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TABLA DE CONTENIDO

EDITORIAL

La Revista Ingeniería, Investigación y Desarrollo publicada desde el año 2005 por la Universidad Pedagógica y Tecnológica de Colombia, es una revista orientada a la divulgación de resultados de investigación, reflexión y revisión, enfocados en las áreas de ingeniería y tecnología. Aunque han pasado más de 15 años desde su primer volumen, a los lectores les sorprenderá que la esencia de la revista se ha mantenido constante en el tiempo ofreciendo contenidos inéditos de alta calidad, en un lenguaje que invita a todos los miembros de la comunidad académica y científica a contribuir en el progreso de la ciencia. Somos conscientes que los grandes avances en la ciencia han sido guiados por la curiosidad y el deseo de alcanzar una verdad objetiva, no obstante, la extensión de la investigación más allá de un ámbito académico amplía el impacto de nuevos descubrimientos y su aplicación en la solución de problemas acuciantes para la sociedad actual. De esta forma, es importante continuar planteando estrategias para que la ciencia sea más abierta e integradora, situando más contenidos técnicos a disposición del público general que promuevan conversaciones interdisciplinarias que logren atraer las futuras generaciones de científicos.

En esta oportunidad, como editor invitado es un gran honor presentar el primer volumen del año 2023, en el cuál se ha dado prioridad a siete artículos de investigación que reúnen los resultados de profesionales provenientes de Colombia, Venezuela, Cuba, Ecuador, México y Estados Unidos. El primero de los artículos titulado "*Increased efficiency in massive transport systems by programming speed profiles between segments*", se estudia el consumo específico de energía eléctrica en sistemas masivos de transporte con el fin de facilitar la identificación de proyectos que incrementen la eficiencia energética. En seguida, el trabajo "*On the correction of dose profile discrepancies by introducing air in the derivation of an electron spectrum*" presenta una simulación de dosis monoenergéticas del espectro de energía para ampliar el conocimiento en radioterapia. Por otro lado, el artículo titulado "*Geochemical evaluation of crude oils in the Llanos Orientales basin*" muestra la evaluación geoquímica de crudos para relacionar compuestos del petróleo y definir los ambientes de depósito en la cuenca más rica en hidrocarburos de Colombia. En cuarto lugar, se encuentra el trabajo titulado "*Naringinase immobilized on modified banana peel with potential application in the citrus industry*" el cual propone la modificación química y térmica de cáscara de banano para inmovilizar la enzima comercial naringinasa *Penicillum Decumbens* como aplicación en la industria alimentaria. En el artículo "*Reliability analysis for a feeder of an electric power distribution company in Ecuador using the Monte Carlo simulation method*" los autores enfocan sus esfuerzos en estudiar índices de confiabilidad de un alimentador perteneciente a una compañía de energía en Ecuador mediante simulación Montecarlo, presentando un análisis de vital importancia para la toma de decisiones. Seguido del trabajo "*Methodology for sustainability analysis for the energy sector: the case of LPG as replacement for firewood in rural households in Colombia*" en el cuál se presenta una metodología de análisis de sostenibilidad del sector energético. Por último, la investigación titulada "*Characterization of meliponiculture in the province of Cienfuegos, Cuba*" caracteriza el sistema de manejo y estado de salud de colmenas de abejas sin aguijón *Melipona beecheii*, una investigación enfocada a promover el desarrollo vital de la especie.

Esperamos que este primer volumen sea del completo agrado y cumpla las expectativas de los lectores. Agradezco sinceramente al equipo editorial de la revista, colegas y demás participantes que hicieron posible el desarrollo de este trabajo.

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Editor invitado

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INCREASED EFFICIENCY IN MASSIVE TRANSPORT SYSTEMS BY PROGRAMMING SPEED PROFILES BETWEEN SEGMENTS

Aumento de eficiencia en sistemas masivos de transporte mediante programación de perfiles de velocidad entre tramos

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Abstract

This study aimed to estimate the specific energy consumption in massive metro-type transport systems, with the aim of guiding the identification of projects aimed at increasing energy efficiency. To achieve the above purposes, this research focused on the estimation, through a software application, of the specific consumption of electrical energy. Results of simulations carried out with an application developed in MATLAB, to generate speed profiles in the operation of the train, allow to observe the sensitivity of the specific consumption of electrical energy to changes made in the cruising speed and in the acceleration and deceleration ramps. The results show that the specific consumptions depend to a large extent on the speed profiles and the operation of the metro, which opens an interesting field of application of optimization techniques aimed at the efficient use of energy.

Key words: *acceleration, cruising speed, energy consumption, metro system, specific energy.*

Resumen

Este estudio tuvo como objetivo estimar el consumo específico de energía en sistemas masivos de transporte tipo metro, con el objetivo de orientar la identificación de proyectos tendientes a incrementar la eficiencia energética. Para lograr los propósitos anteriores, esta investigación se centró en la estimación, a través de una aplicación de software, del consumo específico de energía eléctrica. Resultados de simulaciones realizadas con una aplicación desarrollada en Matlab, para generar perfiles de velocidad en la operación del tren, permiten observar la sensibilidad del consumo específico de energía eléctrica ante cambios realizados en la velocidad de crucero y en las rampas de aceleración y desaceleración. Los resultados muestran que los consumos específicos dependen en gran medida de los perfiles de velocidad y del funcionamiento del metro, lo que abre un interesante campo de aplicación de técnicas de optimización orientadas al uso eficiente de la energía.

Palabras clave: *aceleración, consumo de energía, energía específica, sistema metro, velocidad de crucero.*

1. INTRODUCTION

Subway-type mass transportation systems represent a large load on the distribution circuits of cities and are large consumers of electrical energy, thus constituting important systems when identifying potential opportunities for savings and improvements in the efficient use of energy. A key indicator in energy efficiency is the so-called specific energy consumption (energy per unit of production), which can be established as a benchmark in monitoring projects associated with increased efficiency and productivity and finds application in studies and analyses comparing energy consumption per unit of production between different companies, entities, systems, and modes of transport, etc. The specific consumption indicator is well known by energy managers and is very often used in industrial manufacturing and continuous flow companies, but it is little used in other activities such as mass transportation systems that use electrical energy as an input. Difficulties of various kinds such as the lack of knowledge of the "production unit" of these systems and the difficulty in identifying the variables that have the greatest influence on energy consumption hinder its use, thus causing a problem that prevents, among other things, having reliable benchmarks and comparisons for the proper integrated management of energy.

This paper focuses on the computation of the specific electrical energy consumption of Metro-type systems. The central focus of interest is the energy consumed by the traction subsystem (subsystem responsible for the movement of the train), which represents between 40 and 80 percent of the total energy consumed by these mass transit systems. The approach in estimating the specific energy consumption is carried out considering key mechanical variables in the operation, such as acceleration and deceleration speeds and the stationary or cruising speed in each of the sections that constitute a Metro-type system. A crucial aspect that has emerged in recent years, due to pressure from environmental groups, has to do with the introduction of technological innovations that tend to reduce energy using regenerative braking in deceleration. It is worth mentioning that potentials of up to 50 percent of the energy generated in braking could be returned to the electric power distribution system.

In the calculation of the energy required by a metro-type system, the determination of the traction force to produce the movement is key and this is a function of mechanical variables such as the weight of the train, the number of passengers, the average weight of the passengers and the instantaneous speed.

Internationally, and over several decades, sufficient experience and knowledge has been acquired to determine the traction force required in railway systems, so much so that there is a reliable equation (modified Davis equation) for calculating the instantaneous traction force. Once the instantaneous force is available, the next step is the calculation of the instantaneous power and then its integration over time to quantify the total energy for a complete run of a certain length. Knowing the total energy and the length, the specific energy consumption indicator can be determined, which has units of electrical energy per unit length for each train. This indicator is different, depending on the number of users being transported.

A first work that can be mentioned, related to energy efficiency in metro-type mass transit systems [1], addresses the reduction of energy consumption from the point of view of the system as a whole and considers measures aimed at improving the operation and implementation of technologies. The paper concludes that there are several measures that have proven to be successful and that a key aspect in the implementation of these measures is the continuous monitoring of the proxy indicators that are identified. The research work of [2], focuses on an analysis of energy consumption and time spent per route between stations of metro-type systems, considering two modes of operation. The work identifies an interesting potential for energy savings by introducing improvements in route operation; however, it does not focus on monitoring indicators to observe improvements (decreases in energy consumption) in the savings achieved.

The work of [3] examines various cost estimation methodologies and develops functions involving specific energy consumptions for regional rail transportation systems with different fuels (gasoline, gas, electricity). The work presents a specific reference consumption for regional trains, which varies between 3.5 and 5.5 kWh/(km*train) at the European level; unfortunately, the focus of the study is on regional trains and not on metro-type mass transit systems.

In the work of [4], the fundamental interest is the reduction of energy consumption using automatic operation systems that select, on-line, speed profiles within a preset set of optimized profiles. In the paper they propose the design of an automatic operation system with preset profiles considering the energy recovered with regenerative braking to reduce the consumption of energy extracted from the substations that feed the Metro system. The work is based on a case study of line 3 of Metro de Madrid (17 stations, with a total of 13.5 km in each direction), line in which average values of energy consumed in traction and energy recovered with regenerative braking are obtained by numerical simulation. Average values of 12.91 kWh/(km*train) are reached for the specific traction energy and 3.69 kWh/(km*train) for the specific energy returned to the network by regenerative braking. With the above values, and with several scenarios defined, optimized profiles are proposed, and energy savings are estimated.

Three things can be said about the work that has been developed. On the one hand, traction energy can be managed to make efficient use of it. On the other hand, the studies also establish the recommendation to identify key indicators for monitoring and follow-up in energy reduction projects. As key indicators, cost functions and specific consumption indicators are available as tools for planning and public policy decisions.

This paper is organized as follows: In a first part, a characterization of the energy consumption of a system of this nature is made and some reference consumptions of some metros in the world are mentioned. The work continues with the establishment of the theoretical framework related to energy consumption. Then, in the third session, the methodology is presented, including the description of a developed software application and the description of an operation scenario to determine the specific consumption. In the final part, the results obtained are presented and analyzed and the most important conclusions of the work are drawn.

2. CHARACTERIZATION OF CONSUMPTION

Electrical energy consumption in a metro-type system is basically divided into three items corresponding to consumption for auxiliary services, energy for traction itself and energy for regenerative braking, although the latter is returned to the system's power supply network by regenerative braking.

The energy consumption for traction represents between 50 percent and 70 percent of the total energy consumed by the system [5-6], hence the importance of analyzing this energy with the importance of analyzing this energy with the aim of to establish reliable monitoring indicators in the operation and identify potential savings, increase efficiency, and reduce the emission of pollutants into the environment. To be a little more precise in the discrimination of consumption, Table 1 shows some examples of consumption for various metro systems in the world [5, 7-10].

The energy consumption of a subway system depends on many variables, among which are the instantaneous speed, the weight of the cars, the number of axles, the average weight of the passengers, the acceleration, the deceleration during braking, and the slope of the track.

An inquiry of the specific consumptions (energy consumption per unit of travel length) calculated or obtained through simulations, except for the Medellín, Washington and Valencia subways, various subways around the world are shown in Table 2.

Table 1. Typical discrimination of energy consumption in a metro-type system.

Subway	Line	Energy for auxiliaries [%]	Energy for braking [%]	Energy for traction [%]
Madrid [7]	10	14	22	64
n.a. [10]	n.a.	20	33	47
Beijing [8]	Yizhuang	15	30	55
Beijing [5]	Yizhuang	20	33	47

Table 2. Specific energy in some subways around the world.

Subway	Line	Length [km]	Specific energy [kWh/km*tren]
Madrid [7]	10	23	14.22
Madrid [7]	3	16.4	12.91
Medellín [9]	A	25.6	9.18 (measured)
Beijing [8]	Yizhuang	22.73	11.35 (empty)
Beijing [8]	Yizhuang	22.73	31.2 (service)
Portland [10]	MAX Blue	53	10.6
Chicago [10]	Orange	21	31.42
Chicago [10]	Brown	18.3	25.82
Washington [6]	All lines	171	26.5 (measured)
Valencia [11]	7	15.45	31.95 (measured)
Valencia [11]	7	15.45	32.68
Bangkok [12]	BTS Silom	14.67	20.37

3. ENERGY CONSUMPTION MODEL

The model for energy determination includes the electromechanical variables with which both the energy consumed, and the energy returned to the distribution system can be calculated [13]. Equation (1) quantifies the positive (consumed) energy, EC(t), when the train is in traction mode; that is, when energy flows from the distribution system to the train. On the other hand, when the train is in the regenerative braking (deceleration) mode [14], the energy, ECre(t), flows from the train to the distribution system, is quantified by equation (2) and is considered negative.

$$EC(t)=\begin{Bmatrix}\alpha_1*\beta_1+\alpha_2*\beta_2+P(t),\forall P(t)>0\\(\alpha_1*\beta_1+\alpha_2*\beta_2),\forall P(t)\quad<0\end{Bmatrix} \quad (1)$$

Where:

EC(t): Instantaneous energy consumed with train in motion, [kWh].

P(t): Instantaneous traction power with train in motion, [kW].

α_1 : Headend power, [kW].

α_2 : Fraction of head-end power (kW) (suggested value: 0.05).

β_1 : Dummy logic variable.

β_2 : Dummy logic variable.

The terms in equation (1): $\alpha_1 * \beta_1$ y $\alpha_2 * \beta_2$ are related to the maximum system load. The constants β_1 y β_2 are logical values that can take the values of 0 and 1. The value of 1 applies in the larger case with β_1=1, and β_2=0, except when the train is stopped waiting for passengers,

at which time a fraction of energy must be considered. Equation (2) allows calculating the energy returned to the system and makes sense when the train is braking. For the case of the efficiency with which this energy is returned, a factor must be applied that can be calculated with equation (3) or obtained from Figure 1.

$$ECre(t)=\begin{Bmatrix} P(t)*\eta(t), \forall P(t)<0 \\ 0, \forall P(t)\geq 0 \end{Bmatrix} \quad (2)$$

Where:

ECre(t): instantaneous energy returned to the grid by regenerative braking, [kWh].

η*(t)*: instantaneous regenerative efficiency coefficient.

$$\eta(t)=\begin{Bmatrix} \frac{1}{\frac{\alpha}{e^{|\alpha(t)|}}}, \forall \alpha(t)<0 \\ 0, \forall \alpha(t)>0 \end{Bmatrix} \quad (3)$$

Where:

α: Model calibration parameter (0.65).

α(t): Instantaneous deceleration during braking, [m/s2].

The specific energy during travel in one direction is the sum of the two energies divided by the distance, as shown in equation (4), where the distance, d, is in km.

$$ECtot_{[kWh/tren*km]}=\sum[EC(t)+ECre(t)]/d \quad (4)$$

Where:

ECtot: Average specific energy consumed in a trip per unit distance, [kWh/(train*km)].

d: Length traveled by the train in the whole driving cycle, [km].

$$F(t)=\left[\left(0.6+\frac{20}{W_p}+0.01V(t)+\frac{K*V^2(t)}{W_p*n_p}+C\right)+D\right]*4.44*M \quad (5)$$

Where:

F(t): Instantaneous traction force, [N].

W_p: Train axle load with passengers (75kg/passenger), [ton].

n_p: Number of axles of the train.

K: Drag coefficient (0.65).

V(t): Speed at instant t, [km/h].

M: Total weight of the train including passengers, [ton].

$$C=20*\theta \quad (6)$$

Where:

θ: Track slope, [%].

$$D=70*\left(\frac{V^2(t)-V^2(t-1)}{8.4*L}\right) \quad (7)$$

Where:

L: Distance traveled by the train in one second, [m].

$$P(t)=0.746*F(t)*V(t)/(375*1.61) \quad (8)$$

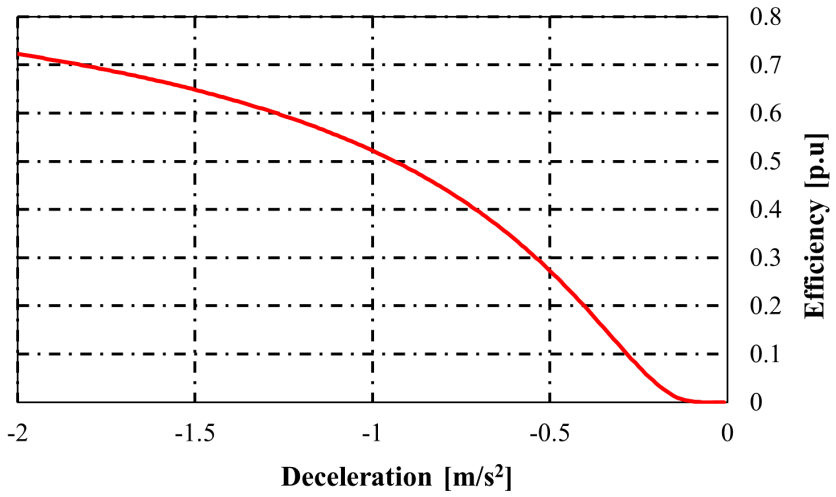

Figure 1. Energy regeneration efficiency depending on deceleration. **Source:** author, 2023.

