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ATN/RF-20637-RG

Innovations for reduced methane emissions in ruminants

MINISTRY FOR
PRIMARY INDUSTRIES
(MPI) OF NEW
ZEALAND

GLOBAL RESEARCH
ALLIANCE ON
AGRICULTURAL
GREENHOUSE GASES
(GRA)

REGIONAL FUND FOR
AGRICULTURAL
TECHNOLOGY
(FONTAGRO)



**Te Kāwanatanga
o Aotearoa**
New Zealand Government



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GREENHOUSE GASES



FONTAGRO

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Abbreviations

AEO: Oregano essential oil

XGBoost: Extreme gradient boosting

RF: Random forest

IVDMD: In vitro dry matter digestibility

GHG: Greenhouse gases

LPM: Liters per minute

SVM: Support vector machines

CH₄: Methane

LR: Logistic regression models

PPM: Parts per million

MLP: Multilayer perceptron

1D-CNN: One-dimensional convolutional neural network

Executive Summary

In Latin America and the Caribbean, real-time assessment of key variables for animal efficiency in ruminants at the farm level, such as feed intake, ingestive behavior, digestibility, and enteric methane (CH₄) emissions under grazing conditions, faces significant limitations. These barriers hinder the implementation of effective management, feeding, and additive use strategies, impeding efforts to reduce CH₄ emissions and improve the competitiveness and sustainability of livestock farming in the region. This project directly addresses this gap by validating a package of innovations for the quantification and mitigation of GHG: a remote sensor system to CH₄ quantification and ingestive behavior monitoring, an anti-methanogenic feed additive, and fecal NIRS technology. During 2025, Component 1 involved developing a Python script that allows for the real-time visualization and analysis of all signals captured by the system and evaluating machine learning models of ingestive behavior labeling tests in grazing cattle. In Component 2, the additive formulation was optimized, reducing the carrier by 50% without modifying the dosage of the active ingredients, achieving methane reductions of 20–55% without compromising dry matter digestibility. In vivo validation was initiated at INTA Balcarce (Argentina) with Holstein calves receiving 5 g of the additive per day, with or without supplementation. Preliminary results indicate that supplementation with the additive does not affect feed intake or weight gain. In Component 3, the UV-Vis colorimetric method for quantifying titanium dioxide (TiO₂) in tropical forages and cattle and sheep feces was adapted and validated. In Component 4, nine events were carried over, training a total of 275 beneficiaries, of which 142 were men (51.7%) and 133 were women (48.3%). Two webinars were offered, with a total of 267 registered participants and 1,444 views. The AlimenTro virtual course was offered, strengthening the technical capacities in ruminant feeding and nutrition of 337 people, with a balanced participation by gender, with 45.4% women and 54.6% men. Additionally, the project strengthened human talent development through the completion of a master's thesis at the University of the Andes and the technical and scientific capabilities of the platform in two workshops. Finally, preliminary results of the project were presented at international scientific events in Colombia, Argentina, and Brazil.

FONTAGRO-MPI-GRA: Partnering for Innovation and Sustainability

We gratefully acknowledge the Ministry for Primary Industries (MPI) of New Zealand and the Global Research Alliance on Agricultural Greenhouse Gases (GRA) for their support of the project “Innovations for reduced methane emissions in ruminants (ATN/RF-20637-RG)”. Their contribution has been instrumental in advancing an integrated, field-oriented approach that tackles one of the key constraints for low-emissions livestock systems in Latin America and the Caribbean: the limited capacity for real-time, farm-level assessment of intake, ingestive behaviour, digestibility, and enteric methane emissions under grazing conditions. Over the reporting period, MPI–GRA support enabled tangible progress across complementary workstreams—remote sensing and data analytics for grazing cattle (including real-time signal visualization and machine-learning classification of ingestive behaviour), optimization and early in vivo validation of a phytogenic additive with promising mitigation performance, and strengthened analytical capability for intake/digestibility studies via adaptation and validation of a UV–Vis method for TiO_2 quantification as a marker. This support also reinforces the GRA’s mission to accelerate practical, science-based mitigation options through international collaboration and shared learning.

