Table 2) and foliar NO_3^- content by 59.3 % (Figure 1). Variables such as RV, RD, TSS, DWS, DWR, and foliar concentrations of Ca^{2+} , K^+ , and Na^+ did not show significant responses to the treatments evaluated (Tables 1 and 2; Figures 1 and 2).

Table 1. Mean value \pm standard error of growth variables in arroqueño agave plants (*Agave spp.*) in response to the application of slow-release fertilizers under field conditions.

Treatments	ULN	PH	SC	RV	RD
		----- cm -----	-----	cm ³	g cm ⁻³
Control	21.4 \pm 1.2b	56.9 \pm 1.2b	41.2 \pm 1.4b	28.0 \pm 4.1a	1.4 \pm 0.1a
Osmocote plus®	25.2 \pm 0.8a	64.6 \pm 0.8a	46.9 \pm 0.9a	35.0 \pm 5.4a	1.4 \pm 0.2a
Multicote agri®	23.7 \pm 2.1ab	59.9 \pm 2.1ab	43.0 \pm 2.0ab	41.0 \pm 4.3a	1.2 \pm 0.06a

ULN: Unfolded leaves number; PH: Plant height; SC: Stem circumference; RV: Root volume; RD: Root density. Mean values followed by different letters within each column are statistically different according to Duncan's multiple range test ($p \leq 0.05$).

Table 2. Mean value \pm standard error of biomass accumulation variables in arroqueño agave (*Agave* spp.) plants in response to the application of slow-release fertilizers under field conditions.

Treatments	FWL	FWS	FWR	DWL	DWS	DWR
Control	2653.1 \pm 247.3b	1187.1 \pm 115.9b	36.7 \pm 3.1b	595.4 \pm 72.3b	393.4 \pm 41.1a	16.2 \pm 2.4a
Osmocote plus®	4042.1 \pm 248.6a	1767.9 \pm 105.4a	41.0 \pm 3.5ab	913.1 \pm 110.6a	518.5 \pm 27.5a	18.9 \pm 2.7a
Multicote agri®	2966.9 \pm 307.0b	1419.3 \pm 152.6ab	49.9 \pm 4.0a	707.0 \pm 82.9ab	466.5 \pm 50.8a	24.0 \pm 2.3a

FWL: Fresh leaf weight; FWS: Fresh stem weight; FWR: Fresh root weight; DWL: Dry leaf weight; DWS: Dry stem weight; DWR: Dry root weight. Mean values followed by different letters within each column are statistically different according to Duncan's multiple range test ($p \leq 0.05$).

Although the application of SRFs promoted increases in growth variables such as ULN, PH, and SC, as well as in biomass-related variables including FWL, FWS, DWL, FWR, and foliar NO_3^- content in arroqueño agave plants, the magnitude of the response varied depending on the type of fertilizer used. In particular, variables associated with plant growth (ULN, PH, and SC) and biomass accumulation (FWL, FWS, and DWL) showed a stronger response to the application of Osmocote Plus®, which can be attributed to its more comprehensive nutrient composition compared to Multicote Agri®. Osmocote Plus® provides not only essential macronutrients but also micronutrients such as Fe, Zn, Mn, and B, which were present at limiting levels in the experimental soil. This additional micronutrient supply may have corrected specific deficiencies and supported key physiological processes in agave development. Furthermore, the shorter nutrient release period of Osmocote (5-6 months) compared to Multicote (8 months) may have contributed to earlier and more efficient nutrient availability, allowing the plants to optimize their metabolism during critical growth stages. Together, these factors may explain the greater development observed in plants treated with Osmocote.