4. CALCULATION OF SPECIFIC CONSUMPTION

To estimate the electrical energy consumption per unit of distance and per vehicle, a software application was developed in MATLAB to generate speed profiles, as shown in Figure 2.

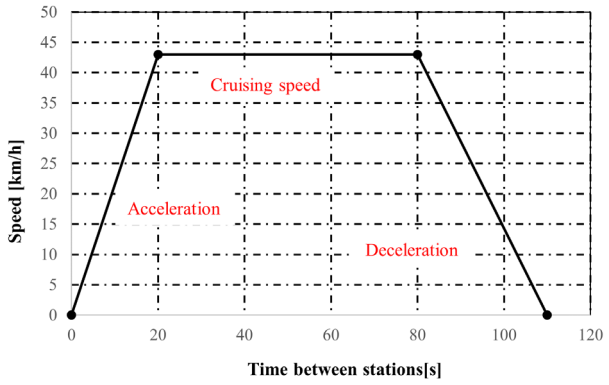

Figure 2. Typical speed profile in a section of a subway type system. **Source:** author, 2023.

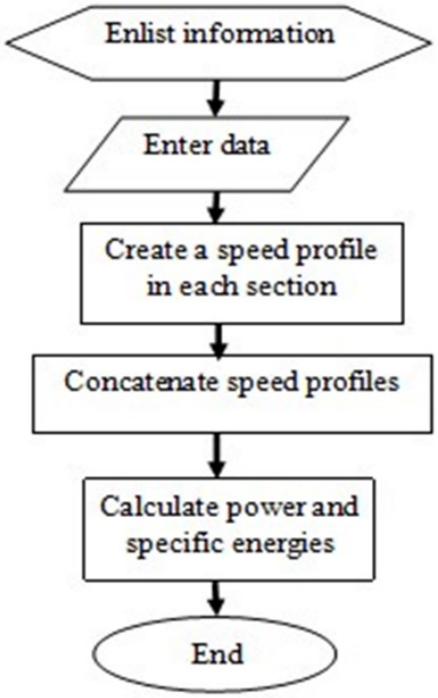

Figure 3. Algorithm flow diagram for calculation of specific energies. **Source:** author, 2023.

The application algorithm or program consists of the following: In the initial part, individual speed profiles are generated for each of the sections, considering an acceleration and an intermediate or cruising constant speed, which last for a certain time in seconds and in the final part there is a deceleration time until reaching the complete stop of the train (see figure 3).

The velocity profiles are generated with a constant initial acceleration of 1 m/s^2 up to a predefined constant or cruising speed. In the final part there is a deceleration period varying around-1 m/s^2.

A second step in the algorithm consists in concatenating the individual profiles of the first step, to obtain the total velocity profile of the total run, as shown in Figure 4, for the particular case of four sections.

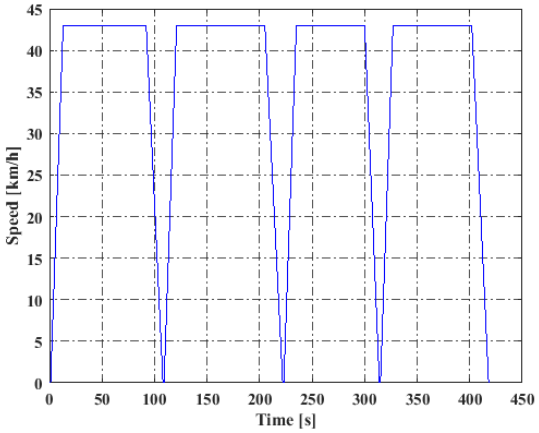

Figure 4. Example of concatenation of speed profiles of a typical route between four stations. **Source:** author, 2023.

5. RESULTS AND DISCUSSION

Representative results were obtained as shown in Figures 5 and 6 for instantaneous power and energy.

The following results were obtained for the specific energy consumed indicator in the 43 km/h cruising speed scenario with 1 m/s^2 acceleration and speed variations above and below the 43 km/h reference speed (see Table 3 and Figure 7).

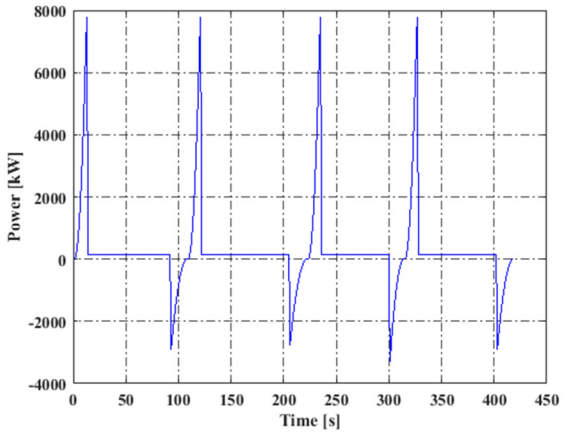

Figure 5. Peaks and valleys of power at acceleration, cruising speed and deceleration instants. **Source:** author, 2023.

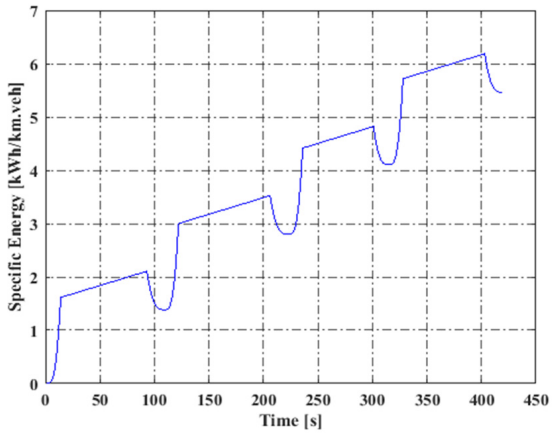

Figure 6. Integration of specific power and energy for a section between four stations. **Source:** author, 2023.

Table 3. Specific energies for different cruise speeds and constant acceleration.

Passengers	38 km/h 1 m/s²	43 km/h 1 m/s²	48 km/h 1 m/s²
450	7.68	10.46	13.82
900	11.57	15.75	20.81
1350	15.46	21.04	27.80
1800	19.34	26.32	34.79

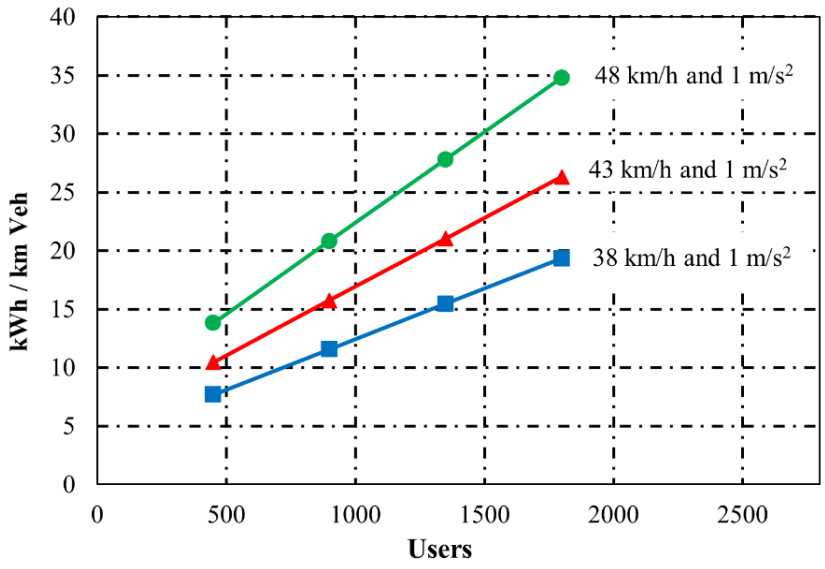

Figure 7. Specific energies for different cruise speeds and constant acceleration. **Source:** author, 2023.

6. CONCLUSIONS

The most important conclusions of this work are the following:

The theoretical formulation for the estimation of the specific electrical energy has been shown to be reliable in producing results that are relatively like the specific consumptions found in various metro-type systems in the world, found either with simulation or with measurements.

Modeling and simulation procedures, to obtain the specific consumptions in subway systems, have a great potential of use to observe the impact of some relevant mechanical variables and to perform sensitivity studies of results to variations of accelerations, decelerations, and cruising speeds.

The management of speed profiles in the operation of a metro-type transport system opens an interesting field of application of optimization techniques in the use of electrical energy.

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ON THE CORRECTION OF DOSE PROFILE DISCREPANCIES BY INTRODUCING AIR IN THE DERIVATION OF AN ELECTRON SPECTRUM

Sobre la corrección de discrepancias del perfil de dosis por introducción de aire en la derivación de un espectro de electrones

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Abstract

Knowledge of the energy spectrum of an electron beam is relevant for accurate dose calculation in radiotherapy. In previous works, it has been possible to reconstruct the electron spectrum of various clinical energies (6, 9, 12 and 15 MeV) within the typical percentage of clinical acceptance (Pa > 95 %) according to the gamma index (GI) (2 %/2mm), for both depth dose percentages (PDD) and dose profiles (DP), except for 6 MeV profiles. Therefore, the purpose of this work was to introduce air between the radiation source and the phantom surface to simulate both the monoenergetic PDDs necessary in the reconstruction of the spectrum of a 6 MeV beam and to obtain the PDD of this spectrum. Validation was performed using the gamma index with the typical threshold for clinical acceptance. The results showed that the PDP of the vacuum spectrum had a better agreement than the PDP of the air spectrum (Pa = 100 %), with respect to the measured PDD (Pa = 97 %). Regarding the PD, the introduction of air improved the agreement in clinical interest but not enough to reach the acceptance percentage. It is concluded that this technique does not seem to be a good alternative to correct the discrepancies in the field edges between the DP of an inversely reconstructed spectrum and the measured DP.

Key words: *inverse reconstruction, electrons, air, gamma index, dose profile.*

Resumen

El conocimiento del espectro de energía de un haz de electrones es relevante para el cálculo preciso de la dosis en radioterapia. En trabajos anteriores, se ha conseguido reconstruir el espectro de electrones de varias energías clínicas (6, 9, 12 y 15 MeV) dentro del porcentaje típico de aceptación clínica (Pa > 95 %) según el ´índice gamma (IG) (2 %/2mm), tanto para los porcentajes de dosis en profundidad (PDP) como para los perfiles de dosis (PD), excepto en perfiles de 6 MeV. Por tanto, el propósito de este trabajo fue introducir aire entre la fuente de radiación y la superficie del fantoma para simular tanto las PDP monoenergéticas necesarias en la reconstrucción del espectro de un haz de 6 MeV como para obtener la PDP de este espectro. La validación se realizó usando el índice gamma con el umbral típico de aceptación clínica. Los resultados mostraron que la PDP del espectro en vacío tuvo mejor coincidencia que la PDP del espectro con aire (Pa = 100 %), respecto a la PDP medida (Pa = 97 %). Respecto a los PD, la introducción de aire mejoró el acuerdo en la zona de interés clínico, pero no lo suficiente como para alcanzar el porcentaje de aceptación. Se concluye que esta técnica no parece ser una buena alternativa para corregir las discrepancias en los bordes de campo entre el PD de un espectro reconstruido inversamente y la PD medida.

Palabras clave: *reconstrucción inversa, electrones, aire, índice gamma, perfil de dosis.*

1. INTRODUCTION

In radiotherapy, knowing the energy spectrum of the electron beam incident on the surface of the patient or phantom is important for the accurate calculation of the delivered dose [1-2]. In the clinic, the delivered dose is perhaps the most relevant factor for tumor control. However, as dose varies with depth and along the lateral axis of the incident plane, the percentage dose at depth (PDP) and the dose profile (DP) are used as parameters for dose adjustment to the tumor. Therefore, the PDP and PD are critically dependent on the shape of the energy spectrum [3].

Of the three existing methods to calculate the electron spectrum, the most accurate is the Monte Carlo Simulation of the accelerator head; the most realistic, the one using electron magnetic spectrometers; and the most practical and simple, the inverse reconstruction (IR) [1-2] [4]. The IR consists of deriving the spectrum from the solution of the Fredholm equation of the first type, previously simulating the monoenergetic PDP matrix, measuring the clinical PDP and calculating the dose of the contaminating photons [1, 3].

In previous work, electron spectra have been obtained with a clinical accuracy as high as more than 95 % of the simulated PDP points from reconstructed spectra within a gamma index of 1 %/1mm with respect to measured PDPs and 2 %/2mm with respect to measured PDs, for clinical electron beams of nominal energy between 9 and 15 MeV [1-2].

However, in these same works, in clinical beams of lower energy (6 MeV), the PD passage criterion should be relaxed up to 4 %/4mm to exceed 95 % clinical acceptance rate.

To improve accuracy in these beams, some authors have proposed considering corrections for angular dispersion, introducing air between the source and the phantom surface or an energy-dependent effective source-surface distance (ESD) [5- 6]. However, there are no works that have explored the latter two options. Therefore, in this study we aim to establish whether introducing air between the source and the phantom surface improves the agreement between the dose profile of a reconstructed electron spectrum of nominal energy 6 MeV and the dose profile of the clinical beam of the same energy from a Varian linear accelerator.

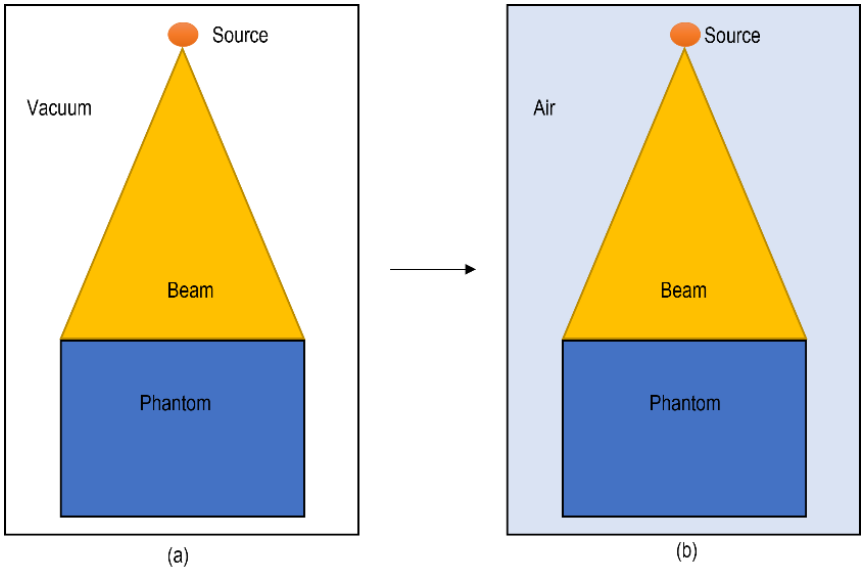

Figure 1. Simulation geometry of the electron beams to obtain the monoenergetic PDP and PDP reconstructed from the spectrum in previous work (a) and current work (b). Field size 10×10 cm2 at 100 cm source-surface distance. **Source:** author, 2023.

2. MATERIALS AND METHODS

To carry out this work, a PDP of 6 MeV was obtained from a Varían Clinac 21EX linear accelerator of the Muriaé Cancer Hospital (Brazil). The linear extrapolation method of the PDP was used to find the dose of the contaminating photons [7]. Then, the electron spectrum of the beam was calculated inversely, using generalized simulated annealing [8] and Tikhonov regularization [9].

These processes are prior to the objective of this work, it is suggested to consult previous articles where each of these processes has been described extensively [1-3] [10-11].

To achieve the objective, two changes were made with respect to previous works: i) the monoenergetic PDPs were simulated with the same geometry as in [1] but introducing air, instead of vacuum. That is, air material is added in the input file in the PENELOPE Monte Carlo code; ii) the same is done to obtain the simulated PDP from the reconstructed spectrum (Figure 1).

All PDPs (monoenergetic and simulated from the spectrum) were obtained using the PENELOPE code with a statistical uncertainty of 2% at the depth of the maximum range corresponding to 2×108 simulated particles.

To assess the agreement between measured and simulated PDP in vacuum and air, the American Association of Physicists in Medicine (AAPM) criteria (>95% within 2%/2mm of dose and distance difference for agreement, respectively) were considered [12].

