Research Article

Comparative Production of Two *Pennisetum* Species under Fertilization with Goat Manure in a Buffer Zone of a Protected Area

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Abstract | The objective of this study was to comparatively and experimentally evaluate the agronomic responses of two *Pennisetum* species, Cuba OM-22 (*Pennisetum purpureum* × *Pennisetum glaucum*) and Maralfalfa (*Pennisetum* sp.), to two application rates of dry goat manure (DGM; 20 and 40 t ha^{-1}) in the buffer zone of the Cerros de Amotape National Park (PNCAM), an equatorial dry forest ecosystem. The study took place during the low rainfall period in this equatorial dry forest environment. The following indicators were evaluated: soil characteristics, percentage of established plants at 30 days (%p), number of tillers per plant (m/p), and plant height (a/p) at 30, 60, and 90 days; final biomass production of green matter (GM) and dry matter (DM); and the nutritional value of the grasses at 90 days for protein (%P) and crude fiber (%CF). The best parameters for the Cuba OM-22 grass included %p and m/p DM, while the Maralfalfa grass showed m/p and a/p CF content, with a similar protein content (%P). Regarding fertilizer application rates, the best results were obtained with 40 t ha^{-1} (D3) for the soil chemical characteristics, %p, m/p, a/p, m/p, DM, and protein content (%P). Both pastures showed adequate adaptation to the improved environment created by the addition of goat manure in the buffer zone of PNCAM, which is characterized by dry forest conditions. The adaptability of both species to organic fertilization supports their use as tools to strengthen livestock production while contributing to the conservation of vulnerable ecosystems.

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Introduction

Equatorial dry forests are fragile areas susceptible to the loss of their floristic diversity due to rainfall and grazing. This loss of biodiversity is directly influenced by these factors, as grazing exerts significant pressure on native vegetation in ecologically fragile areas (Huaman *et al*., 2018). One alternative for protecting these areas is the incorporation of buffer. External zones that reduce risk and allow some anthropogenic productive activity. In the study area, buffer zone has been established. zone, but its effectiveness is usually limited due to the fragility of the ecosystem's characteristic of equatorial dry forests, such as the Cerros de Amotape National Park (Govierno, 1975).

Restrictive climatic conditions substantially reduce the natural supply of forage, increasing the risk of livestock encroachment into protected areas. Given that forage production in buffer conditions is affected, to reduce this pressure, there is a need to identify and propose adaptable forage species that can be cultivated with organic fertilizers, enabling clean agriculture and improving pasture availability in these areas (Washaya and Washaya, 2023) and reducing anthropogenic pressure on natural ecosystems. Forage grasses represent a primary feed resource for livestock systems, providing a substantial portion of forage year-round. Perennial grasses, particularly those of the genus *Pennisetum*, are highly effective. They have attracted attention for their high biomass production and adaptability to tropical and subtropical environments. Their genetic improvement and clonal selection significantly enhance forage yield and agronomic characteristics, positioning them as a strategic species in forage production (Surtina *et al*., 2019; Susumu *et al*., 2023). Its productivity and forage availability is affected by prolonged periods of drought throughout the year (Peña García *et al*., 2020).

Two valuable *Pennisetum* species have emerged as promising alternatives: Cuba OM-22, known for its high biomass yield, and Maralfalfa, recognized for its adaptability to varying environmental conditions and resilience under water-scarce conditions (Arrieta-González *et al*., 2024). However, the sustainable intensification of forage systems faces multiple limitations. One of the most pressing challenges is the limited availability of suitable arable land for pasture, which contributes to increased production costs, higher meat prices, and intensified grazing pressure in ecologically fragile areas (Huaman *et al*., 2018). Furthermore, the widespread use of synthetic fertilizers raises environmental and economic concerns, highlighting the need for more sustainable nutrient sources.

In this regard, organic fertilizers, particularly goat manure, available in the study area, have been identified as a viable alternative for improving soil fertility and pasture productivity. In agricultural systems with established goat production, an adult goat produces an average of 1.4 kg of manure per day, resulting in an estimated daily generation of approximately 200 kg of solid waste at the population level (Ananda *et al*., 2024). Although its use as an organic fertilizer has been relatively unexplored, goat manure has considerable agronomic potential (Julca-Otiniano *et al*., 2006), as it provides essential macro- and micronutrients, improves soil structure, enhances water retention, and contributes to long-term soil fertility (Surtina *et al*., 2019; Susumu *et al*., 2023). Furthermore, its application can be integrated into sustainable management strategies (anaerobic digestion), thus reducing dependence on chemical inputs (Washaya and Washaya, 2023).