This project generates clear benefits for New Zealand by expanding transferable knowledge and tools that align closely with New Zealand’s priorities for reducing enteric methane from predominantly grazing ruminant systems. New Zealand is actively investing in methane mitigation options (including inhibitors and practical delivery strategies for grazing animals) and in the coordination of agricultural emissions research through national and international partnerships. In that context, the project’s advances in low-cost, real-time monitoring combining wearable/remote sensors, on-farm data capture and a real-time visualization pipeline, together with the high-accuracy machine-learning classification of ingestive behaviour are directly relevant to New Zealand’s push toward precision livestock tools that can support measurement, verification, and decision-making for emissions efficiency in grazing systems. Likewise, the additive workstream (showing substantial methane reductions in vitro and initiating in vivo validation without compromising intake or weight gain) contributes to the global evidence base on anti-methanogenic interventions and the practical questions that matter in New Zealand: efficacy under realistic feeding contexts, animal performance, and pathways for adoption. Finally, the TiO_2 analytical method development aimed at improving intake/digestibility estimation under grazing adds methodological value to research communities working on methane intensity and feed efficiency, strengthening the shared toolkit that New Zealand-supported research networks (including the GRA) rely on to compare results across countries and accelerate innovation.

I. Introduction

Cattle farming plays a strategic role in food security and rural development in Latin America and the Caribbean. However, it is also responsible for a significant proportion of anthropogenic methane (CH₄) emissions, a greenhouse gas (GHG) with a greater global warming potential than carbon dioxide (FAO, 2021). In this context, the sustainability of livestock systems in the region encounters a dual challenge: reducing their environmental impact while simultaneously maintaining or improving productivity and competitiveness of production systems.

One factor limiting progress toward more sustainable livestock systems in Latin America and the Caribbean is the low adoption of technologies aimed at increasing production efficiency without compromising the environment. This technological gap restricts the ability of these systems to optimize indicators such as feed efficiency, emissions intensity, and profitability, affecting their competitiveness compared to more technologically advanced systems in other regions (FAO, 2019). In particular, the adoption of innovative nutritional strategies and emissions measurement tools remains limited, partly due to a lack of robust local evidence, validation under real-world production conditions, and technical capacity for their implementation.

The validation and scaling up of cost-effective strategies for mitigating enteric CH₄, compatible with animal productivity and the conditions of tropical pasture systems, constitute a regional and global priority. Thus, the main objective of this project is to reduce the emission intensity (g of CO₂ equivalent/kg of beef) by 10% in grazing-based cattle production systems, through the implementation of technological innovations developed in Latin America for the quantification and mitigation of GHG.

The incorporation of technologies to measure CH₄ emissions, intake, and ingestive behavior of cattle in grazing systems, along with the use of phytogetic additives, will contribute to improving the sustainability and resilience of livestock farms against the impacts of climate change. The goal is to achieve a significant reduction in CH₄ emissions per animal, as well as a potential increase of up to 10% in daily weight gain (kg/day), driven by greater efficiency in the use of forage resources and the modulation of ruminal fermentation. Additionally, the project aims to improve the accuracy of CH₄ emissions quantification in Latin America compared to estimates derived from IPCC emission factors. This will enable a more accurate assessment of the environmental impact of livestock activity and help develop effective strategies for GHG mitigation. This report details the progress made in 2025 towards achieving this goal through four interconnected components: 1) Deploying a remote sensor system to monitor cattle behavior and CH₄ emissions; 2) Validating a novel phytogetic feed additive to reduce enteric CH₄; 3) Improving local equations for predicting feed intake and digestibility; and 4) Disseminating these innovations to the livestock sector.

II. Project Portfolio Execution and Results

Innovations for reduced methane emissions in ruminants (ATN/RF-20637-RG)

II.1 Objective

The objective of this proposal is to reduce by 10% the emission intensity (g of CO₂Eq/kg meat) in bovine production systems, through the implementation of technological innovations developed in Latin America for the quantification and mitigation of GHG.