3. RESULTS AND DISCUSSION

The 6 MeV electron beam energy spectra reconstructed from monoenergetic PDPs in vacuum and in air, in Fig. 1 show noticeable discrepancies in the peak and pre-peak region. The spectrum in air has a narrower peak than its vacuum counterpart (Figure 2), making it more energetic. The PDP simulated from the two spectra above show different results (Figure 3).

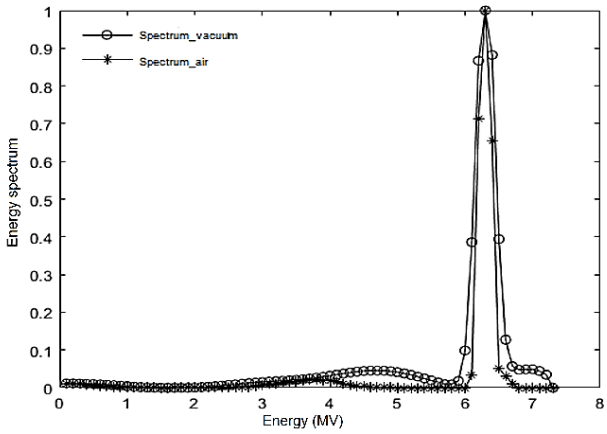

Figure 2. 6 MeV energy spectra obtained from PDPs in vacuum and air. **Source:** author, 2023.

While the vacuum spectrum shows a 100% agreement of the gamma index (2 %/2mm), in the air spectrum the passage percentage drops to 100%, which is still acceptable. The greatest discrepancies are in the surface

As observed, the PDP of the vacuum spectrum more closely represents the measured PDP, indicating that this spectrum, under this indirect validation criterion, is close to the real one (not shown).

When observing the reconstructed dose profiles of the vacuum and air spectra, with respect to the measured dose profile, it is noted that the vacuum one presents serious discrepancies in the field edge region, while the air one improves in this region, worsening beyond the twilight zone, below the 20 % line (Figure. 4).

Indeed, for the PD passage percentage of the simulated spectrum in vacuum it is 78%, for that of the spectrum in air, 73%. However, when the analysis is restricted to the area of clinical interest (-6 cm to +6 cm, approx.), the air spectrum improves the coincidence up to 90 %. The vacuum spectrum reaches 83%.

However, as their results in PDP coincidence improved, it would be worthwhile to explore the other alternative: changing the effective source-surface distance as a function of nominal energy.

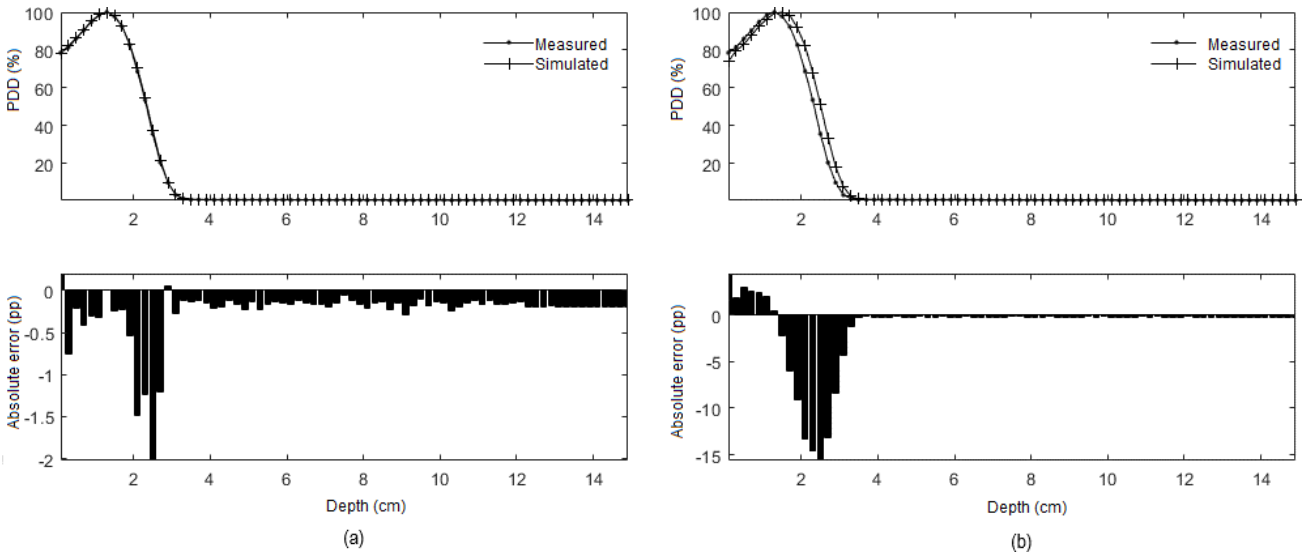

Figure 3. Comparison of measured and simulated PDP in vacuum (a) and air (b). **Source:** author, 2023.

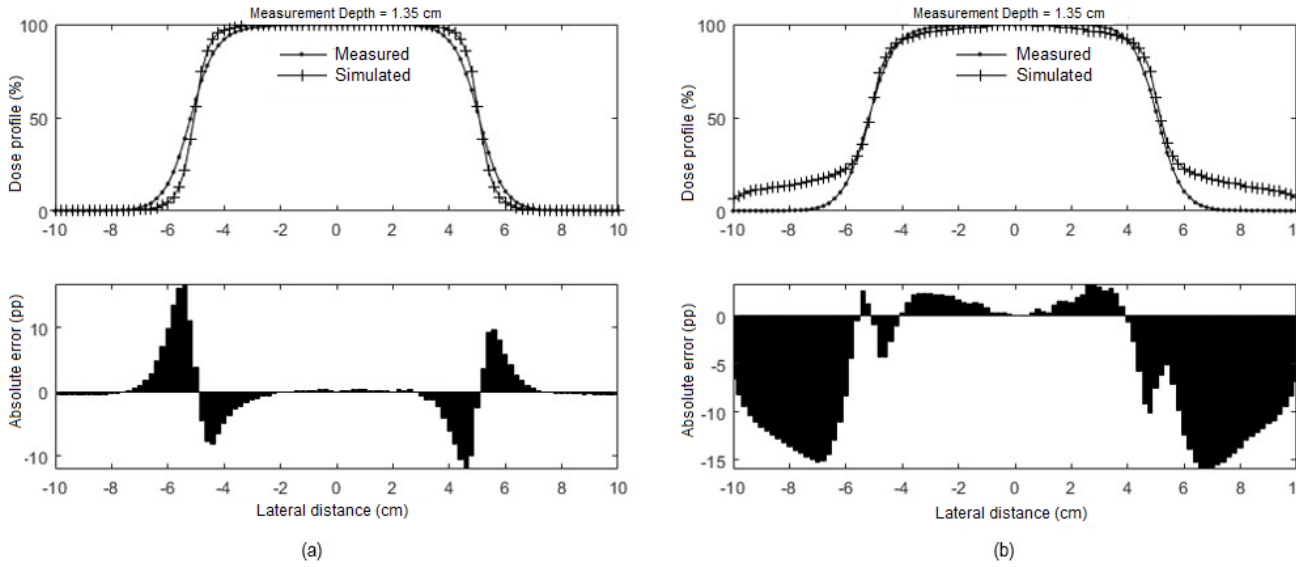

Figure 4. Comparison of measured and simulated PD in vacuum (a) and air (b). Measuring depth: 1.35 cm. **Source:** author, 2023.

4. CONCLUSIONS

The introduction of air between the radiation source and the phantom surface, while improving the agreement between the Monte Carlo simulated dose profile from an inversely reconstructed spectrum and the clinically measured dose profile for a 6 MeV electron beam, does not achieve the 95% clinical acceptance threshold of the 2%/2mm gamma index suggested by the American Association of Physicists in Medicine (AAPM). It is recommended that the effective source-surface distance method be explored.

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GEOCHEMICAL EVALUATION OF CRUDE OILS IN THE LLANOS ORIENTALES BASIN

Evaluación geoquímica de crudos en la cuenca llanos orientales

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Abstract

The area of the present study is located in the Llanos Orientales basin, in which the main objective was a geochemical evaluation of crude oil in the geological and production provinces: Piedemonte, Arauca, Casanare and Meta-Vichada based on related information about bulk parameters, gas chromatography and biomarkers. The data for each of the provinces were analyzed and reorganized according to the geological formation corresponding to the reservoir rock indicated for each crude oil sample, from which 576 crude oil samples were obtained with the information that allowed relating some petroleum compounds and defining the depositional environments of the source rock facies of crude oil, identify biodegradation processes and mixtures of crude oils. In the same way, maps were made where the crudes were classified according to their quality. It was established that the best quality crudes belong to the Piedemonte sector in the Mirador Formation. On the other hand, the sector where the crudes show lower quality corresponds to Meta-Vichada in the San Fernando Formation. This analysis was carried out for the four provinces, obtaining key information for future exploratory campaigns in the Llanos Orientales basin, taking into account that it is the richest basin in hydrocarbons in Colombia.

Key words: *biodegradation, biomarkers, bulk parameters, chromatography, crude oil mix, reservoir rock, source rock.*

Resumen

El área del presente estudio se localiza en la cuenca de los Llanos Orientales, en la cual se realizó como objetivo principal una evaluación geoquímica de crudos en las provincias geológicas y de producción: Piedemonte, Arauca, Casanare y Meta-Vichada a partir de información relacionada con parámetros bulk, cromatografía de gases y biomarcadores. Se analizaron los datos por cada una de las provincias y se reorganizaron de acuerdo con la formación geológica correspondiente a la roca reservorio indicada para cada muestra de crudo de donde resultaron 576 muestras de crudos con la información que permitió relacionar algunos compuestos del petróleo y definir los ambientes de depósito de las facies de las rocas generadoras de los crudos, identificar procesos de biodegradación y mezclas de crudos. De igual manera, se realizaron mapas donde se clasificaron los crudos de acuerdo a su calidad. Se logró establecer que los crudos de mejor calidad pertenecen al sector Piedemonte en la Formación Mirador. Por otra parte, el sector donde los crudos muestran menor calidad corresponde a Meta-Vichada en la Formación San Fernando. Este análisis se realizó para las cuatro provincias obteniendo información clave para futuras campañas exploratorias en la cuenca Llanos Orientales, teniendo en cuenta que es la cuenca más rica en hidrocarburos de Colombia.

Palabras clave: *biodegradación, biomarcadores, cromatografía, mezcla de crudos, parámetros bulk, roca generadora, roca reservorio.*

1. INTRODUCTION

Th The sedimentary basin known as Llanos Orientales is the largest in Colombia, with an area of 225,706 km², in this basin are located approximately 358 oil fields of which 89 are productive. It covers the departments of Casanare, Meta, Arauca, and Vichada [1]. Oil production in the basin is distributed as follows: Meta contributes 71.5%, Casanare 19.1% and Arauca 7.8%. In terms of the quality of the crude extracted, heavy crudes account for 68.6% of total production, while normal and light crudes correspond to 12.8% and 5.6%, respectively [2].

In this basin there is a great variety of crudes in terms of their basic properties (bulk parameters such as API gravity and sulfur, vanadium and nickel content). These variations in crudes may be a consequence of complex petroleum systems and are associated with different generating intervals, biodegradation processes and hydrocarbon mixing [3].

Considering that this basin is the most important in Colombia in terms of discovered resources (37,000 Mmbpe / OOIP) [4], it is necessary to understand the temporal, stratigraphic and geographic distribution of these processes with the purpose of obtaining conclusions that contribute to the visualization of additional exploratory opportunities. Petroleum geochemistry is a powerful tool that can effectively contribute to the understanding of hydrocarbon generation, migration, loading and preservation processes.

This work is developed using geochemical information published by the ANH in 2011 and covers the geological and production provinces recognized in the Llanos basin: Piedemonte, Arauca, Casanare and Meta-Vichada. Information from approximately 631 crude samples and geological and petroleum geology information published in different regional and local studies that talk about depositional environments of source rock facies and the relationship with the reservoir rock is used [5-6].

The geochemical information used includes bulk parameters (API gravity, sulfur, vanadium, and nickel content), gas chromatography, liquid chromatography and biomarkers [7].

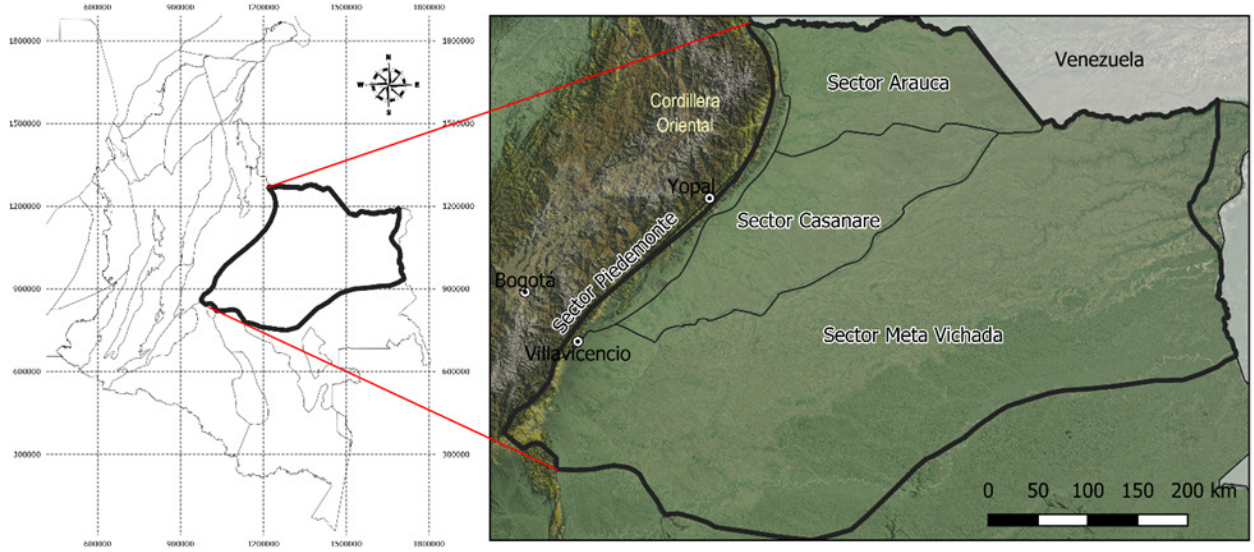

Figure 1. Location map of the Eastern Plains Basin and its sectors. **Source:** author, 2023.

2. LOCATION OF STUDY AREA

The Llanos Orientales basin is located east of the Eastern Cordillera of Colombia, comprising the departments of Casanare, Arauca, Meta and Vichada. It is located approximately 123 km east of the city of Bogotá D.C. According to [4] and ECOPETROL-ICP (1991), it is a flat topographic depression, southwest- northeast oriented, with altitudes ranging from 50 to 500 meters above sea level, said basin developed on the western flank of the Guyana Shield. It covers an area of 225,706 km² and its tectonic evolution has been extensively studied in several studies [8-12].

Also, within this basin are the recognized geological and production provinces: piedmont, Arauca, Casanare and Meta (see Figure 1). The area in question has well-defined morphological limits. To the north, it is bordered by the Venezuelan political frontier; to the east, by the Guyana shield; to the south, by the La Macarena Mountain range, the Vaupés arc, and Precambrian metamorphic rocks; and to the west by the Cordillera Oriental fault system [13].

3. THEORETICAL BACKGROUND

3.1 Regional geological framework - Stratigraphy

The stratigraphy of the Llanos Orientales basin is described in Figure 2 and begins with the deposition in the crystalline basement of detrital Paleozoic sediments [14], overlain in discordant contact by Cretaceous rocks. The latter correspond to the Une, Gachetá and Guadalupe formations.

Une Formation: In the Casanare sector, the Formation Une is also called Ubaque Formation and Lower Sands Formation (Lower Sandstones) according to [4][15].

Gachetá Formation: In the study area it is present in the Casanare sector. Likewise, the Chipaque Formation is a stratigraphic equivalent of the Gachetá Formation [16].

Guadalupe Formation: In the study area it is present as reservoir rock in the Arauca, Casanare and Meta-Vichada sectors.