The Cerros de Amotape National Park (PNCAM), located in northern Peru, encompasses two distinct ecoregions and harbors rich biodiversity. However, its buffer zone is increasingly affected by climate variability, agricultural expansion, and transhumant grazing (Govierno, 1975). Implementing sustainable land-use practices in these transition areas is essential for conserving biodiversity and maintaining ecosystem services. Incorporating organic amendments, such as goat manure, into forage systems in buffer zone could offer a double benefit: reducing environmental degradation and strengthening local livestock systems.

Smallholder livestock systems in ecologically sensitive regions face significant challenges related to forage availability and sustainability. Therefore, fertilization of *Pennisetum* grasses with goat manure, in addition to improving forage quality and availability in these areas, is fundamental for maintaining livestock productivity, particularly under adverse climatic conditions. This practice also reduces dependence on chemical inputs and contributes to sustainable development. Accordingly, the objective of this study was to evaluate the agronomic response of two

Pennisetum species, Cuba OM-22 and Maralfalfa, to two levels of goat manure application in the buffer zone of the Cerros de Amotape National Park.

Materials and Methods

Study area

The study was conducted in the buffer zone is part of the Cerros de Amotape National Park (PNCAM), located in the Tumbes region of northern Peru, characterized by an equatorial dry forest ecosystem. Fieldwork was conducted in the rural community of El Tablazo (04°05′10″ S, 81°09′38″ W). The climate is semi-arid tropical, with an average annual rainfall of 300 mm, concentrated mainly between January and March. The soil is sandy loam with moderate fertility. The site, located within a buffer zone was selected for its representativeness of the restrictive edaphoclimatic conditions of equatorial dry forests, which allows for the evaluation of the adaptation of forage species under organic fertilization strategies.

Experimental design and treatments

A completely randomized block design (CRBD) with a 2 x 3 factorial arrangement was used. The factors evaluated were: Two species of grasses (*Pennisetum* sp. Cuba OM-22 and *Pennisetum* sp. Maralfalfa) and three doses of dry goat manure (DM): D1 (control, 0 t ha^{-1}), D2 (20 t ha^{-1}) and D3 (40 t ha^{-1}). Each treatment had four replicates. The total experimental area was 1064 m^2, composed of 24 plots of 5 m x 7 m each (24 plots in total).

Crop establishment and management

The plant material (cuttings) was obtained from the agroecological garden of the PROCAP-INIA project. Planting was carried out manually using stem cuttings placed at a 45° angle and inserted to a depth of 5 cm. Goat manure was applied in two stages: at planting (50% of the dose) and 30 days later (the remaining 50%), distributing it evenly in the furrow. Irrigation was carried out by gravity every 15 days in furrows (0.3 m x 0.4 m) with a 3% slope and an approximate flow rate of 0.8 L/s per furrow. Weeding was done manually as needed (no herbicides or insecticides were applied during this period). Harvesting took place 90 days after planting.

Variables evaluated

Agronomic variables: Percentage of successful establishment (%p) at 30 days, evaluated as the number of live cuttings in relation to the total planted per plot. Plant height (a/p, in cm) and number of tillers per plant (m/p), measured in five randomly selected plants per plot at 30, 60 and 90 days (Peña García, 2020).

Biomass production: At 90 days, all aboveground biomass from 1 m^2 per plot was harvested. It was immediately weighed to obtain the green matter yield (DM, kg m^{-2}). A 250 g subsample was dried in a Memmert oven (model UN 30) at 105 °C for 48 hours to constant weight to determine the percentage of dry matter (%DM) and calculate the dry matter yield (DM, kg m^{-2}).

Nutritional analysis: In the dry subsample, crude protein content (%P) was determined using the micro-Kjeldahl method (N x 6.25) and crude fiber content (%CF) using the Weende method. The analyses were performed at the Animal Nutrition Laboratory of the National Agrarian University La Molina (UNALM).