II.2 Summary of Project Activities

The project is divided into four simultaneous components. The first consists of implementing a remote sensor-based system for monitoring ingestive behavior and quantifying enteric methane emissions in grazing cattle. The second component focuses on validating the mitigating effect of an additive under different feeding conditions in cattle. The third component aims to adjust local equations for the prediction of dry matter intake and digestibility in grazing cattle using fecal NIRS. Finally, the fourth component is dedicated to managing, communicating and transferring the knowledge generated (Table 1).

Table 1: Project components and activities.

Component	Activities	Results	Current Status
Component 1 Implement a remote sensor-based system for monitoring ingestive behavior and quantifying enteric methane emissions in grazing cattle	1.1. Design and implementation of a system based on remote sensors.	Product 1: Working document containing at least one article submitted to a national or international indexed journal.	In progress
		Product 2: Technical note on the electronic prototype with the complete design and plans for possible replicas.	In progress
	1.2. Evaluation of the system based on remote sensors in cattle.	Product 3: Monograph on the characterization of the ingestive behavior of Colombian Creole cattle under grazing conditions through the use of a system based on remote sensors, resulting from an undergraduate thesis.	In progress
		Product 4: Monograph on the quantification of enteric methane emissions in Colombian Creole cattle under grazing conditions using a remote sensing system, resulting from an undergraduate thesis.	In progress
		Product 5: Database on the ingestive behavior of cattle under grazing conditions in Colombia.	In progress

Component	Activities	Results	Current Status
Component 2 Validate the mitigating effect of an additive under different feeding conditions in cattle	2.1. Evaluation of the effect of the additive under different feeding conditions in Argentina.	Product 6: Working document containing at least one article submitted to a national or international indexed journal.	In progress
		Product 7: Database on enteric methane emissions from beef cattle under different feeding conditions.	In progress
	2.2. Evaluation of the effect of the additive under different supplementation conditions in Colombia.	Product 8: Working document containing at least one article submitted to a national or international indexed journal.	In progress
		Product 9: Technical note with feeding protocols for livestock production with lower GHG emissions.	In progress
Component 3 Fit local equations for the prediction of dry matter intake and digestibility in grazing cattle using fecal NIRS	3.1 Calibration of NIRS equations from feces for the prediction of dry matter intake and digestibility in beef cattle.	Product 10: Technical note on recommendations for fecal sampling to predict voluntary intake and dry matter digestibility of grazing cattle using NIRS.	In progress
		Product 11: Working document containing at least one article submitted to a national or international indexed journal.	In progress
	3.2 Compare methodologies for the quantification of titanium in feces.	Product 12: Technical note on the comparison and validation of methodologies for the quantification of titanium in feces.	In progress
Component 4 Manage, communicate and transfer the knowledge generated	4.1 Implement strategies for training and dissemination of technological innovations.	Product 13: At least 12 events held with the beneficiary population and reports of these.	In progress
		Product 14: Technical note containing the technical and scientific advances made through the platform's face-to-face and virtual meetings.	In progress
	4.2 Strengthen the technical-scientific capabilities of the platform.	Product 15: 20 students, teachers and researchers trained.	In progress

III. Project Implementation and Results

III.1 Component 1

The objective in this component was to implement a sensor-based system that can automatically record and analyze two critical parameters in grazing cattle: ingestive behavior (time spent grazing, ruminating, and resting) and enteric methane emissions. During the second year, a Python script was developed that allows for the real-time visualization and analysis of all signals captured by the system (Figure 1), facilitating comparison between laboratory tests and field measurements. Data is read via Bluetooth (laboratory tests) or LoRa long-range transient (field tests) from the ESP32-Thing Plus microcontroller (WROOM), which is responsible for data acquisition, processing, and transmission. A total of eleven trials of ingestive behavior labeling in grazing cattle were conducted at the El Nus and Tibaitatá research centers of AGROSAVIA (Figure 2).