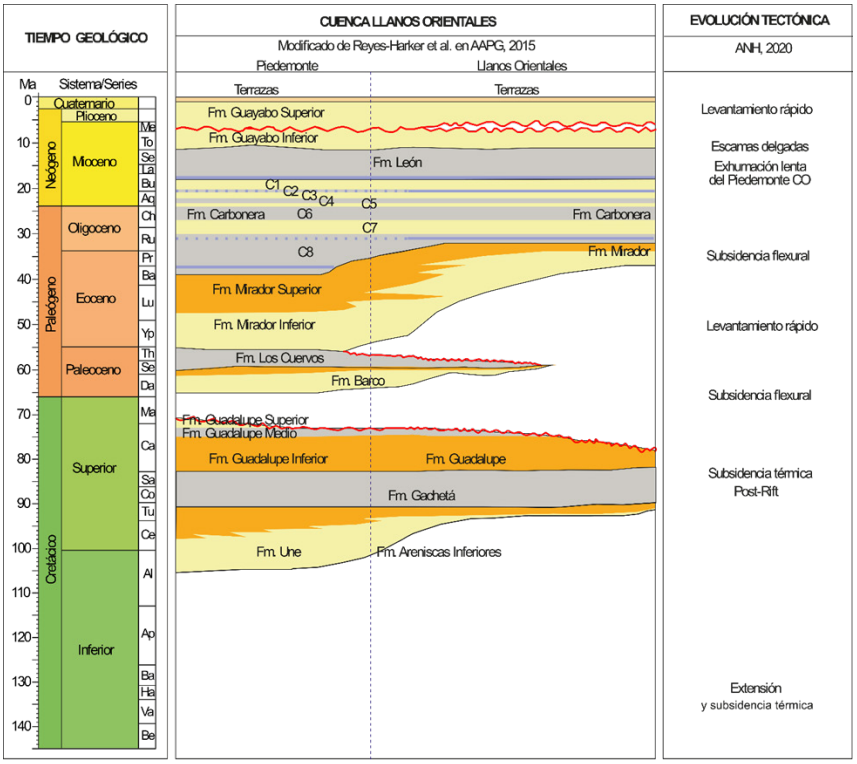

Figure 2. Stratigraphic column of the Llanos Orientales basin. **Source:** kuenka ,2023.

In the Cenozoic, from the Paleocene to the Quaternary, the following formations were deposited:

Barco and Los Cuervos Formations: these formations are associated with depositional environments of sandy fluvial facies and an increase of coastal plain. Their age ranges from Early Paleocene to Late Paleocene. In the study area, the Barco Formation is a reservoir rock in the Casanare sector.

Mirador Formation: This formation is present in the four sectors and constitutes the most important reservoir in the basin. Operationally in the Castilla area it is called the San Fernando Formation [17].

Carbonera Formation: It is a sedimentary sequence composed of clayey, silty rocks and sandstones, with occasional coal levels [18]. It was deposited during the late Eocene and early Miocene, in environments ranging from transitional marine to continental. This formation is divided into 8 operational units (C1 to C8), where the even levels are transgressive and act as regional seals, while the odd ones are sandy and hydrocarbon-producing from C7 to C3 [19]. The Carbonera Formation is distributed in the Arauca, Casanare and Meta-Vichada sectors, where it is used as reservoir rock.

Leon and Guayabo Formations: The León Formation represents the maximum invasion of Tertiary seas and is composed almost exclusively of clays [19], ending with the deposition of thick molasse-like layers of the Pliocene-Quaternary Guayabo Formation deposited in a marine environment towards the base and marine to continental fluvial at the top [14].

3.2 Geochemistry of crude oil

Petroleum is a complex chemical substance which constitutes a non-renewable natural resource. In addition to API gravity, sulfur, vanadium and nickel content, there are other compounds that make it up, which contain molecules known as biomarkers. In the hydrocarbon sector, basic geochemical analysis, also known as bulk analysis, is fundamental to determine the characteristics of crude oil.

These analyses include the measurement of API Gravity, Sulfur Content, Vanadium Content and Nickel Content. The data obtained in this type of analysis are essential to define the type of crude oil relating its quality and the source rock environment [2]. Another relevant aspect provided by crude geochemistry is to analyze the quality of crudes, which is reflected in their physical properties together with their general composition and is the result of the interaction of different variables from which it can be stated that a good quality crude has high API gravity, low sulfur content, low content of 25-norhopane/C30 hopane and enrichment in saturates together with origin from non-marine rocks.

Lower quality crudes have low API gravity, high sulfur content, high 25-norhopane/C30 hopane content, loss of saturates, significant bacterial alteration and origin from marine (carbonate) rocks. Likewise, most crudes have low concentrations of vanadium and nickel and sulfur content lower than 1%, however, it can be associated to medium to high quality crudes, otherwise it is related to marine source rocks subjected to biodegradation processes.

Biodegradation processes affect the quality of crudes when the percentage of saturates decreases along with their API gravity and the concentration of sulfur, nickel and vanadium increases. Since 25-norhopanes are formed in states of intense biodegradation, they are an indicator of a mixture of intensely biodegraded crudes [20].

Regarding the depositional environment of the source rocks, geochemistry is a useful tool in the definition of petroleum systems. Likewise, Colombian crudes correlate with Cretaceous and Tertiary source facies deposited in marine environments that vary between deltaic marine, predominantly siliciclastic shallow marine and predominantly carbonate shelf marine.

For Cretaceous source rocks there are three main depositional environments: anoxic marine with carbonate influence (anoxic conditions, high ambient salinity and minimal input of continental-derived organic matter), siliciclastic marine, anoxic to suboxic (moderate oxygen

level, high to moderate ambient salinity and moderate input of continental-derived organic matter) and suboxic deltaic marine (relatively high oxygen level, low to moderate ambient salinity and high input of continental-derived organic matter).

For Tertiary source rocks the main depositional environment is deltaic marine. The age of crude oils in source rocks can be classified thanks to biomarkers and although the methodology is not developed, it is possible to differentiate crude oils generated from Upper Cretaceous or Tertiary rocks [20].

4. MATERIALS AND METHODS

For the execution of the project, a 6-stage methodology was established (see Figure 3), which describes each of the activities carried out to achieve the proposed objectives in the study area, which covers the recognized production sectors (Piedemonte, Arauca, Casanare and Meta-Vichada) in the Eastern Plains basin.

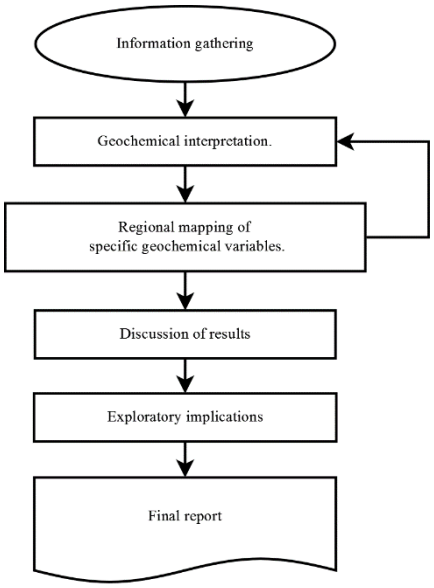

Figure 3. Diagram of the methodology used. **Source:** author, 2023.

4.1 Information gathering

This first stage consists of collecting information regarding crude geochemistry to begin to understand the relationship of bulk parameters and biomarkers, with crude quality. Likewise, this stage seeks to obtain from the database provided by the ANH, published information on geochemical data for crude samples in the Llanos Orientales basin.

Another important information obtained from this database is the shapefile of crude, fields and basins. It is also necessary to compile all the necessary information that the company has, whether it is bibliographic information, similar works that serve as a guide and information to use in the GIS.

4.2 Geochemical interpretation

The second stage consists of compiling and organizing the information in Excel files so that the data are plotted correctly for interpretation; in general, 631 data were collected, however, some of them lack information and therefore are not plotted, being necessary a reclassification. The organization is done by classifying the data by provinces or recognized production sectors, which are piedmont, Arauca, Casanare and Meta.

For each sector the wells that have information of the reservoir rock formation are extracted, likewise with the help of GIS and the shapefile previously obtained, the wells of the evaluated crudes are related with their coordinates and production field to which they belong, 576 crude data are obtained for the formation of source rock and 619 data for the quality related to API gravity. Through the accompaniment of the company, several trainings and meetings are held to prepare the interpreter and review the progress.

Seven graphs must be prepared for each sector. To understand the quality of the crude related to the type of crude, biodegradation processes and mixture, the graphs of API gravity and sulfur content; 25-norhopane/C30 hopane content and API gravity; ratio between Ni/V and sulfur content; ratio of percentage of saturates and API gravity are used. On the other hand, to interpret and find relationships with the age and depositional environment of the source rock facies in the sectors, the graphs

of pristane/phytane to oleanane/C30 hopane ratio; pristane/phytane to C35/C34 hopane ratio; gamacerane/C30 hopane and Ts/Tm ratios are used.

4.3 Regional mapping of specific geochemical variables

For the third stage it is necessary to take into account the geographic location, together with the quality and reservoir rock formation information of each well performed in the second stage. For quality, the wells were classified according to the API gravity value, having either heavy, normal or light crude in each sector. Likewise, mapping is established by geological formation of the reservoir rock of the crude sample, such data is also mapped by sectors to observe the location of each sample and thus better relate the interpretation.

4.4 Discussion of results

The fourth stage seeks to establish the reservoir rock formation(s) of better and lower quality in the basin, as well as suggesting depositional environment for the source rock facies. With the help of the mapping of the variables, the location of these formations is related to the geochemical interpretation.

4.5 Exploratory implications

The Llanos basin is of vital importance for oil production in our country. Due to its strategic location and abundance of resources, this region has become a key point for the national energy industry. The fifth stage seeks to propose the most favorable location, sector, geological formation and depositional environment to find good and lower quality crude oil.

4.6 Final report

Taking into account the density of data and the extensive interpretations for each sector, we seek to condense everything in a report that evidences the results by sector, in the same way the mapping of the data helps to improve the interpretation to propose some exploratory implications, discussion and analysis of these results.

5. RESULTS

Based on bulk parameters (API gravity, %sulfur, vanadium and nickel), liquid chromatography, gas chromatography and saturated biomarkers, a geochemical interpretation was performed to evaluate the quality of the crudes and the depositional environments of the source rock facies.

The interpretation was carried out for crude oils from the Arauca, Casanare, Meta-Vichada and Piedemonte sectors of the Llanos Orientales basin.

Figure 4a corresponds to the location map of the wells with geochemical information used for this interpretation. From the graphs for the interpretation of crude geochemical data of these sectors, relevant aspects were identified, mentioned below. The mapping of duly classified and organized variables is used as a complement at the time of interpretation to better propose the exploratory implications; for this reason, for the geological formation of the reservoir rock, 576 data classified by each sector were mapped in order to relate the location of each sample with the formation being described, as shown in Figure 4b.

The API gravity mapping is used as an input to better understand the location of the samples with heavy, normal and light crudes, as shown in Figure 4c; this is convenient since this variable is the most used in the geochemical quality charts, which displays 619 crude oil sample data classified for the production sectors of the Llanos basin.

5.1 Arauca Sector

The API gravity of the crudes evaluated in the Arauca sector of the Eastern Llanos basin varies between 24.4 and 39.9 and the sulfur content between 0.10 and 0.66%. A slight tendency of increase in API gravity is observed in the crudes, going from normal to light, likewise the sulfur content and 25-norhopane/C30 hopane content have a notable decrease, which suggests a combination between intense to incipient biodegradation processes and possible mixture of crudes (see Figure 5).

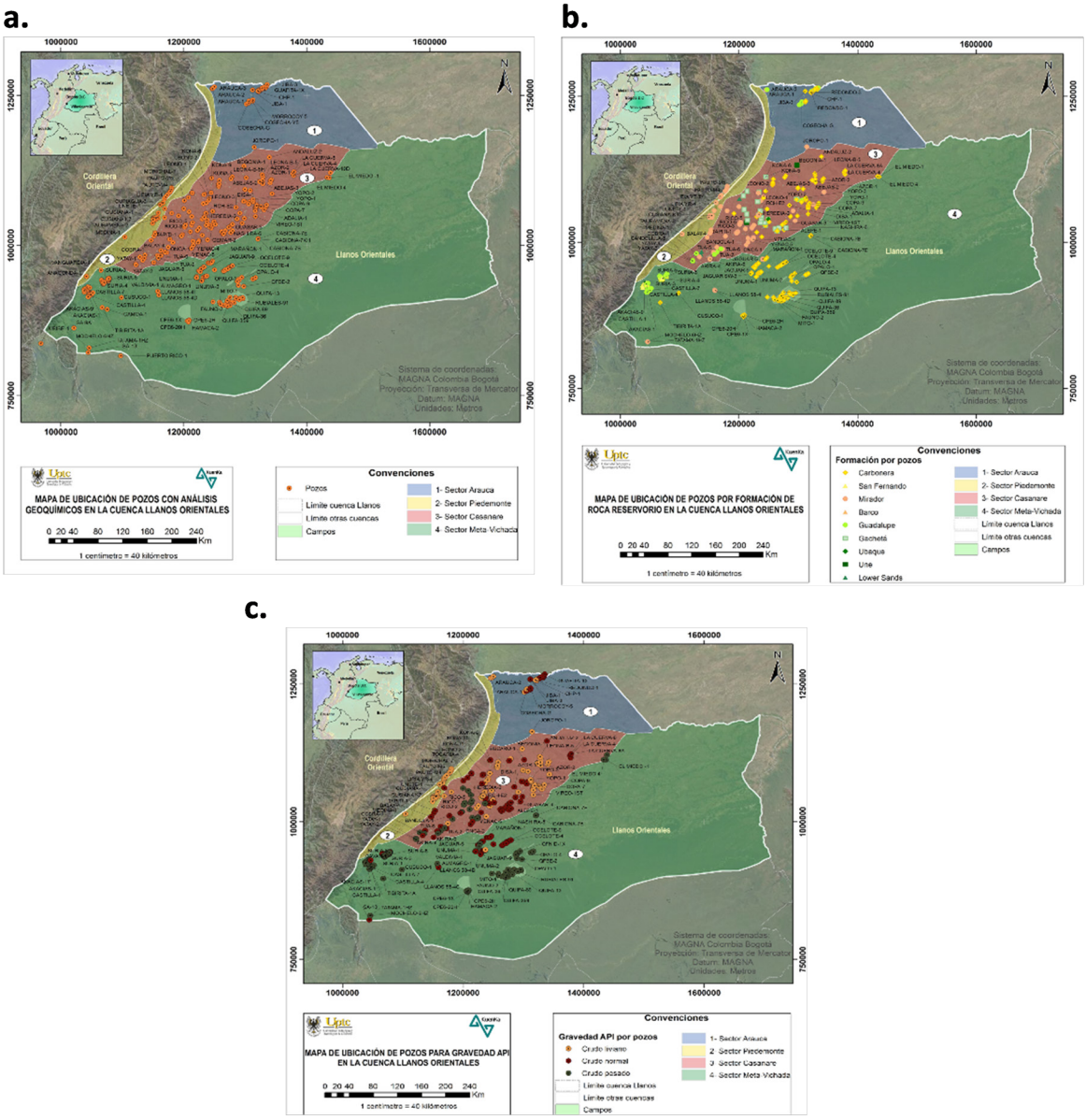

Figure 4. (a) Map of well locations with geochemical analysis (b) Map of well locations with geochemical analysis and (c) Map of well locations for API gravity. **Source:** author, 2023.

According to the pristane/phytane and C35/C34 hopane ratios, the evaluated crudes correlate with generative organic facies deposited in anoxic-suboxic to carbonate marine platform environment. According to the relationship between pristane/phytane and oleanane/C30 hopane the evaluated crudes correlate with generating organic facies deposited from shelf marine environments (siliciclastic) with variable and slight carbonate contribution to carbonate marine environment, the period to which most of the crudes in the sector belong for the Carbonera, Mirador and Guadalupe reservoir formations corresponds to Cretaceous (see Figure 6).