Soil and manure analysis: At the beginning and end of the experiment, soil samples were taken from each treatment for physicochemical analysis (texture, pH, organic matter, electrical conductivity, phosphorus, potassium, CEC) at the UNALM Soil Laboratory. The goat manure used was characterized by the analysis of various parameters, such as pH, electrical conductivity, organic matter and the macronutrients N, P, K, Ca and Mg (Banayo *et al.*, 2012; Freire *et al.*, 2023).

Data analysis

Data were analyzed using two-way analysis of variance (ANOVA) to assess the effect of species, dose, and their interaction. When ANOVA showed significant differences ($P < 0.05$), means were compared using Tukey's test ($\alpha = 0.05$). All analyses were performed using SPSS software, version 25.0.

Results and Discussion

Initial characterization of the soil and manure

Soils with low rainfall typically have low organic matter content, which limits nutrient availability and forage productivity. In this study, the application of goat manure significantly improved soil fertility and directly enhanced the agronomic performance of *Pennisetum* species. The initial soil had a sandy loam texture, a slightly alkaline pH (7.52), low

organic matter content (1.02%), and a moderate cation exchange capacity (16.64 meq 100 g^{-1}), typical conditions associated with restricted plant growth (Banayo *et al.*, 2012; Freire *et al.*, 2023) in equatorial dry forest environments. In contrast, goat manure provided a high content of organic matter (42.07%) and nutrients, presented a pH of 8.5 and concentrations of 1.92% N, 0.67% P, 5.2% K, 5.2% Ca and 1.63% Mg, with a high electrical conductivity (11.66 dS/m) (Kurniawan *et al.*, 2022), which constitutes an effective organic amendment.

Post-harvest analyses revealed increases in soil organic matter (1.90%), available phosphorus (up to 54.9 ppm), exchangeable potassium (up to 540 ppm), and cation exchange capacity, particularly with higher application rates. These improvements were associated with better plant establishment, tillering, biomass accumulation, and dry matter yield of *Pennisetum*, with the strongest response observed with the 40tha^{-1} treatment. The improved soil nutritional status and water-holding capacity likely promoted root development and water-use efficiency (Bardhan et al., 2016), explaining the superior *Pennisetum* performance under dry forest conditions. Overall, the results confirm that goat manure application is directly related to restoring soil fertility and increasing forage productivity, supporting its use as a sustainable fertilization strategy in buffer zone of the equatorial dry forest.

The percentage of establishment (%p) at 30 days showed no statistically significant differences (P > 0.05) between the two grass species (Cuba OM-22: 90.81%; Maralfalfa: 89.68%). However, the dose factor was highly significant (P < 0.01). Treatments D2 (20 t ha^{-1}) and D3 (40 t ha^{-1}) showed significantly higher values (91.12% and 91.48%, respectively) in Maralfalfa (Mas *et al.*, 2021)and lower than the 72.5% reported by Blanco *et al.* (2018) in *Pennisetum purpureum*, compared to control D1 (88.14%) (Table 1 and Figure 1). This is consistent with previous studies that report an improvement in pasture establishment with the addition of goat organic matter (Leyva *et al.*, 2012), which improves the physical conditions and nutrient availability in the soil (Kurniawan *et al.*, 2022). This improvement is attributed to the fact that manure optimizes soil structure, increases moisture retention, and enhances the availability of essential nutrients (Leyva *et al.*, 2012; Kurniawan *et al.*, 2022), which are particularly crucial in dry forests where water stress is limiting. The high establishment stability observed in the Cuba OM-22 hybrid, along with its positive response to higher fertilization rates, reinforces its potential as an adaptable and resilient forage species under water-deficit conditions, supporting the use of organically fertilized *Pennisetum* in buffer zone is a functional strategy to increase forage availability, reduce overgrazing pressure and contribute to the conservation of core protected areas, thus promoting sustainable livestock farming aligned with conservation policies in fragile ecosystems such as the equatorial dry forest.