Aside from the studies conducted by Castillejos-Reyes et al. (2023), Sánchez-Mendoza & Bautista-Cruz (2022), and Sánchez-Mendoza et al. (2020), research evaluating the effects of SRFs on *Agave* species remains limited. In this context, Castillejos-Reyes et al. (2023) assessed the impact of Osmocote and Multicote fertilization on coyote agave (*Agave* spp.) under field conditions. Their study reported significant increases in several growth parameters with Osmocote application, including PH by 21.2 %, ULN by 20.8 %, FWL by 77.0%, FWS by 62.8 %, DWL by 177.0 %, DWS by 53.1 %, and DWR by 39.1 %. Similarly, fertilization with Multicote resulted in a 15.3 % increase in PH and elevated foliar content of K^+ , NO_3^- , and Na^+ by 25.6 %, 26.2 %, and 29.8 %, respectively. These findings are consistent with the results of the present study, particularly

regarding improvements in PH, ULN, FWL, FWS, and DWL with the addition of Osmocote, as well as the observed increase in foliar NO_3^- content following Multicote application.

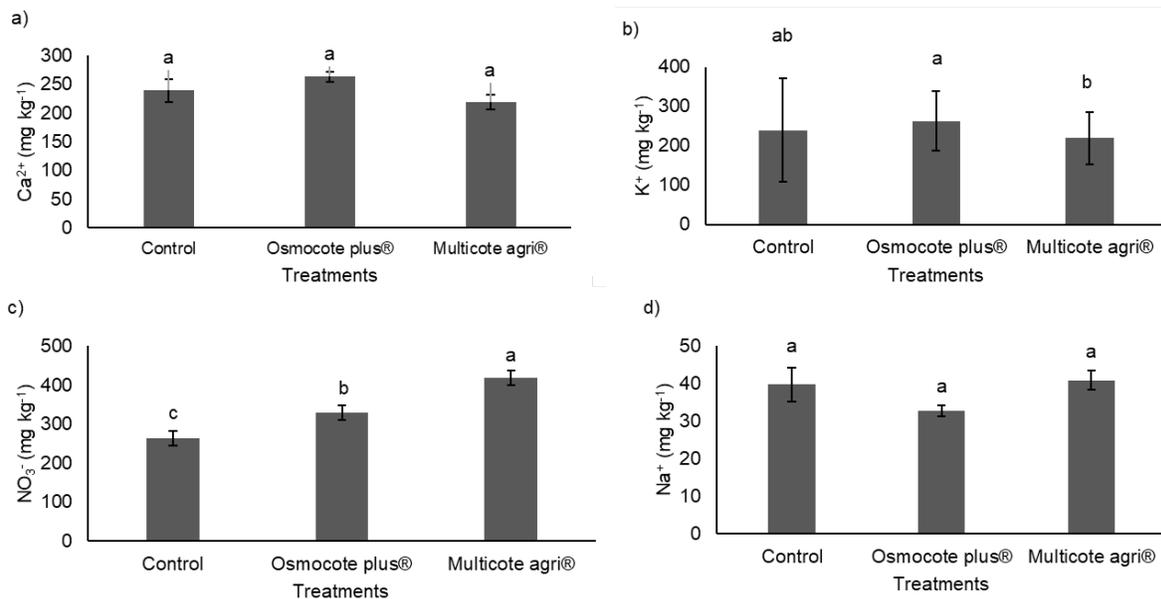


Figure 1. Mean value \pm standard error of foliar content of Ca^{2+} (a), K^+ (b), NO_3^- (c), and Na^+ (d) in arroqueño agave plants (*Agave spp.*) in response to the application of slow-release fertilizers under field conditions.

Mean values with different letters on each bar are statistically different according to Duncan's test ($p \leq 0.05$).

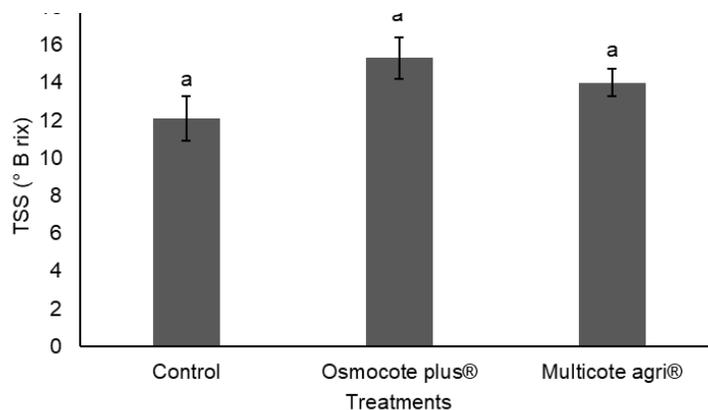


Figure 2. Mean value \pm standard error of total soluble solids (TSS) content in arroqueño agave (*Agave spp.*) plants in response to the field application of slow-release fertilizers.