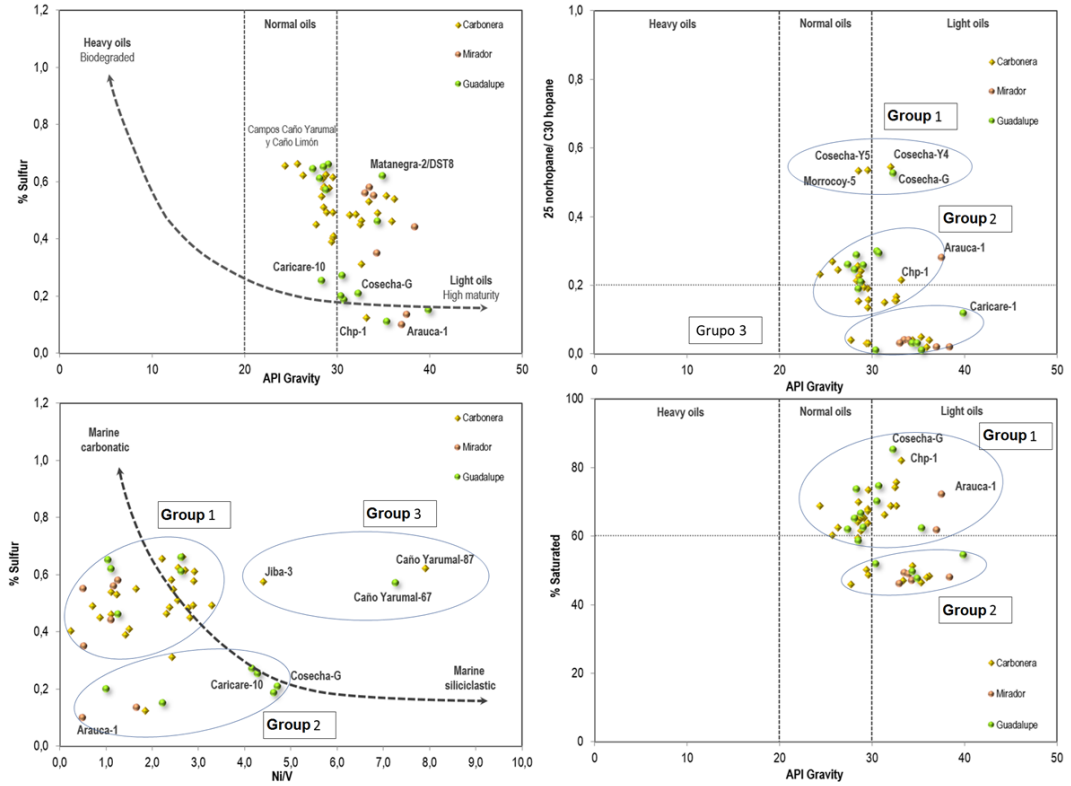

Figure 5. Quality graphs for the Arauca sector. **Source:** author, 2023.

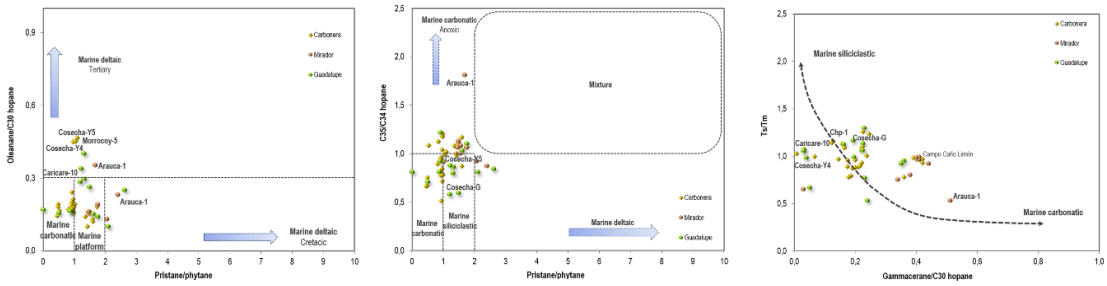

Figure 6. Depositional environment and age plots for the Arauca sector. **Source:** author, 2023.

5.2 Piedemonte Sector

The API gravity of the crudes evaluated in the Piedemonte sector of the Eastern Llanos basin varies between 25.7 and 48.4. Most of the crude data correspond to light crudes and have the best quality in the basin; likewise, the sulfur content and 25-norhopane/C30 hopane content have a notable decrease, which suggests a combination between intense to incipient biodegradation processes and crude mixture by refreshing (see Figure 7).

According to the pristane/phytane and C35/C34 hopane ratios, the evaluated crudes correlate with organic generating facies deposited from shelf marine to deltaic marine environments. According to the pristane/phytane and oleanane/C30 hopane ratios, the evaluated crude oils correlate with generating organic facies deposited from deltaic marine to shelf marine environments with low carbonate input, some from the Cretaceous and others from the Tertiary (see Figure 8).

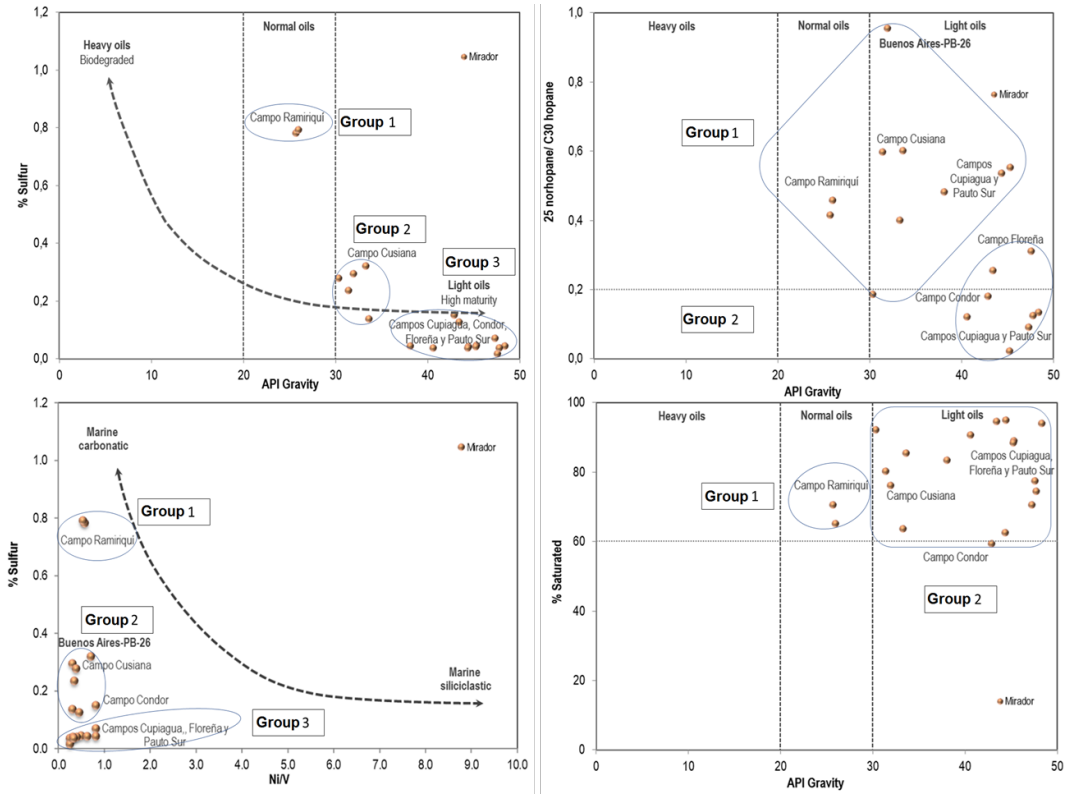

Figure 7. Quality plots for the Piedemonte sector. **Source:** author, 2023.

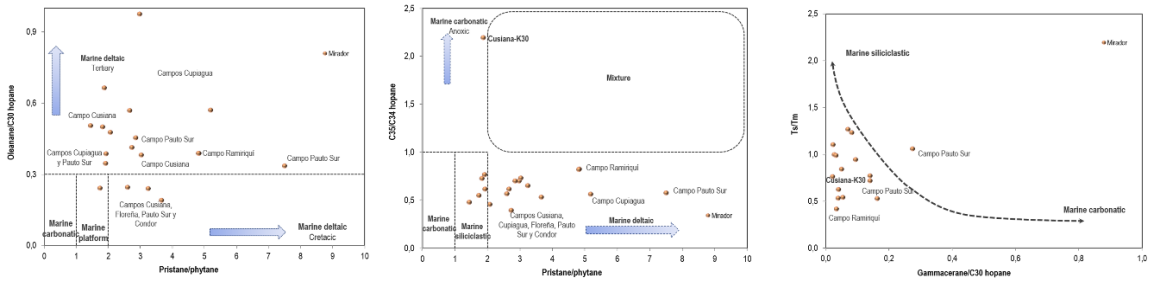

Figure 8. Depositional environment and age plots for the Piedemonte sector. **Source:** author, 2023.

5.3 Casanare Sector

The API gravity of the crudes evaluated in the Casanare sector of the Eastern Llanos basin varies between 11.0 and 42.1 and the sulfur content between 0.07 and 2.47 %. A tendency of increase in API gravity is observed in the crudes, going from heavy to light, likewise the sulfur content and the 25-norhopane/C30 hopane content have a notable decrease, finding crudes of low to very good quality, which suggests a mixture of crudes by refreshing and intense to incipient biodegradation processes (see Figure 9). According to the pristane/phytane and C35/C34 hopane ratios, the evaluated crudes correlate with generative organic facies deposited in shelf to shallow deltaic marine environments with variable carbonate input. According to the ratio between pristane/phytane and oleanane/C30 hopane the evaluated crude oils correlate with generating organic facies deposited from shelf marine and deltaic marine with variable carbonate

input, also crude oils from all reservoirs are in both Tertiary and Cretaceous zones (see Figure 10).

5.4 Meta-Vichada Sector

The API gravity of the crudes evaluated in the Meta-Vichada sector of the Eastern Llanos basin varies between 5.0 and 37.8. The crudes range from heavy to light, which have a tendency in which the sulfur content decreases while the API gravity increases, which could suggest that there is a mixture of crudes by refreshing and according to the content of 25-norhopane/C30 hopane suggests biodegradation ranging from intense to incipient (see Figure 11).

According to the pristane/phytane and C35/C34 hopane ratios, the evaluated crudes correlate with organic generating facies deposited in a siliciclastic marine platform environment with suboxic carbonate to carbonate marine environment. According to the ratio between pristane/phytane and oleanane/C30 hopane the evaluated crudes correlate with generative organic facies deposited from shelf marine and deltaic marine environments with variable carbonate input, also the crudes from all reservoirs are in both Tertiary and Cretaceous zones (see Figure 12).

6. ANALYSIS AND DISCUSSION

According to [23] the Llanos Orientales basin has a generation-accumulation efficiency (EGA) of approximately 5% and according to its geological and geochemical characteristics could reach an EGA of at least 8%, considering for this basin greater expectations and opportunities to find reserves where the risk associated to the hydrocarbon load is lower compared to the other basins in Colombia.

According to the analysis made regarding the quality of the crude, in the Arauca and Piedemonte sectors the crude is mostly light and of high quality, aligned in a northeast-southwest direction. In the Casanare sector the distribution of crudes shows that there are high, medium and low quality crudes, and a corridor of heavy crudes is observed oriented in a northeast-southwest direction from the Candelilla-Yatay field to the north in the Tilodirán and La Gloria Norte fields, and to the east of the corridor with the Rancho Hermoso and Carrizales fields; normal crudes are distributed from the eastern limit of the Piedemonte sector to the La Cuerva field and light crudes are widely shown from the La Punta, Maurita Norte, Rancho Hermoso, Barquereña and Trinidad fields, towards the east with the Dorotea, Corocora and Remache Norte fields. In addition, in the Casanare sector there is a distribution of heavy crude in the eastern end corresponding to the Caño Negro and El Miedo fields.

In the Meta-Vichada sector, the quality of crude is low and most of the crude is heavy, where the Akacias, Castilla, Chichimene, Hamaca, Suria, Quifa and Rubiales fields stand out. In general, the Eastern Llanos basin in its four sectors shows high prospectivity for crudes of all types of quality (Figure 6), the best quality crudes, light and better preserved, are shown in the north and center-west of the basin, in the sectors of Arauca, Piedemonte and central part of Casanare corresponding to the reservoirs of the Mirador, part of Carbonera and Guadalupe formations.

On the contrary, lower quality crudes with low API gravity values and more biodegraded are located in greater proportion towards the south, southwest and west of the basin, also in the Meta-Vichada sectors with reservoirs of the San Fernando formations, and part of Carbonera and Guadalupe, and Casanare in some data from the Mirador, Guadalupe and Lower Sands formations.

Regarding the depositional environments of the organic facies of the source rocks, a transitional deltaic marine to siliciclastic platform marine environment is suggested for the Arauca and Piedemonte crude oil fields, with variable carbonatic contribution, mild-suboxic (see Figure 9 and 10). In the Casanare sector, a depositional environment of the organic facies of the deltaic marine to siliciclastic platform marine source rocks with variable carbonatic contribution, suboxic-anoxic for most of the reservoir samples of the Carbonera Formation (see Figure 12).

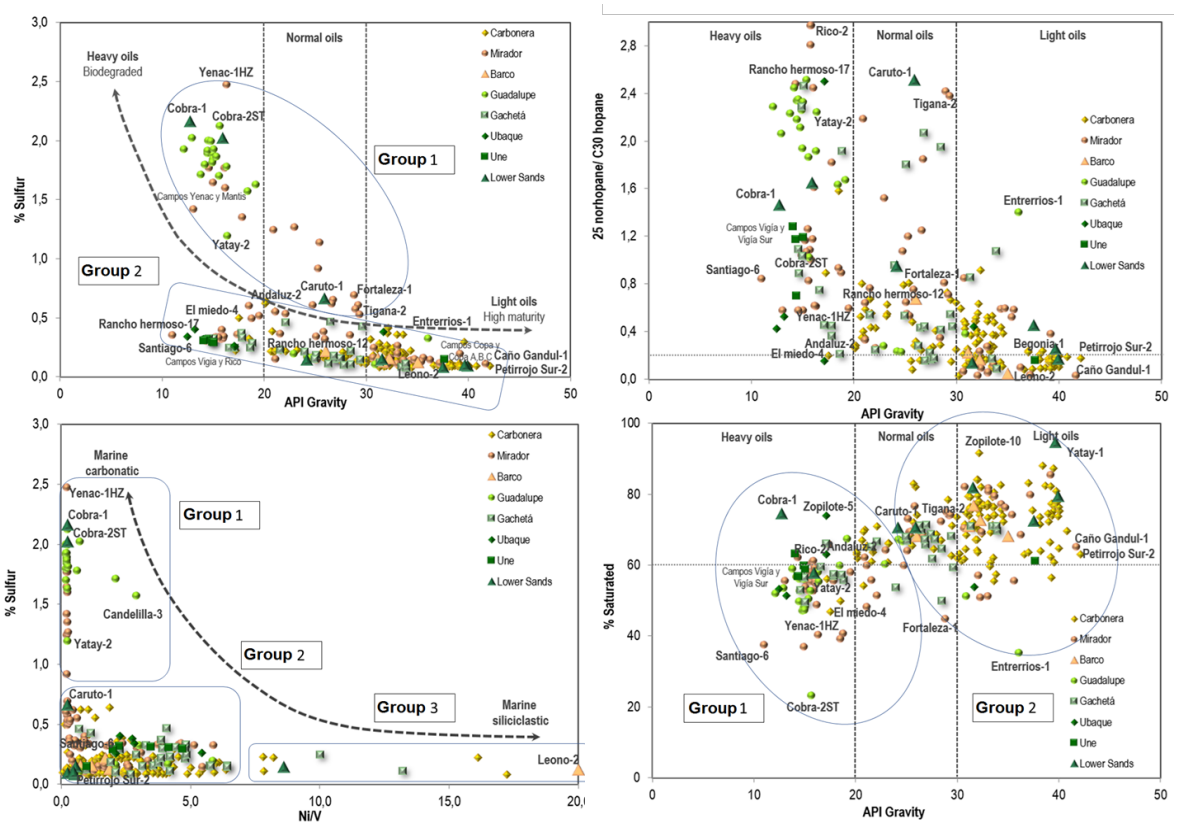

Figure 9. Quality plots for the Casanare sector. **Source:** author, 2023.

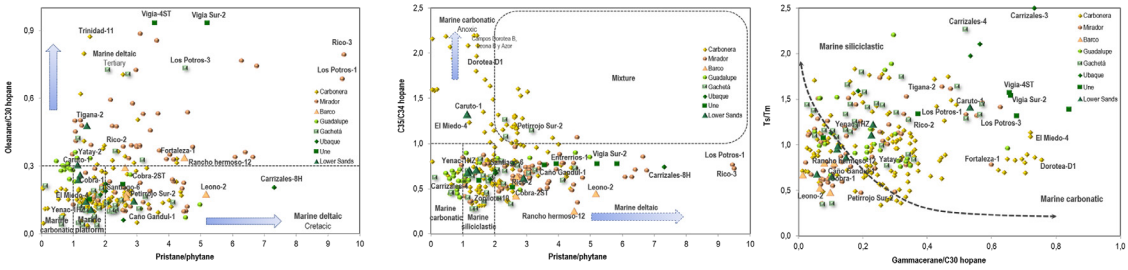

Figure 10. Depositional environment and age plots for Casanare sector. **Source:** author, 2023.