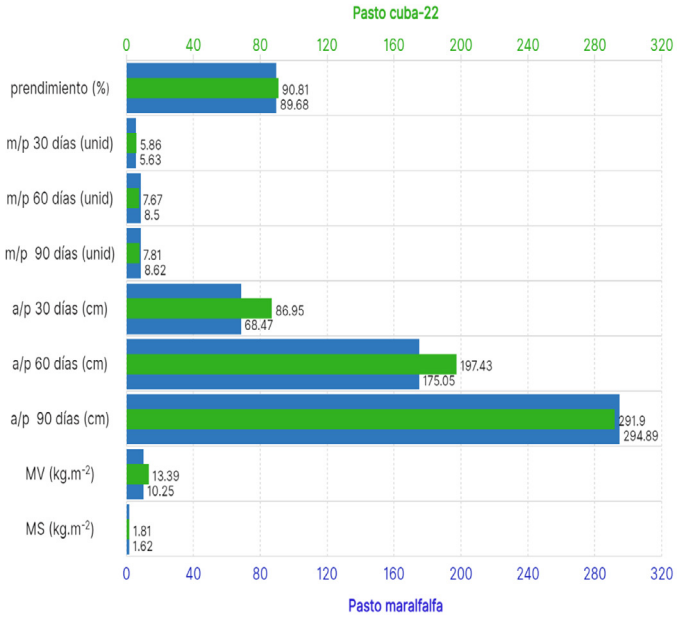

Figure 1: *Main comparative variables of Maralfalafa grass and Cuba OM-22 fertilized with three doses of goat manure.*

Number of tillers per plant (t/p)

As shown in Table 1, at 30 days, the number of tillers per plant responded according to the dose of organic fertilization and the time of evaluation, with a statistically significant dose effect at 30 days (P < 0.05) where treatment D3 (40 t ha^{-1}) showed the highest average (6.19 t/p), followed by D2 (6.05 t/p), both higher than the control D1 (5.00 t/p), evidencing an early positive response of tillering to the greater availability of nutrients and better soil conditions from the goat manure; however, at 60 and 90 days, the differences between treatments were not statistically significant (P > 0.05), suggesting that the effect of organic fertilization on tillering decreases as the crop cycle progresses in dry forest conditions, attributable to the increasing influence of limiting environmental factors such as water deficit. In the comparison of species at 90 days, Maralfalfa presented a higher

Table 1: *Main variables of Maralfalafa and Cuba OM-22 grass fertilized with three doses of goat manure.*

Term	%P	m/p 30 days	m/p 60 days	m/p 90 days	a/p 30 d days	a/p 60 days	a/p 90 d days	VM (kg.m^{-2})	DM (kg.m^{-2})
Block									
G. Maralfalfa	89.68a	5.63a	8.50a	8.62a	68.47b	175.05b	294.89a	10.25b	1.62b
G. Cuba OM-22	90.81a	5.86a	7.67a	7.81a	86.95a	197.43a	291.90	13.39a	1.81a
Treatment									
D1	88.14b	5.00b	7.76a	7.93a	73.09b	178.61b	286.76b	9.790b	1.32b
D2	91.12a	6.05a	8.10a	8.20a	78.13ab	184.84b	294.34a	12.050ab	1.79a
D3	91.48a	6.19a	8.39a	8.51a	81.91a	195.28a	299.09a	13.20a	2.03a

%p: Rooting percentage; m/p: Tiller per plant in units; a/p: Plant height in cm; VM: Green matter biomass kg.m^{-2}; DM: Dry matter biomass kg.m^{-2}.

average tiller count (8.62 t/p) than Cuba OM-22 (7.81 t/p), although this difference was not statistically significant (P > 0.05), both values being higher than those reported by Tinini and Limache (2017) under conventional management, but lower than the records of (Mas *et al*., 2021) for Maralfalfa in humid climates but higher than those reported by Pinchi-Carbajal *et al.* (2024) under comparable equatorial dry forest conditions, highlighting the marked environmental influence on tillering and confirming that organic fertilization stimulates this key biomass accumulation process (Maldonado-Peralta *et al*., 2019), although in equatorial dry forests this effect is modulated by seasonal water stress that limits the high sustained rates of tillering (Huaman *et al*., 2018), so the capacity of *Pennisetum*, particularly hybrids such as Cuba OM-22, to maintain stable tillering under organic fertilization and moderate water stress represents a strategic advantage for buffer zone, establish productive pastures to reduce grazing pressure in protected core areas, promoting sustainable livestock systems and the conservation of the dry forest through policies that favor organic fertilization and resilient pastures as productive and environmental management tools in fragile areas.