Mean values with different letters on each bar are statistically different according to Duncan's test ($p \leq 0.05$).

Contrary to the findings reported in this study, Sánchez-Mendoza *et al.* (2020) did not observe significant differences in PH or ULN compared to the control in *A. angustifolia* plants grown in the field and fertilized with the SRFs Multigro 6® (21-14-10 NPK + 2 MgO), Multigro 3® (24-05-13 NPK + 2 MgO), and Turf Builder® (27-03-04 NPK). However, these authors reported increases in root length, FWL, FWS, and stem diameter in *A. angustifolia* fertilized with Multigro 6®. In the present study, the application of Osmocote positively impacted FWL and FWS in arroqueño agave, consistent with the results of Sánchez-Mendoza *et al.* (2020).

Previous studies have also reported favorable responses of certain agave species to conventional synthetic fertilization. For example, in agreement with our findings, Cruz-Vásconcelos *et al.* (2020) observed that, compared to control plants, the AP of *A. salmiana* increased by 51.1 % when fertilized with conventional products such as triple 17 (17-17-17), urea (46-00-00), and Yara Star (21-17-3). Similarly, Martínez-Ramírez *et al.* (2013) reported ULN increases of 15.5 % in *A. potatorum* and 18.9 % in *A. angustifolia* plants subjected to high (90-60-45 kg ha⁻¹) and medium (60-40-30 kg ha⁻¹) doses of synthetic fertilizers (triple superphosphate, potassium sulfate, and ammonium sulfate).

García-Martínez *et al.* (2020) found that the addition of 43.5 mg kg⁻¹ of P led to improvements of 13.2 % in PH, 34.9 % in FWL, 36.1 % in FWS, and 21.5 % in stem diameter in *A. potatorum*. They also reported that, in coyote agave, a P dose of 29.0 mg kg⁻¹ increased PH by 16.4% and FWS by 44.4 %, which aligns with our findings. Furthermore, Enríquez del Valle *et al.* (2016) evaluated different concentrations (1, 20, 40, 60, 80, and 100 %) of Steiner nutrient solution on the growth of *A. potatorum*. Their results revealed increases of 132.9 % in DWL, 210.0 % in leaf area, and 27.9 % in stem diameter with the full-strength (100 %) solution.

Agave plants are characterized by their high fructan content (fructose-based polysaccharides). In agave species, fructans are carbohydrate reserves that are synthesized and stored in the stems. Fructans serve as storage before flowering, and they also act as osmoprotectants during periods of drought (Arrizon *et al.*, 2010). Carbohydrate content varies as agave plants reach reproductive stages (Mellado-Mojica *et al.*, 2009). As carbohydrates are synthesized via photosynthesis, seasonal variations in climate influence both net carbon gain in photosynthetic organs and the transport of photoassimilates to economically important storage tissues such as the stem or “piña” (Nobel *et al.*, 1998; Pimienta-Barrios *et al.*, 2001). In line with our findings, Sánchez-Mendoza *et al.* (2020) did not observe significant effects of SRFs on TSS content in the stem of *A. angustifolia*. Conversely, García-Martínez *et al.* (2020) reported a 40.0 % increase in TSS content in coyote agave grown under macrotunnel conditions and fertilized with 43.5 mg kg⁻¹ of P. Likewise, Zúñiga-Estrada *et al.* (2018) found that *A. tequilana* plants subjected to basal fertilization (162-150-250 kg ha⁻¹ of N, P, and K) combined with fertigation (315.3 g N, 179.9 g P₂O₅, 353.4 g K₂O, 111 g CaO, and 89.1 g MgO) did not exhibit significant increases in TSS content. The absence of a significant response in TSS content in arroqueño agave stems following SRFs application may result from the interaction of multiple physiological and environmental factors. Various studies have documented contrasting fertilization responses among agave species, which may be attributed to phenotypic and genotypic differences that determine species-specific nutrient requirements according to phenological stage (Nobel *et al.*, 1998; Pimienta-Barrios *et al.*, 2001).