In the Meta-Vichada sector, a depositional environment of the organic facies of the siliciclastic marine platform source rocks with variable carbonatic contribution, suboxic for some of the samples from the Carbonera Formation reservoir (see Figure 14) and higher carbonatic contribution for the crude samples from the San Fernando Formation reservoir is suggested. In general, for the four sectors of the Llanos Orientales basin, the predominant depositional environment of the organic facies of the source rocks is deltaic marine to siliciclastic shelf marine with variable carbonatic contribution, suggesting crudes formed in complex organic facies environmental conditions. Regarding the age of the source rock, it shows that the crudes of each of the reservoirs are located in both the Tertiary and Cretaceous zones, which shows complexity in the basin and suggests a mixture of two crudes generated by very different stratigraphic facies.

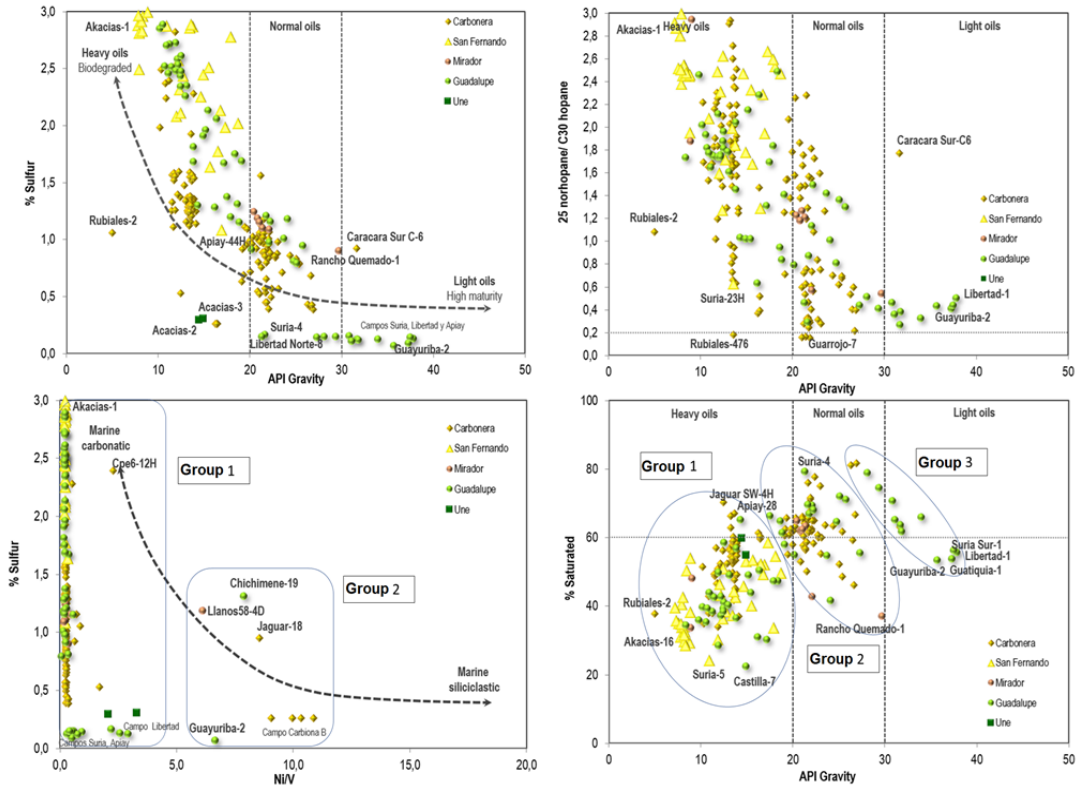

Figure 11. Quality plots for the Meta-Vichada sector. **Source:** author, 2023.

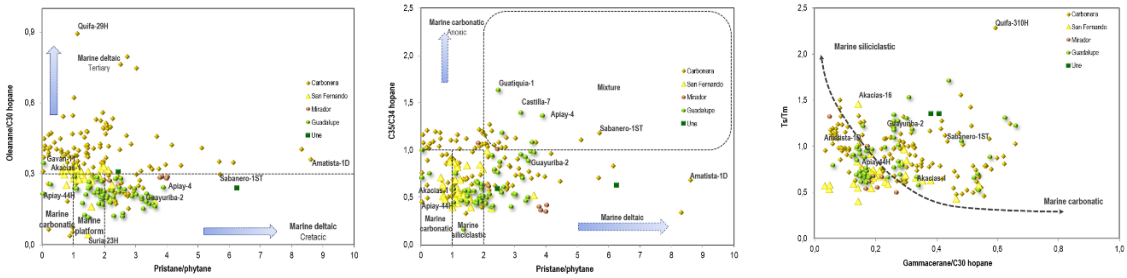

Figure 12. Depositional environment and age plots for the Meta-Vichada sector. **Source:** author, 2023.

It is necessary to complement this work with structural seismic interpretation that allows a good analysis of the reservoir formations coverage in the area, and thus link it with the geochemical interpretation performed. The above is a tool that allows a regional vision to analyze the areas in which possible prospectivity corridors can be found if combined with 1D and 3D petroleum systems modeling and even yet to find analysis, and check if the plays associated to the fields with commercial production are also present in these areas.

7. CONCLUSIONS

It was found that the best quality, light and better preserved crudes were found in the piedmont sector with the Mirador Formation as reservoir, suggesting a depositional environment of the deltaic marine to shelf marine generating facies. Lower quality crudes, with low API gravity values and more biodegraded, were found in the Meta-Vichada sector with the San

Fernando Formation reservoir, suggesting a depositional environment of predominantly carbonate shelf marine generating facies. Regarding the age of the source rock, it showed that the crudes from each of the reservoirs are located in both the Tertiary and Cretaceous zones, which evidences complexity in the basin and suggests a mixture of two crudes generated by very different stratigraphic facies.

A total of 631 crude oil sample data were compiled, classified by geological and production provinces of the Eastern Plains basin; samples with complete information on reservoir rock and API gravity were also analyzed. Finally, information on coordinates, field to which the sample belongs, crude quality and generalized name of geological formation for each reservoir rock present was added to the compiled data.

A mapping of 576 data with reservoir rock information and 619 data with crude quality information was performed for the four sectors of the Llanos Orientales basin, which has very varied quality, finding crudes ranging from heavy to light. The best quality crudes are located in the north and center-west of the basin, in the sectors of Arauca, Piedemonte and central part of Casanare corresponding to the reservoirs of the Mirador, part of Carbonera and Guadalupe formations. Lower quality crudes are located in the south, southwest and west of the basin in the Meta-Vichada sectors with reservoirs in the San Fernando, part of Carbonera and Guadalupe formations; and Casanare in some data from the Mirador, Guadalupe and Lower Sands formations.

The exploratory implications evaluated in this work can be associated with a complete geochemical modeling that includes 1D, 3D modeling and prospectivity corridor analysis that represents an input for the current exploration in the Llanos Orientales basin. It is known that several companies of the Oil and Gas industry continue making efforts and large investments in the search for resources that preserve Colombia's energy sufficiency in the energy transition process it is facing. It is also necessary to combine this type of work with other disciplines in order to have a grounded regional vision of the prospectivity in the basin.

8. FUTURE WORK

For the continuation of the interpretation it is convenient to map other variables so that the correlation with the geochemistry graphs is more accurate and thus to obtain more information of the crudes with biodegradation and blending.

The graphs used for the interpretation had to be used with predetermined values in their axes, for this reason some data, although they were plotted, do not appear, therefore, their analysis was omitted. According to the above, it would be necessary to complement the geochemical interpretation with other graphs or techniques.

Since the data obtained from crude oil comes from the public database of the ANH, it would be useful to feed this database so that crude samples appear with more information and thus perform analysis and studies of better quality.

A complementary work would be to perform an analysis of crude families for each sector, based on the geochemical interpretation, the geographic location of the data and the use of a statistical analysis software; to obtain correlation diagrams "cluster" type.

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NARINGINASE IMMOBILIZED ON MODIFIED BANANA PEEL WITH POTENTIAL APPLICATION IN THE CITRUS INDUSTRY

Naringinasa inmovilizada en cáscara de banano modificada con potencial aplicación en la industria de cítricos

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Abstract

Banana peel after chemical ant thermal modification was used as an alternative support to immobilize the commercial enzyme naringinase (*Penicillum Decumbens*); an immobilization yields greater than 70% was observed at pH 7. The structural characteristics of the support were determined by scanning electron microscopy with elemental analysis, showing the presence of pores and elements such as carbon, oxygen, sulfur, and zinc, while the attachment of the enzyme was concluded by infrared spectroscopy. For the free and immobilized enzyme, the K_M and V_{max} values were 0.0006 molar and 2000 U, and 0.0003 molar and 1666 U, respectively. The temperatures of the greatest activity for the free was 70°C and for the immobilized enzyme was 50°C, respectively, and the best pH was 4.5 in both cases. It was found that, after the third use, the catalyst maintained 50% of the enzymatic activity. These results seem to suggest the potential of the synthesized material for its application in the debittering of citrus juices.

Key words: *enzyme, immobilization, naringinase.*

Resumen

La cáscara de banano después de modificación química y térmica se utilizó como soporte alternativo para inmovilizar la enzima comercial naringinasa (*Penicillum Decumbens*); obteniéndose un rendimiento de inmovilización superior al 70% a pH 7. La morfología del soporte se caracterizó por microscopía electronica de barrido con análisis elemental, mostrando la presencia de poros y elementos como carbono, oxígeno, azufre y zinc; la inmovilización de la enzima fue confirmada por espectroscopía infrarroja. Para la enzima libre e inmovilizada, los valores de K_M y V_{max} fueron 0,0006 molar y 2000 U, y 0,0003 molar y 1666 U, respectivamente. Las temperaturas de mayor actividad para la enzima libre e inmovilizada fueron 70°C y 50 °C, respectivamente, y el pH óptimo fue 4,5 en ambos casos. De las pruebas de reutilización se encontró que luego del tercer uso, el catalizador mantuvo el 50% de la actividad enzimática. Los resultados de esta investigación sugieren el potencial del material sintetizado para su aplicación en la industria alimentaria, específicamente en el desamargado de jugos de cítricos.

Palabras clave: *enzima, inmovilización, naringinasa.*

1. INTRODUCTION

Enzymes are selective biocatalysts with industrial applications fields as food [1], textiles [2] biosensors [3], and wastewater treatment [4-7]. However, the use of free enzymes generates drawbacks related to the difficult of reusing them, the effects of the environmental modifications and the recovery of the enzyme, which limits its use on a large scale. These problems can be solved using a support where it is possible to immobilize the enzyme [8] and although the enzymatic immobilization techniques in an insoluble support are expensive, they represent an important alternative, especially in continuous operation processes with possibilities of application at industrial level [9] since immobilized enzymes are more stable and have the advantage to eaiser recovery and reuse [10].

Enzyme immobilization on a support can be done by several ways: adsorption, covalent bonding, encapsulation/ entrapment, and crosslinking [11]. Weak binding forces are involved in the adsorption immobilization while in the other cases, immobilization implies covalent bond formation between the enzyme and the support [12]. Materials used as support of enzymes must have high surface area, high chemical and thermal resistance, no reactivity to microbial environment, no soluble in the solvent, low cost, [13]. Different types of materials have been used for supporting enzymes [14]; however, the use of alternative materials as supports in the immobilization of enzymes, considering the principles of green chemistry, constitutes one of the main challenges from the academic and industrial point of view. In this way, economic and environmental advantages can be obtained using agroindustrial wastes for attaching enzymes. Banana is one of the most popular fruits in the world owing to its nutritional value and cost effectiveness [15]. The peel waste is an available and low-cost material and can be used for commercial application. This waste could be used as a potential candidate in the immobilization of enzymes.

The complex enzyme naringinase is used in several industries as biotechnology and pharmaceuticals [16]; in the citrus juice industry it is useful because the reduction of the intensity of its bitter taste [17]. The naringinase was immobilized on zeolite ITQ-2 functionalized with glutaraldehyde and was tested in the hydrolysis of naringin giving a high conversion (> 90 %) and excellent selectivity. In the continuous debittering grapefruit juices during 300 h, excellent results were obtained [18].

In this study, we focused on the immobilization of narainginase on a material from banana peel. The solid was prepared by one step method, impregnated with $ZnSO_4.7H_2O$ and heat treated in a nitrogen atmosphere at 500 °C. The material was analyzed by scanning electron microscopy and infrared spectroscopy. Initial enzyme activity and enzymatic kinetic were evaluated for immobilized and not immobilized enzyme. The effect of the pH, time, and temperature parameters on the immobilization of enzyme was evaluated. Immobilized enzyme was reused aiming to determinate immobilization success.

2. MATERIALS AND METHODS

2.1. Materials

Banana peel was obtained from the local supplier, Medellín, Antioquia. Naringinase enzyme from Sigma, naringin (grapefruit extract) from L´eternel World, LLC; $ZnSO_4.7H_2O$ was analytical reagent grade from Merck, ethyl alcohol denatured 40 B was purchased from J. T. Baker. Nitrogen gas UPA (99.999 %) from Messer. All chemicals were used as they were received.

2.2. Methods

2.2.1. Pretreatment of banana peel

Once in the laboratory, the banana peels were washed with water and dried with absorbent paper and treated at 80 °C during 24 h. 1 g of pulverized peel dust was suspended in 20 mL of water and subjected to microwave (Mars 5, CEM) heating from room temperature to 50 °C (3 min). The residue was separated from the aqueous extract and treated at 80 °C during 24 h. The obtained material was mixed in an autoclave at 121° C and 0.13 MPa with 70 % ethanol solution using a 1:10 w/v ratio for

20 min, and then rapidly decompressed [19]. The solid material was treated with NaOH (2 M) in a banana peel/ NaOH 1:10 w/v and stirred for 24 h at room temperature; then, the solid was filtered and washed until pH 7.

Finally, the solid was dried for 24 h. Dried banana peel was mixed with an aqueous solution of $ZnSO_4.7H_2O$ (1.4 M) using an activating agent/peel weight ratio of 2:1 [20], and the system was kept at room temperature for 24 h at 500 rpm. Then, the resulting paste was dried in an oven at 100 °C for 18 h. The dried and pulverized peels were thermal treated in a nitrogen flow (100 mL/min) at 500 °C for 1 h. Finally, the solid was washed with ethanol and hot water and subsequently dried at 80 ºC for 4 h. This material was labelled as BS.

2.2.2. Support characterization

ATR-FTIR analysis between 400 and 4000 cm^{-1} (Frontier Spectrum 65, Perkin Elmer) was used for identified the functional groups on surface of support material. Material morphology was analyzed using Scanning electron microscopy (JEOL JSM 6490 LV); elemental compositions was identified by EDX (INCA PentaFETx3 Oxford Instruments). The samples were analyzed in a high vacuum scanning electron microscope operating at 20 kV, fixed on a graphite tape, and coated with gold.

2.2.3. Enzymatic assay

The reducing sugars concentration was evaluated by dinitrosalicylic acid (DNS) test at λ = 540 nm (Thermo Fisher model GENESYS 50 spectrophotometer). The naringin hydrolysis (0.5% w/v) was carried out in standard solutions in citrate buffer (50.0 mM), at pH 4.5. The enzyme activity was determined with Eq (1):

$$Activity(U/mL) = \frac{A * 1000 * V_T}{\varepsilon * l * t * EV} \quad (1)$$

where:

A = sample absorbance

l= light-path length (cm)

V_T = Reaction total volume (µL)

ε = molar extinction coefficient (µmol/mL*cm)

t = reaction time (min)

EV = Enzyme volume (µL)

With U the amount of enzyme necessary to convert 1 mol of DNS per minute.

2.2.5. Immobilization of naringinase on the banana peel suport (BS-NG)

The enzyme (1 mg/mL) was solubilized in a HPO_4^{2-}/H_2PO^{4-} buffer (25 mmol/L), pH 7. Then 2 mL of the enzymatic solution and 30 mg of SB were stirred for 1 h at 22°C in a roll bed. During the immobilization process, aliquots of the supernatant were removed. Bradford method [21] was used for protein quantification on the supernatant before starting the contact between enzyme and support and at the end to calculate the immobilization percentage of the enzyme on the support. Yield immobilization was calculated using Eq (2).

$$YI = \frac{1 - FP}{IP} * 100 \quad (2)$$

where:

YI = Yield immobilization (%)

FP = final protein content (mg/mL)

IP= initial protein content (mg/mL)

2.2.5. pH Influence on the enzymatic immobilization

To determinate the pH influence on the yield immobilization, YI was calculated by solubilizing the enzyme at 22 °C in buffer solutions between pH 4 and 8 that were prepared using 1 M citric acid ($C_6H_8O_7$) solution and a 2 M sodium phosphate (Na_2HPO_4) solution according to McIlvaine [22]. Buffer solutions between pH 9 and 10 were prepared using a bicarbonate buffer ($NaHCO_3/Na_2CO_3$).