Floor height (a/p)

Plant height showed a significant interaction between species and manure dose at 60 days (P < 0.05), with dose D3 (40 t ha^{-1}) promoting the greatest heights throughout the cycle. By 90 days, there were no significant differences between species, with both reaching final heights close to 293 cm (Table 1). These values exceed those reported for Maralfalfa at 90 days (157–195 cm) by Maldonado-Quiñones *et al.* (2021) and align with the high phenotypic plasticity and rapid growth of *Pennisetum* under tropical conditions with non-limiting nutrients (Mas *et al*., 2021; Osorio *et al*., 2022; Arrieta-González *et al*., 2024), although they were lower than the heights reported under optimal irrigation and temperature (Pinchi-Carbajal *et al*. 2024), suggesting the moderating effect of water stress in the equatorial dry forest. The dose-dependent response is physiologically associated with the supply of nitrogen and other macronutrients from manure, which stimulate cell elongation and meristematic activity, a mechanism supported by studies that confirm that organic fertilization, alone or combined with amendments such as biochar, significantly increases *Pennisetum* height (Kurniawan *et al*., 2022). The heights achieved substantially exceed those obtained with mineral fertilization (NPK), reported between 96 and 176 cm for Maralfalfa (Vargas Linares, 2024; Blanco-Roa *et al*., 2025), and those of other organic sources such as biofertilizers and various manures (145 cm) (Carvalho *et al*., 2023), which demonstrates the superior effectiveness of goat manure in high doses to promote vegetative growth even under water scarcity conditions.

Biomass production of green matter (GM) and dry matter (DM)

As shown in Table 1, GM and DM production was significantly higher (P < 0.01) for Cuba OM-22 (13.39 and 1.81 kg m^{-2}, respectively) than for Maralfalfa (10.25 and 1.62 kg m^{-2}). Similarly, dose D3 produced the highest GM (13.20 kg m^{-2}) and DM (2.03 kg m^{-2}) yields, followed by D2 and D1 (Table 1 and Figure 1). There was no significant interaction between species and dose. DM yield with D3 (20.3 t ha^{-1}) was almost double that of the control D1 (13.2 t ha^{-1}). Significant differences were observed between species and dose (Pinchi-Carbajal *et al*., 2024). Yields exceeded those obtained without fertilization (Condori-Vargas *et*

al. 2018), with foliar fertilizer (Peña-García *et al*., 2020), in cold climates (Carvalho *et al*., 2023; Vargas Linares, 2024), and with NPK fertilization under arid conditions (Reyes-Pérez *et al*., 2021). However, they were lower than those reported under optimal conditions in Mexico (Arrieta-González *et al*., 2024) and of 11.3 t ha^{-1} per cut with 200 units of N at 56 days (Cerdas-Ramírez *et al*., 2021). Dry matter (DM) production was comparable to that observed in Maralfalfa during the dry season (Sari *et al*., 2021; Kurniawan *et al*., 2022; Arrieta-González *et al*., 2024) and similar to previous reports at 60 days (Mas *et al*., 2021). Agro-environmental factors such as climate and soil may have a greater influence than fertilization on final production (Condori-Vargas *et al*., 2018; Arrieta-González *et al*., 2024). These results confirm the effectiveness of goat manure as a nutrient source for increasing biomass production (Surtina *et al*., 2019; Susumu *et al*., 2023), comparable to or better than that reported with synthetic fertilizers in other studies (Reyes-Pérez *et al*., 2021; Kurniawan *et al*., 2022). The higher production of OM-22 in Cuba highlights its potential for systems that prioritize forage volume.

Nutritional composition and crude protein content (%P)