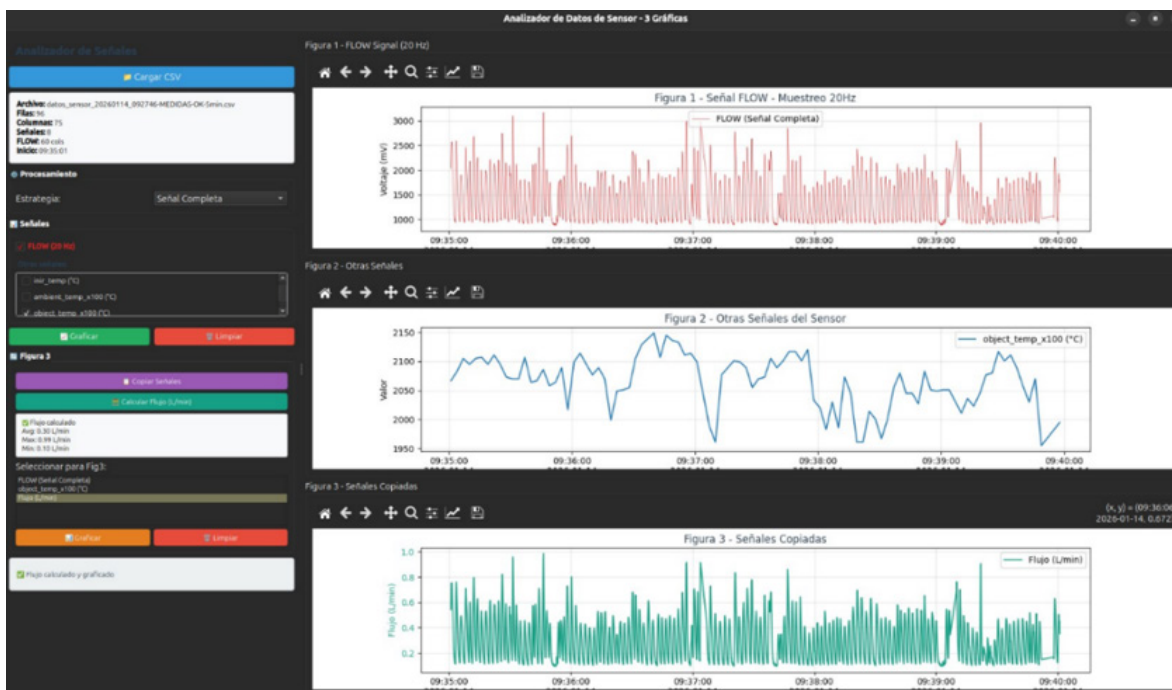


Figure 1. Real-time visualization and analysis interface of the signals captured by the remote sensor-based system for monitoring ingestive behavior and quantifying enteric methane emissions in grazing cattle.

Machine learning models such as logistic regression (LR), support vector machines (SVM), random forest (RF), extreme gradient augmentation (XGBoost), multilayer perceptron (MLP), and one-dimensional convolutional neural network (1D-CNN) were evaluated for the automatic identification of grazing, ruminating, and resting behaviors. All models showed accuracies greater than 90%. The LR model presented the lowest average accuracy among the evaluated models (90.69%), with a standard deviation of 0.93%. Conversely, the 1D-CNN presented the highest average accuracy (94.76%), although it also had the highest standard deviation (0.96%). XGBoost was the second most accurate model (93.91%), followed by RF (93.63%) and MLP (93.65%). The SVM showed an accuracy of 93.39% and the lowest standard deviation (0.54%). This is a crucial finding, as it suggests that highly accurate, real-time behavior monitoring on farms is achievable with existing technology.



Figure 2. Researchers labeling ingestive behavior in Blanco Orejinegro cattle on pasture carried out at the El Nus research center of AGROSAVIA. This process creates the essential data used to train artificial intelligence models for automated monitoring.