2.2.6. Enzyme kinetics for free and immobilized enzyme

Enzyme kinetics was performed with different concentrations 0.1 – 2 mg/mL of naringin substrate at 22°C, enzyme load of 1 mg/mL and at 15 min. The enzymatic activity was calculated at each concentration and subsequently the V_o reported in mg/min/mg. K_M and V_{max} were calculated by the Lineweaver-Burk method [23].

2.2.7. Effect of pH and temperature on non-immobilized and immobilized naringinase

The enzyme behavior at different pHs was prolonged by measuring the enzyme activity at a constant temperature of 22 °C in a pH range between 2-10 and intervals of one. Buffer solutions between pH 2 and 8 were prepared using a 1 M citric acid ($C_6H_8O_7$) solution and a 2 M sodium phosphate (Na_2HPO_4) [19].

Buffer solutions between pH 9 and 10 were prepared using a bicarbonate buffer ($NaHCO_3/Na_2CO_3$). After knowing the optimum pH, the effect of temperature in the 22 – 90 °C range was analyzed by measuring the enzymatic activity at optimum pH. The measure of naringin activity was realized using the spectrophotometric technique previously described in 2.2.4. section.

2.2.8. Reusability of immobilized naringinase

The reuse was verified by the reaction of 0.5 g of SB derivative with 2 mL of naringinase solution 1 mg/mL in 50 mM sodium citrate buffer at pH 4.5, at 22 °C, and each cycle lasted until the amount of reducing sugars formed was constant with time. The derivative was then rinsed with solution of sodium acetate 100 mM (pH 5.0) at 25 °C, finally the biocatalyst was separated from the product by centrifugation and then submitted to a subsequent cycle.

3. RESULTS AND DISCUSSION

3.1. Support characterization

Figure 1 shows Fourier Transform Infrared (FTIR) spectra of free naringinase (Figure 1a), banana support (Figure 1b) and naringinase immobilised on banana support (Figure 1c). The signal observed in the FTIR spectrum of non-immobilized naringinase (Figure 1a) at 1650 cm^{-1} corresponding to amide I while the signal at 1546 cm^{-1} can be assigned to the amide II [24]. Additionally, the carbohydrate moiety of the enzyme shows the asymmetric and symmetric stretching vibrations of methylene at at 2933 cm^{-1} [25] and the band at 1029 cm^{-1} corresponds to C-O [26].

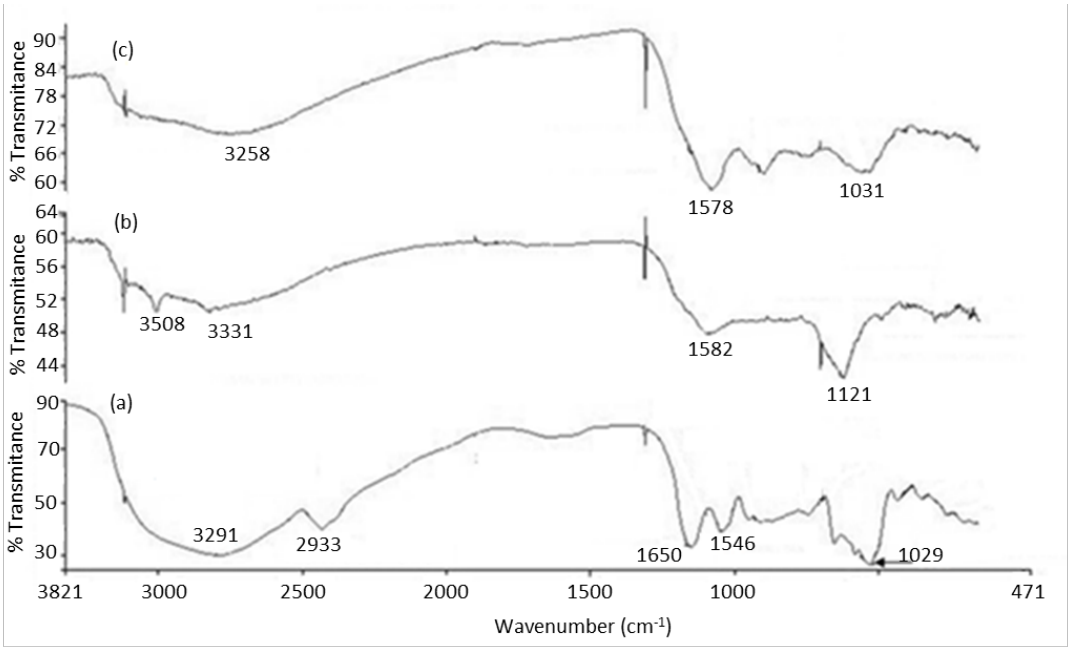
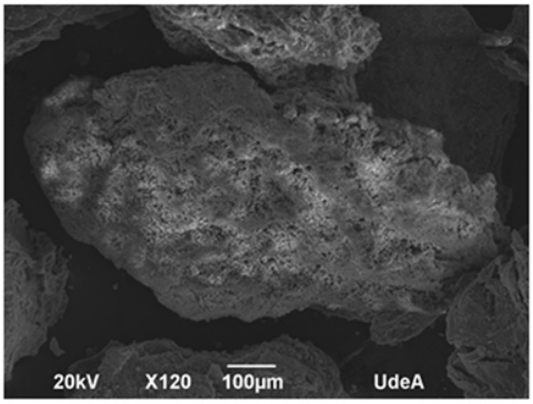
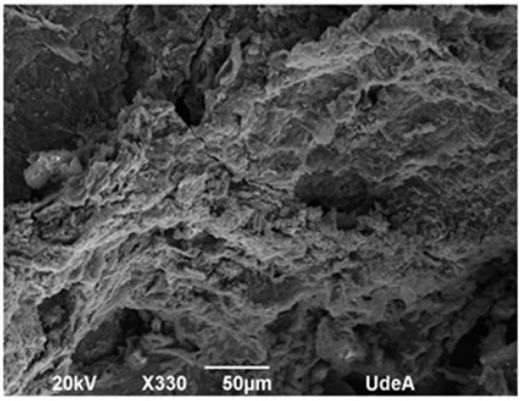


Figure 1. Infrared spectra of: (a) naringinase (NG), (b) BS, (c) BS-NG. **Source:** authors, 2023.





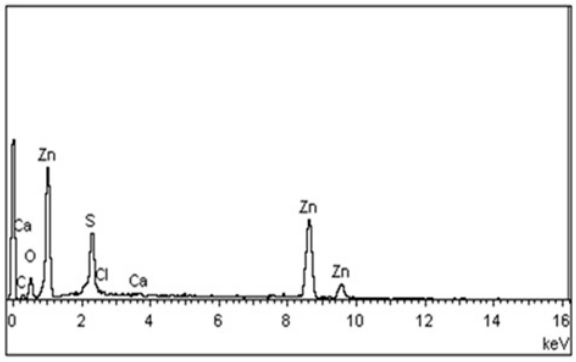


Table 1. Mean elemental composition

Element	Weight (%)
C	4.44
O	12.03
S	7.04
Al	0.89
Zn	75.36
Ca	0.38
Cl	0.59

Figure 2. SEM photograhs, EDX spectra and mean elemental composition of BS. **Source:** authors, 2023.

Furthermore, the FTIR spectrum of BS (Figure 1b) shows signal at 3508-3331 cm^{-1}, 1582 cm^{-1} and 1121 cm^{-1} can be assigned to O–H stretching, C= C stretching vibration in aromatic rings and asymmetric stretching of aromatic ethers, esters, and phenols [27]. Appearance and disappearance of some peaks in the spectrum of the naringinase immobilized on banana support (Figure 1c) can confirm the immobilization [28]. These results are comparable with those reported in the literature [29]. The morphology of the banana support before naringinase immobilization analyzed by SEM are shown in Figure 2.

The images indicated the presence of structure with opening in the material surface resembled the formation of pores. These pores can result of the activation process with $ZnSO_4.7H_2O$ and release of volatile compounds during the thermal treatment, it makes possible naringinase immobilization. The analysis of constituent elements was performed using EDX and this analysis showed that the banana support is formed by carbon, oxygen, sulfur, and zinc and calcium, aluminum, and chloride as minor elements.

3.2. Immobilization of naringinase on SB Support

The immobilization yield (YI) was determined at different pHs (see Figure 3a), and it was observed the maximum YI (above 70%) at pH 7. The residual protein during the immobilization process at pH 7 after 30 minutes decreased around 30% and 70% in 60 minutes (see Figure 3b). These values suggest that the enzyme is immobilized on the support through physical interactions such as electrostatic forces of van der Waals that corresponds to immobilization by adsorption.

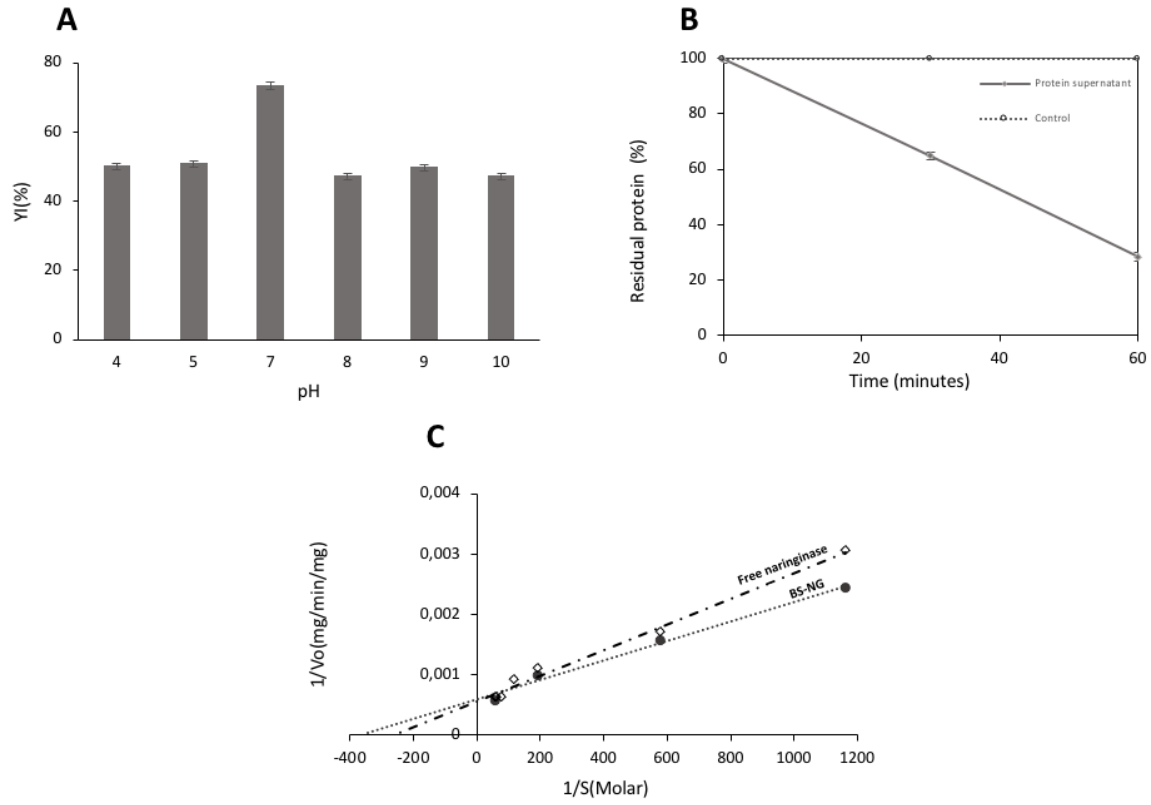


Figure 3. (a) pH influence on yield immobilization of naringinase, (b) quantification of residual protein of the supernatant during the immobilization of naringinase on BS at pH 7 and (c) Lineweaver-Burk graph for free naringinase and BS- NG.
Source: authors, 2023.

3.3. Michaelis-Menten Kinetics

The determination of K_M and V_{max} was done from various concentrations until a saturating concentration of the substrate was identified. The K_M and V_{max} values obtained by the Lineweaver-Burk method [23] for non-immobilized enzyme was 0.0006 molar and 2000 U, and 0.0003 molar and 1666 U, for the immobilized enzyme. The straight line obtained for the concentration of substrate with the free and the immobilized enzyme present a regression coefficient R^2 = 0.9819 and R^2 = 0.9876, respectively (see Figure 3c).

The lower value of K_M suggest that the immobilized enzyme has a higher affinity to the substrate that the non-immobilized enzyme enzyme, due to its lower value in K_M [30].

3.4. Variations of temperature and pH on the behavior of non-immobilized and immobilized naringinase

Figure 4 shows the variations of temperature and pH on the behavior of non-immobilized and BS-naringinase. It can be observed that 4.5 was the best value of pH for non-immobilized and SB- naringinase, which agrees with reported pH effect [31-34]. The behavior of both enzymes was very similar increasing from pH 2 to 4.5 as a maximum of relative activity and decreased from pH 6.5 to 10.

Variations of the temperature were different for free naringinase and BS-naringinase, the optimum temperature for free naringinase was 70 °C which agrees with reported values in the literature (60 – 70 °C) [31,32]. For BS- naringinase, 50 °C was the optimum temperature, nevertheless at 55 °C relative activity fluctuated slightly

retaining 95% of activity which suggest that the enzyme immobilization improved thermostability.

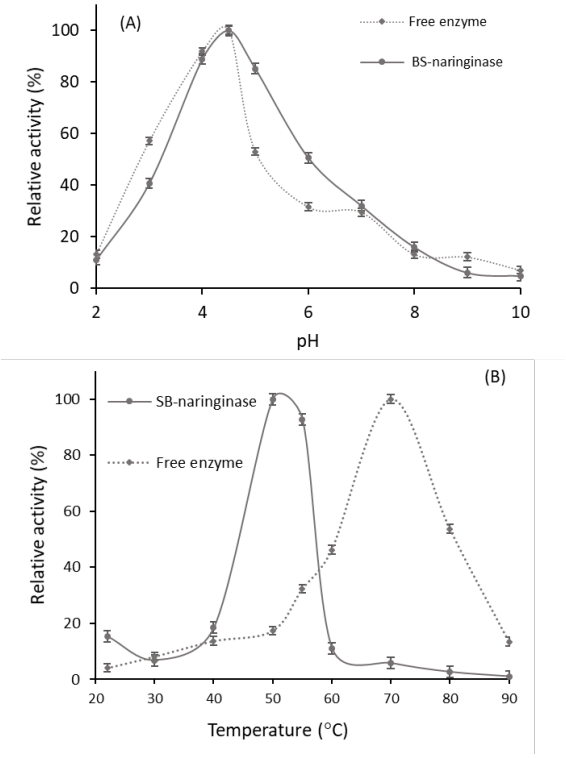


Figure 4. Variations of pH (A) and temperature (B) on the behavior of non-immobilized and immobilized naringinase. **Source:** authors, 2023.

3.5. Reusability of naringinase immobilized (BS-naringinase)

It was found that the SB-support was able to retain at least 100% in the first recycle. The naringinase activity decreased 50% in the second recycle, and in the fourth recycle the relative activity decreased drastically (see Figure 5). Enzyme leaching from the SB supports or denaturation of the naringinase during the intermediate processes between each reuse could be the causes of the activity lost. Successive studies must be carried out to improve the reusability of the BS-support. There are other characteristics that makes attractive the reported synthesis because the low cost of the material, the simple immobilization technique, the considerably required lower enzyme amount, and the relatively high yield of prunin and naringenin that can be obtained in a short period of time.

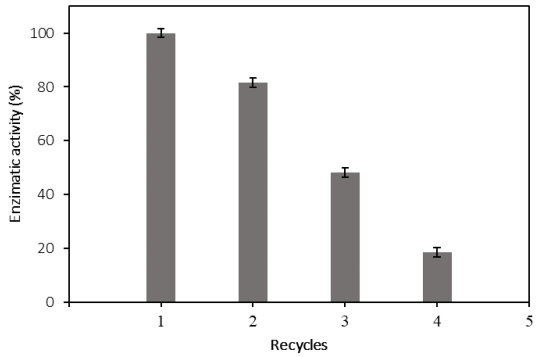


Figure 5. Reusability of BS-naringinase. Conditions: 0.5 g of BS; 2 mL of naringinase (1 mg/mL) in 50 mM sodium citrate buffer; pH 4.5; 22 °C. **Source:** authors, 2023.

4. CONCLUSIONS

This study shows the procedure for obtaining a support from banana peel for the immobilization of naringinase enzyme. The solid was prepared by chemical activation by $ZnSO_4.7H_2O$, then a thermal treatment in nitrogen atmosphere at 500 °C. The FT-IR analysis allowed us to confirm that the enzymatic immobilization process was carried out efficiently, while SEM-EDX showed the presence of pores and carbon, oxygen, sulfur, zinc as main elements. The methodologies applied to immobilize the commercial naringinase produced enzymatic derivatives with excellent kinetic properties. The value of yield of naringinase immobilized and its activity suggested that banana peel materials are promising matrices for immobilization of naringinase. The obtained material showed catalytic potential in the hydrolysis of naringin.