In this sense, sugar accumulation does not depend solely on nutrient availability but also on the timing of plant demand for key processes such as vegetative growth, leaf expansion, or reserve formation. In addition, plant age and climatic conditions play crucial roles in TSS accumulation. Rendón-Salcido *et al.* (2009) reported that maximum TSS levels occur in older agave plants (up to 19 years), and that drought conditions promote this accumulation. In this study, the harvested plants were approximately 1.5 years old, an early developmental stage in which carbohydrate storage mechanisms may not yet be fully established. Therefore, it is plausible that the effects of SRFs on TSS content may not be evident at this stage, as plants likely prioritize the use of available nutrients for structural growth rather than photoassimilate storage.

N plays a fundamental role in plants, participating in the synthesis of chlorophyll, structural and enzymatic proteins, and key compounds such as phytohormones. However, it has been documented that plants exhibit limited efficiency in N uptake and utilization (Tiong *et al.*, 2021). In this study, agave plants fertilized with Multicote showed the highest foliar N-NO₃⁻ content, which is directly related to the higher nitrogen percentage in its formulation. Multicote contains 18 % N, compared to 15 % in Osmocote Plus®. These results are consistent with those of Aguilera-Rodríguez *et al.* (2016), who evaluated the effects of Basacote, Multicote, and Osmocote fertilizers on *Pinus montezumae* Lamb. seedlings under nursery conditions and found that Multicote treatments resulted in the highest foliar N concentrations. These findings support the direct relationship between N content in the fertilizer and its accumulation in plant tissues.

Although vegetative propagation via bulbils or rhizomes is the common practice in agave cultivation in Mexico (Infante *et al.*, 2003), sexual reproduction via seed production remains the primary mechanism in natural populations. However, seedling establishment rates in the wild are typically very low (Arizaga & Ezcurra, 2002; González-Iturbe *et al.*, 2002), likely contributing to the sharp decline in wild agave populations, such as arroqueño, due to ongoing harvesting for mezcal production. In commercial plantations, fertilization is often neglected or performed sporadically with conventional fertilizers just before the rainy season, typically without scientific or technical guidance. This practice likely reduces productivity per area, sugar content in the stem, and overall crop cycle efficiency, ultimately affecting the competitiveness of the value chain.

While agave can develop in shallow, rocky, and nutrient-poor soils, commercial cultivation would benefit from soil fertility optimization and improved plant nutrition to achieve larger piñas with higher sugar content (Bravo *et al.*, 2007). In this context, the findings of the present study provide evidence supporting the use of SRFs as a potentially viable and environmentally sustainable fertilization strategy to improve growth and nutritional quality in arroqueño agave.

Conclusions

The application of Osmocote Plus® promoted greater development in key morphological variables, while Multicote Agri® proved more efficient in increasing foliar nitrate (NO₃⁻) concentrations.

These functional differences between the fertilizers suggest that their use can be strategically optimized according to specific production goals. However, given the prolonged life cycle of agave plants, which ranges from 5 to 20 years depending on management systems and agro-environmental conditions, it is essential to conduct long-term follow-up studies. Such studies will allow for the validation and optimization of arroqueño agave's agronomic response to slow-release fertilizers, ultimately enabling the development of more precise technical recommendations for their use in sustainable cultivation systems.

Author contributions

Methodology development, C.C.R. Work conceptualization, funding acquisition, methodology development, writing and manuscript preparation, A.B.C. Methodology development, data analysis, and manuscript editing, S.S.M. Manuscript review and editing, R.S.G.

All authors have read and approved the published version of this manuscript.

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Conflict of interest

The authors declare no conflict of interest.

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