III.2 Component 2

The project is testing a novel dietary additive based on *Lippia origanoides*-Kunth essential oil and a yeast on enteric methane emissions and nutritional parameters in beef cattle. Initially, the additive formulation was optimized through in vitro fermentation and digestibility evaluations, maintaining the target dosage of the active ingredients and reducing the carrier by 50% to improve shipping and usage logistics. Thus, five treatments were evaluated in 0–48 h incubations with kikuyu grass (*Pennisetum clandestinum*) as a substrate, using the ANKOM RF® system: (i) inactivated native yeast (*Meyerozyma guilliermondii* Lev196) combined with 2.5% or 5% oregano essential oil (AEO), (ii) live commercial yeast (*Saccharomyces cerevisiae*, Yea-Sacc® 1026) combined with 2.5% AEO, (iii) commercial yeast alone, and (iv) a control without additive. Total gas production as milligrams of gas produced by gram of dry matter of the incubated Kikuyu grass substrate, accumulated CH₄, and in vitro dry matter digestibility (IVDMD, 48 h) were quantified. The gas kinetics were fitted using the Gompertz model (Figure 3). From a kinetic perspective, the additives shortened the lag phase and advanced the inflection point of gas production, without affecting the final asymptotic production, indicating a lower methanogenic intensity without a reduction in the extent of digestion. The blank treatments confirmed the adequacy and stability of the experimental system, as the fluid blank showed minimal gas production while the inoculum blank reflected the basal fermentative activity of the ruminal microbial consortium.

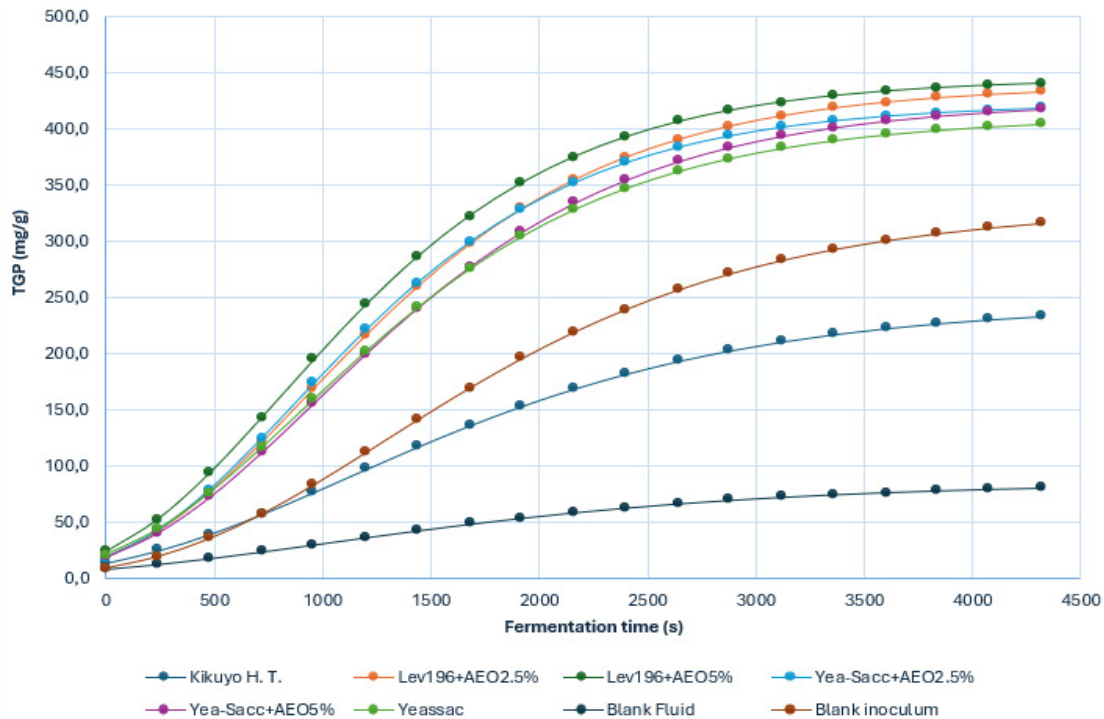


Figure 3. Total gas production (TGP) kinetics over 48 hours adjusted with the Gompertz model of Kikuyo forage (*Pennisetum clandestinum*) associated with the treatments: inactivated native yeast Lev196 (*Meyerozyma guilliermondii*) or live commercial yeast Yea-Sacc® (*Saccharomyces cerevisiae*) combined with oregano essential oil (AEO) at 2.5% or 5%. TGP is expressed as milligrams of total gas produced per gram of dry matter of the incubated grass substrate.