As shown in Table 2, crude protein content (%CP) did not differ significantly between species but showed a significant dose effect ($P < 0.05$), with doses D2 and D3 reaching the highest values (8.1–8.4%), consistently outperforming control D1 (7.4%), demonstrating a positive response of nitrogen metabolism to increased supply of organic nutrients; These values align with those reported for organic fertilization systems (Kurniawan *et al*., 2022; Watanabe-Escobedo *et al*., 2023) but are lower than the levels observed in early cuts (45–60 days) where protein can reach 14.6–16% in Maralfalfa (Tinini and Limache, 2017; Rupay *et al*., 2023; Barbera *et al*., 2025), corroborating the progressive decrease in protein associated with physiological maturity and tissue lignification (Maldonado-Méndez *et al*., 2024). Crude fiber content (%CF) showed greater variability, with the lowest values recorded in Cuba OM-22 under dose D3 (32.8%), suggesting a potentially better digestibility of the forage when combining hybrid genotypes with high organic fertilization; These values were lower than those reported for fibrous fractions in *Pennisetum* spp. (Tinini and Limache, 2017; Rupay *et al*., 2023; Barbera *et al*., 2025), indicating a relevant nutritional advantage. The percentage of dry matter (%DM) was significantly higher in Maralfalfa (average 15.72%) than in Cuba OM-22 (13.37%) and increased with the manure dose, reaching its maximum with D3 (15.08%); a higher %DM is associated with a greater accumulation of structural compounds and a consequent relative reduction in protein content (Fayos-Febrer *et al*., 2023; Pinchi-Carbajal *et al*., 2024), which explains the inverse relationship observed between %DM and %CP in higher dose treatments. The observed nutritional quality is closely linked to morpho-agronomic variables such as plant height and tillering, similar to King Grass (*P. purpureum* × *P. typhoides*) according to (Estrada *et al*., 2024), which determine both yield and forage composition. In tropical environments, these interactions have allowed for yields exceeding 200 t ha^{-1} per cutting in intensive systems (Maldonado-Peralta *et al*., 2019; Vimos *et al*., 2020); however, in fragile ecosystems such as the equatorial dry forest, optimizing the balance between quality and quantity is not well understood.

Table 2: *Composition of dry matter content (% DM), crude fiber (% CF) and protein (% P) of marafalfa grass and OM-22 cubed grass at cut.*

	G. Maralfalfa			G. Cuba OM-22		
Variable	**D1**	**D2**	**D3**	**D1**	**D2**	**D3**
Dry matter %	14.62	16.47	16.08	12.69	13.47	14.07
Crude fiber %	41.6	45.7	39.3	41.1	35.5	32.8
Protein %	7.3	8.2	8.2	7.4	8.4	8.1
Ash %	11.05	15.21	15.48	10.4	12.1	11.8

Producing forage with adequate levels of protein and fiber through fertilization helps reduce grazing pressure on native vegetation, thus protecting adjacent natural areas. Furthermore, the ability of both *Pennisetum* species to produce biomass with potential forage use expands their possibilities for integration into sustainable land management strategies. These results support the proposal of using these adapted grasses with local organic fertilization as tools to strengthen conservation, production, livestock resilience, and the preservation of vulnerable ecosystems.

Conclusion

The two forage species of the genus *Pennisetum* evaluated, Cuba OM-22 and Maralfalfa, showed adequate adaptation and a positive productive response to fertilization with goat manure under

tropical dry forest conditions in the buffer zone of the Cerros de Amotape National Park. A dose of 40 t ha^{-1} of goat manure was the most effective in improving most agronomic parameters, including seedling establishment, plant height, and number of tillers, as well as productive parameters such as green and dry matter yield, in addition to increasing forage protein content. Cuba OM-22 stood out for its higher biomass production, whereas Maralfalfa exhibited a greater number of tillers and higher dry matter content. The incorporation of goat manure also significantly improved soil fertility. Therefore, the use of this organic fertilizer represents a viable and sustainable strategy to enhance forage production in buffer zones of protected natural areas, potentially reducing overgrazing pressure and promoting livestock systems more compatible with ecosystem conservation. Longer-term studies are recommended to assess residual effects and to conduct evaluations across different seasons and with additional forage species.

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Novelty Statement

Ecosystems vulnerable to biodiversity loss due to low rainfall can be adapted to agricultural management involving grass species adapted to these conditions with organic fertilization, thus providing an alternative to reduce the pressure of overgrazing.

Author's Contribution

HRB and GOM: Conceptualization, methodology, research, writing (original draft).
AOZ, VTS, PFC: Methodology, formal analysis, revision, and editing.
JCO: Research, data curation.
HSS: Supervision, project management, fundraising, writing (revision and editing).
All authors read and approved the final manuscript.

Ethical approval
Not applicable.

Statement on generative AI and AI-assisted technology
The authors state that they did not use generative artificial intelligence for the production of tables or figures in the manuscript. The authors declare that they have used AI to improve the translation and writing of the manuscript.

Conflicts of interest
The authors have declared no conflict of interest.

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