All additive treatments tended to reduced CH_4 production compared to the control, with reductions between 23% and 55%, without compromising digestibility (Table 2). The greatest mitigation (~55%) as a a lower CH_4 fraction in the total gas was observed with live commercial yeast (Yea-Sacc) + 2.5% AEO. The AEO dose was a determining factor: the 2.5% level outperformed the 5% level in the mitigation-fermentation balance, supporting the use of subinhibitory doses. The type and condition of the yeast also influenced the results, with live yeast showing a superior response compared to the inactivated native strain (Table 2). Reducing the carrier by 50% did not negatively impact fermentation or digestibility, with both 2.5% and 5% of AEO resulting in similar IVDMD and a marked reduction in CH_4 when using Yea-Sacc.

Table 2. *In vitro* dry matter digestibility (IVDMD) and total methane production at 48 hours of incubation of Kikuyo forage (*Pennisetum clandestinum*) associated with the treatments: inactivated native yeast Lev196 (*Meyerozyma guilliermondii*) or live commercial yeast Yea-Sacc® (*Saccharomyces cerevisiae*) combined with oregano essential oil (AEO) at 2.5% or 5%. Letters *ab* indicate significant differences ($p < 0.05$) between treatments (*a > b*).

Treatment	IVDMD (%)	CH_4 (mg/48 h)
Control	47.5 b	4.784
Lev196 + AEO 2,5%	50.5 ab	3.661
Lev196 + AEO 5%	52.5 ab	4.375
Yea-Sacc + AEO 2,5%	54.5 ab	2.178
Yea-Sacc + AEO 5%	54.8 a	2.660
Yea-Sacc	59.4 b	3.408
p-value	0.021	0.101

The first *in vivo* trial to validate the anti-methanogenic effect of the additive AEO 5% and *Saccharomyces cerevisiae* was conducted at INTA Balcarce (Argentina) between September and December. Twelve six-month-old Holstein calves (Figure 4) were fed a 50:50 forage: concentrate diet and assigned to two treatments: Control (no additive) and Additive (5 g/day). Methane production was measured in open-circuit respiration chambers for 48 h before (day 0), and at 21 and 42 days of supplementation. Live weight was recorded weekly, and dry matter intake was determined by the difference between offered and refused feed. Preliminary results show similar weight gains between groups (764 ± 159 vs. 748 ± 132 g/d as mean and standard deviation for Control and Additive, respectively), indicating that the inclusion of the additive does not compromise productive performance.



Figure 4. Holstein calves in the *in vivo* validation trial of the anti-methanogenic additive AEO 5% and *Saccharomyces cerevisiae* in the methane laboratory of INTA Balcarce (Buenos Aires, Argentina).

III.3 Component 3

To know with confidence whether our strategies for reducing emissions are working, we must be able to accurately measure how much feed an animal consumes and how efficiently it digests that feed while out on pasture. This component focuses on fit local equations for the prediction of dry matter intake and digestibility in grazing cattle using fecal NIRS and improving a standard laboratory technique that uses titanium dioxide (TiO_2) as indigestible marker to estimate these parameters. In the advancements of this component, the UV-Vis colorimetric method based on the formation of the peroxo-titanium complex (Myers et al., 2004) was adapted and validated to quantify titanium dioxide (TiO_2) in tropical forages and cattle and sheep feces. Samples, obtained from trials conducted at C.I. Tibaitatá and C.I. Nus (Colombia) and INTA (Argentina), were dried, ground (<1 mm), and subjected to acid digestion with H_2SO_4 and $(\text{NH}_4)_2\text{SO}_4$, followed by oxidation with H_2O_2 . Spectrophotometric readings were performed at 396 nm, applying blank correction and confirming endogenous Ti contents <0.005% DM. Internal analytical validation was performed according to international guidelines ICH (2022), AOAC (2016), and Eurachem (2014) and included the evaluation of linearity, sensitivity, precision, accuracy, selectivity, trueness, uncertainty, and robustness. A summary of the main analytical performance parameters of the method is presented in Table 3.

Table 3. Analytical performance parameters of the UV-Vis colorimetric method for the quantification of TiO₂ in forages and feces.

Parameter	Results	Interpretation / relevance
Analytical principle	Formation of the peroxy–titanium complex (UV–Vis)	Method widely reported for TiO ₂ as a marker
Optimal wavelength	396 nm (plateau 394–396 nm; variation <0.2%)	Stable reading; low sensitivity to small variations
Development time	≥ 5 min (variation <1% between 5–10 min)	Stable signal (variation <1% between 5–10 min)
Recommended linear range	5–70 µg/mL	Operational range for routine quantification
Linearity (R²)	≥ 0.998	Excellent linear fit within the working range
Limit of detection (LOD)	3 µg/mL (adopted)	Adequate for complex matrices
Limit of quantification (LOQ)	10 µg/mL (adopted)	Reliable quantification under routine conditions
Intra-day precision (RSD)	≤ 5% (higher variability near the LOQ)	Good method repeatability
Accuracy – medium/high levels	70–85% de recovery	Acceptable for intake and digestibility studies
Accuracy – low levels	< 15% de recovery	Marked underestimation; method limitation
Selectivity	Adequate under simple conditions; interference in complex matrices	Requires matrix control
Trueness (bias)	Not significant	Results consistent with reference values
Expanded uncertainty (U, k=2)	≈ 0.058 mg/L	Dominated by reproducibility
Robustness	No relevant effects (±2 nm, ±10% H ₂ O ₂ , digestion 90–120 min)	Method stable against minor variations
Applicability	Forages and feces with TiO ₂ at medium–high levels	Suitable for routine use within the project context
Limitations	Underestimation at low concentrations	Requires optimization of digestion/oxidation
Recommendations	Spiked samples per run and verification with ICP-OES	Improved accuracy and quality control

Calibration curves were constructed across different concentration ranges, revealing highly linear behavior in the 5–70 µg/mL range, which was defined as the recommended operating range. The reporting limits adopted were LOD = 3 µg/mL and LOQ = 10 µg/mL, conservative values suitable for complex matrices such as forage and feces. Intra-day precision was satisfactory, with coefficients of variation generally ≤5%, although with greater variability at concentrations near the LOQ. The robustness of the method was confirmed against small, controlled variations in wavelength (±2 nm), H₂O₂ volume (±10%), and digestion time, without significant effects on the results.

The accuracy was assessed through recoveries in fortified samples and showed a performance dependent on the TiO₂ level. At medium and high concentrations (≈200–500 mg/kg DM), recoveries were moderate to acceptable (70–85%), while at low levels (≤100 mg/kg DM) a marked underestimation was observed, mainly attributable to matrix effects and incomplete digestion or oxidation. Selectivity was adequate under simple conditions, although significant interference was identified in more complex matrix scenarios. Overall accuracy was acceptable, and the expanded uncertainty (U, k = 2) was dominated by the method's reproducibility.

The UV-Vis colorimetric method is linear, accurate, robust, and operationally suitable for routine TiO₂ analysis in forages and feces when working within medium-to-high ranges of interest, typical of intake and digestibility studies in ruminants. However, accuracy limitations are identified at low levels, so it is recommended to optimize digestion and oxidation, include fortified samples in each analytical run, and perform selective verifications using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES).

III.4 Component 4

The ultimate success and legacy of this project will be measured by its impact on the ground—in the daily practices of livestock producers and the skills of the next generation of scientists. This component is dedicated to ensuring that the knowledge and technologies we develop do not remain within academic circles but are actively transferred to those who can apply them. In the area of dissemination and training during 2025, nine in-person events were held in different municipalities of Antioquia (San Roque, San Pedro de Los Milagros and Puerto Berrio) and Cundinamarca (Tenjo). These events covered training workshops on topics related to grazing management, supplementation, the use of additives in cattle diets, good livestock practices (GLP) and herd health (Figure 5), training a total of 275 beneficiaries, of which 142 were men (51.7%) and 133 were women (48.3%).

Additionally, as part of the dissemination and knowledge transfer activities, the AlimenTro virtual course (<https://fontagro.org/es/proyectos/rumiantes/novedades/curso-virtual-alimentro-impulsa-decisiones-inteligentes-en-la-alimentacion-de-rumiantes>) was offered, aimed at strengthening technical capacities in animal feeding and nutrition. A total of 337 people were trained in this course, with balanced participation by gender, at 45.4% women and 54.6% men.



Figure 5. Training in good livestock practices (GLP) and herd health at the El Nus Research Center of AGROSAVIA. These face-to-face events are crucial for building trust, demonstrating new technologies, and ensuring that project findings are directly transferred to the farming community.

Two webinars were held and broadcast via AGROSAVIA's YouTube channel. The first webinar focused on pasture management in beef cattle farming in different regions of Argentina, Colombia, and Brazil and its impact on enteric methane emissions (<https://www.youtube.com/watch?v=2FSq9HulcXw>). It had 120 registered participants and has accumulated a total of 668 views. On the other hand, the second webinar, "From Pasture to Rumen: Improving Ruminant Productive Performance Through Consumption" (<https://www.youtube.com/watch?v=nrfNqSq1oSE&t=2s>), had 147 registered participants and has accumulated 776 views. Participation included agricultural producers (16%), students and apprentices (18%), teachers and instructors (24%), extension agents and technical assistants (18%), and researchers, private companies, and government entities in the sector (24%), demonstrating the multisectoral reach of

the dissemination activities and the potential for transferring and appropriating the knowledge generated within production systems.

As part of strengthening the platform's technical and scientific capacities, two workshops were held: 1) the "Virtual Workshop on Reviewing In Vitro Methods to Determine Digestibility and Methanogenic Potential in Ruminants," which fostered scientific collaboration and strengthened the capacities of 21 researchers from the INTA (5), AGROSAVIA (15), and UNC (1) teams, with high participation from women (61%). 2) The "Face-to-face Training Workshop on Remote Monitoring of Ingestive Behavior in Grazing Cattle" allowed strengthening the capacities of six members of the AGROSAVIA team and two from the University of the Andes (Figure 6).



Figure 6. Practice during the training workshop on remote monitoring of ingestive behavior in grazing cattle between Agrosavia and Universidad de Los Andes. These collaborative sessions are vital for building technical expertise and ensuring the long-term sustainability of the project's innovations.

Three presentations were made at scientific events in Colombia, Argentina, and Brazil: In April, partial results of the study "Perceptions of the use of additives for climate change mitigation in livestock farms of the Middle Magdalena region of Antioquia" were presented at the "International Congress on Ruminant Production in the Tropics – CONRUMINT" in Villavicencio, Colombia. In September, progress on the project was presented at the "XI Integrated Research, Extension, and Teaching Conference of the Faculty of Agricultural Sciences of the National University of Córdoba" in Córdoba, Argentina. Finally, in November, the work "Machine learning models to classify the ingestive behavior of grazing cattle" was presented at the "XIX Northeastern Congress of Animal Production" in Maceió, Brazil.

Finally, a master's thesis was developed at the University of Los Andes focused on the "Implementation of remote sensors for monitoring ingestive behavior in grazing cattle" (Minú Quiroga, 2025), within the framework of the activities of Component 1.

IV. Conclusions

Significant progress has been made across all four components of the project, with particular emphasis on the creation of a real-time visualization and analysis interface for all signals captured by the remote sensor-based system for monitoring ingestive behavior and enteric methane emissions in cattle. Significant advances have also been made in validating the anti-methanogenic potential of the additive in vitro and in vivo. Preliminary results indicate no negative effects on feed intake and productive performance, ensuring the zootechnical viability of the approach while generating robust emissions data under standardized protocols. Validation of a uv-vis colorimetric method for quantifying TiO₂ as a marker has also been achieved, demonstrating high linearity, precision, and robustness for routine applications in complex matrices such as forages and feces. Despite limitations in accuracy at very low concentrations, the method proved suitable for the ranges of interest in digestibility and feed efficiency studies, with recommendations for optimization and cross-verification using instrumental techniques (ICP-OES). Finally, the project has made a significant contribution to human talent development, international cooperation and knowledge transfer, through face-to-face and virtual activities.

V. Digital Links

Project's web site: <https://fontagro.org/en/proyectos/rumiantes>

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