5. ACKNOWLEDGMENTS

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RELIABILITY ANALYSIS FOR A FEEDER OF AN ELECTRIC POWER DISTRIBUTION COMPANY IN ECUADOR USING THE MONTECARLO SIMULATION METHOD

Análisis de confiabilidad para un alimentador de una empresa distribuidora de energía eléctrica en Ecuador utilizando el método de simulación Montecarlo

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Abstract

This study focuses on the evaluation of the reliability indexes of a feeder belonging to an Ecuadorian energy distribution company, reliability analysis is currently a topic of vital importance when making decisions in the area. technique for the electrical supply, in this way, in the first instance, a general evaluation of the feeder is carried out with the objective of collecting important information focused on; areas of influence, global indicators, failures and their causes. With the collection of information, we proceed to design a computational algorithm in the Matlab environment following the Montecarlo simulation methodology because this allows us to evaluate complex mathematical expressions with greater accuracy, concluding with results that allow us to estimate the reliability in the feeder to subsequently take measures to improve the reliability of the feeder.

Key words: *reliability, Montecarlo simulation, distribution feeder, indices.*

Resumen

Este estudio se enfoca en la evaluación de los índices de confiabilidad de un alimentador perteneciente a una compañía Ecuatoriana de distribución de energía, el análisis de confiabilidad en la actualidad es un tema de vital importancia al momento de tomar decisiones en el área técnica para el suministro eléctrico, de esta forma en primera instancia se realiza una evaluación general del alimentador con el objetico de recopilar información importante enfocada a; áreas de influencia, indicadores globales, fallas y sus causas. Con el levantamiento de información se procede a diseñar un algoritmo computacional en el entorno de Matlab siguiendo la metodología de la simulación Montecarlo debido a que esta nos permite evaluar expresiones matemáticas complejas con una mayor exactitud, concluyendo con resultados que permiten estimar la confiabilidad en el alimentador para posteriormente tomar acciones con la finalidad de mejorar la confiabilidad del alimentador.

Palabras clave: *confiablidad, método Montecarlo, alimentador de distribución, índices.*

1. INTRODUCTION

Electric power is one of the main bases for socioeconomic progress. Today, thanks to the progress of engineering as a discipline based on applied sciences and technology, clean technologies have been successfully implemented in power generation processes. This represents an important step towards a more sustainable and environmentally friendly future [1]. But the progressive increase of energy consumption due to the increase of loads establishes the fundamental precedent on which the present study is based, the distribution systems are subject to regulations such as ARCERNNR 002/20 for Ecuador, which decrees the indexes, quality parameters and indicators of the distribution service and commercialization of electric energy with the objective of granting reliability and continuity of the electric service to the Ecuadorian population [2].

Reliability seeks to quantify the performance of a system under specific operating conditions, the use of reliability concepts in power distribution systems emphasizes the load points considering their failures or interruptions that may occur, therefore, it is necessary to perform reliability assessments by examining all facets of engineering; design, planning and operation [3-5].

Failures are not always independent as assumed in many mathematical calculations, the failure of one element can increase the probability of failure of other equipment in a feeder, the most probable causes are lightning, snow, high winds, etc. Not only weather conditions affect the continuity of the electrical service, but also internal causes such as; protection failure, human failure, overloads, faulty equipment and short circuit failures [6-7].

The Monte Carlo method uses a quantitative perception of the data, it can be classified within the experimental methods, because it stochastically generates variables and the results are measured, without directly solving the equations, therefore, it is an efficient method that helps to perform the analysis of reliability behavior in the distribution feeder [8-10].

2. MATERIALS AND METHODS

The analysis of reliability indicators is based on the Monte Carlo simulation model for medium voltage (MV) radial distribution electrical networks, and its results are compared based on two distributions; Exponential and Weibull. The analysis is conceived from globalized indexes of duration and frequency of faults per kVA installed and is modeled from the behavior of the feeder and its components (Disconnections, Transformers and MV Lines).

2.1. Regulation 002/20 ARCERNNR.

Regulation No. 002/20 established by the Agency for Regulation and Control of Energy and Non-Renewable Natural Resources (ARCERNNR) aims to guarantee the continuity and reliability of the electric service to end users, through quality standards established in the section "QUALITY OF THE TECHNICAL SERVICE" with which different electric power distribution companies within the Ecuadorian territory are governed by regulations.

2.2. Indices used for feeder components modelling

2.2.1. Failure rate

It represents the number of failures occurred in a component of the system in the observation period (e.g. 1 year) in which such component was operating.

$$\lambda = \frac{m}{\sum Toi}\left[\frac{Failures}{Year}\right] \quad (1)$$

Where:

m = Total number of failures of element i

Toi = Duration in which the element i is in operative or available state

Σto = Cumulative duration of the maneuver of element i

2.2.2. Average time to failure

Indicates the amount of time it takes for component "i" to fail. It is obtained as the inverse of the failure rate.

$$MTTD = \frac{1}{\lambda} * 8760\left[\frac{Hours}{Failure}\right] \quad (2)$$

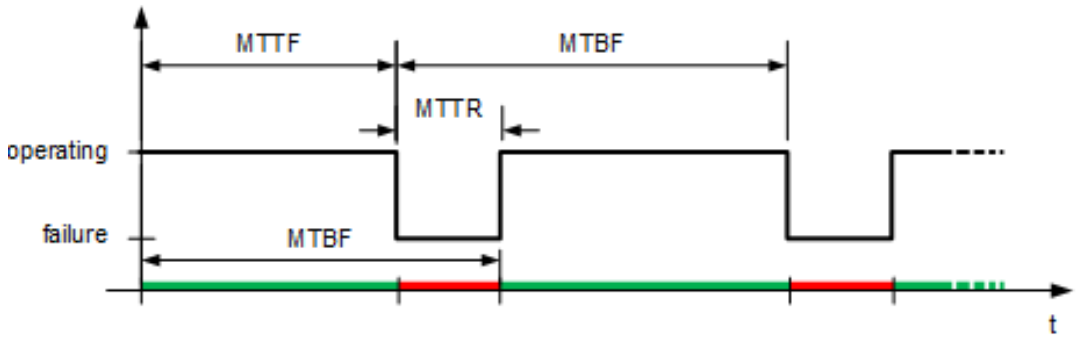

Figure 1. Temporal availability diagram used for modeling. **Source:** reliability analysis, 2019.

2.2.3. Repair rate

Indicates the number of repairs of a system component in the period in which it was operational.

$$\mu = \frac{1}{MTTR} \left[\frac{1}{Hours}\right] \quad (3)$$

2.2.4. Mean time to repair

Indicates the average time required to repair a component when it becomes unavailable or fails.

$$MTTR = \frac{\Sigma Tr}{m} \left[\frac{Hours}{Failure}\right] \quad (4)$$

The sum of the MTTF and MTTF mean times provided the mean time between failures (MTBF) as shown in figure 1.

2.3. Characteristics of the Feeder in 2020 and 2021

For the year 2021 there is a decrease in the number of users due to adverse causes, however, the growing demand can be evidenced with a differential of 419.78 kW per year in the year 2021 with respect to the year 2020.

2.4. Historical analysis of the feeder distribution system

For the evaluation of the indexes, it is necessary to categorize and classify the interruptions according to their origin, within the feeder there are scheduled and unscheduled interruptions that were recorded during the years 2020 and 2021, all interruptions exceed 3 minutes of duration and are classified into internal and external interruptions to the Distribution system. The external scheduled and unscheduled outages were:

- Transmission and Generation.

Internal scheduled and unscheduled outages were:

- Network disturbances
- Environmental
- Third-party

The feeder is a high-density urban feeder, so its FMIK limit value is 7 failures per year and the TTIK limit is 10 hours per year. These indexes reflect the total duration out of service of the distribution network, to define that a parameter "exceeds" the allowed limits in the case of FMIK its value must be less than 7 and TTIK less than 10. However, the overall indices in figure 2a exceed the values allowed by the ARCERNNR, in violation of regulation 002/20 in its "Technical Service Quality" section.

Within the historical period of record, it can be observed that the greatest number of interruptions were caused by failures in the distribution network equipment and accessories (see figure 2b), and the interruptions that left the feeder out of service for the longest time were caused by external maintenance interventions programmed by the electric power distribution company (see figure 2c). For the reliability analysis, the availability model for distribution systems is used, since this is a proactive model for diagnosing reliability and service factor of a distribution process for a period of time (2 years), it seeks to describe and characterize the current status of a process and predict its future behavior based on the reliability and configuration of its components, by analyzing the history of repairs, failures, operating conditions and technical data.

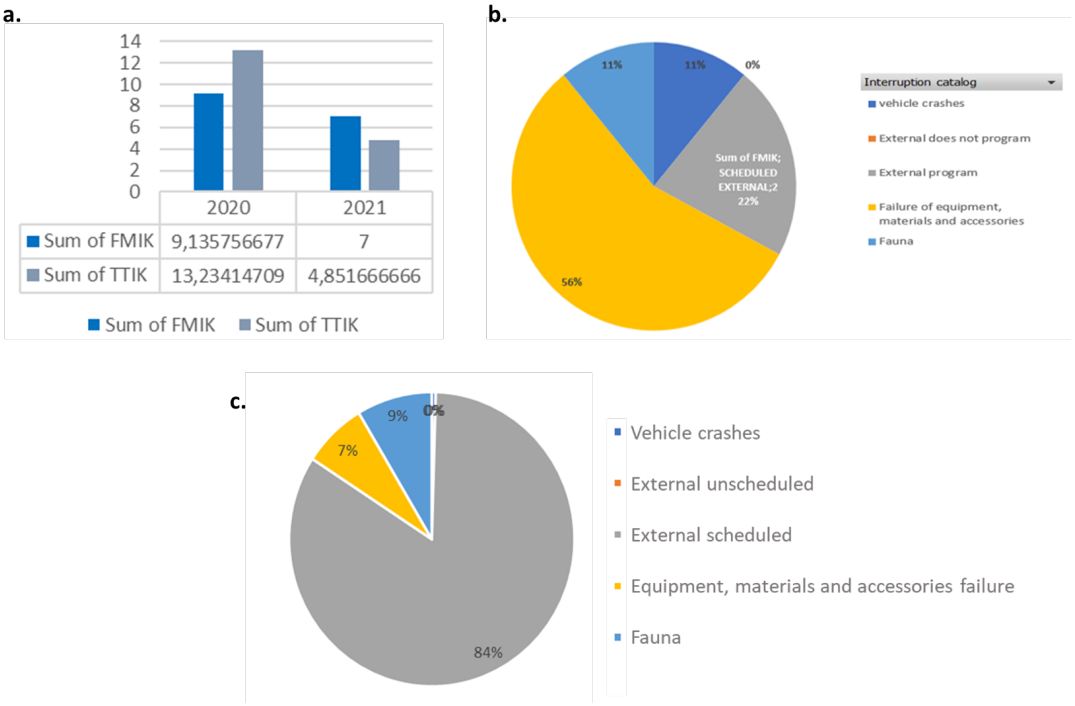

Figure 2. (a) Global indicators of total interruptions registered in the year 2020 and 2021, (b) Impact of interruptions on the Distribution Feeder and (c)Impact of interruption time on the Distribution Feeder. **Source:** authors, 2023.

Components are the equipment that make up a feeder, such as: transformers, disconnectors, transmission lines, protections, etc. Within the research field the components studied are generalized to 3 main elements which are:

- Main and lateral lines
- Disconnectors
- Transformers

For the year 2021 it can be observed that there is an improvement in the electric service quality indexes, this is due to the fact that the electric power distribution company has applied corrective and preventive maintenance measures, thus reducing the unavailability index from 68% in the year 2020 to 30% in the year 2021.

To calculate the total availability of the system, the historical record time (2 years) must be taken into account, in the case of the feeder, this period of time includes the years 2020 and 2021, resulting in a total of 1,720 hours and an availability of 99.8968%.

From the dates of failures recorded for the years 2020 and 2021, a distribution adjustment is made through goodness of fit tests to know which distribution function best fits the data obtained from the time between failures, for this purpose a description of the data for distribution adjustments is made within the STATGRAPHICS 19 program.

P-values less than 0.05 would indicate that Hours Between Failures does not come from the distribution selected with 95% confidence, while P-values close to 1 indicate that the correlation of the data coincides with 95% confidence, for this reason the research will focus on applying the Weibull Distribution model to estimate the reliability in the Excel environment under the criterion of being the second distribution with a correlation of 97.15% as shown in figure 3.

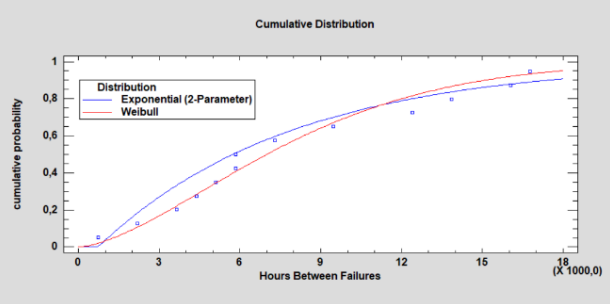

Figure 3. Comparison between cumulative distribution traces of Selected distributions. **Source:** Authors, 2023.

The Exponential distribution model is chosen for its high degree of correlation to analyze the reliability indexes; it will be designed by means of an algorithm following the Monte Carlo methodology in the MATLAB environment.

3. RESULTS AND DISCUSSION

3.1. Reliability and unavailability for the feeder using the Weibull method

Parameters to estimate the reliability through the Weibull density function are obtained by calculating the equation of the straight line, these parameters are the slope "β", the value of the scale "θ" and the constant "b", to calculate the value of the scale the exponential of the value of the constant divided by the value of the slope must be found; by performing the data curve fitting the following parameters are obtained.

3.1.1. Weibull parameters

Beta (β)=1,56564
Eta (θ)= 8853.6
Cte (b)=-11,6147

To find the Weibull density function, the eta and beta parameters are replaced in equation 6:

$$R(t)=\int_{S}^{\infty} f(s)ds = e^{\left[-\left(t-\frac{\delta}{\theta}\right)\wedge\beta\right]} \quad (6)$$

Unavailability is calculated from expression 7:

$$F(t)=1-R(T)=1-e^{\left[-\left(t-\frac{\delta}{\theta}\right)\wedge\beta\right]} \quad (7)$$

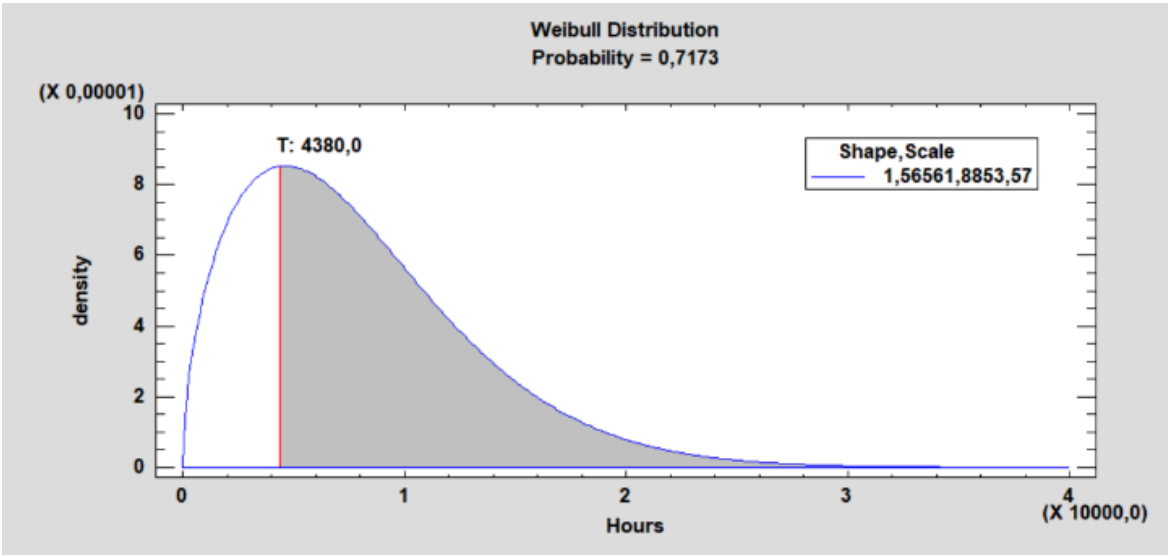

Figure 4. Distribution function for the Weibull density with t=4380. **Source:** authors, 2023.

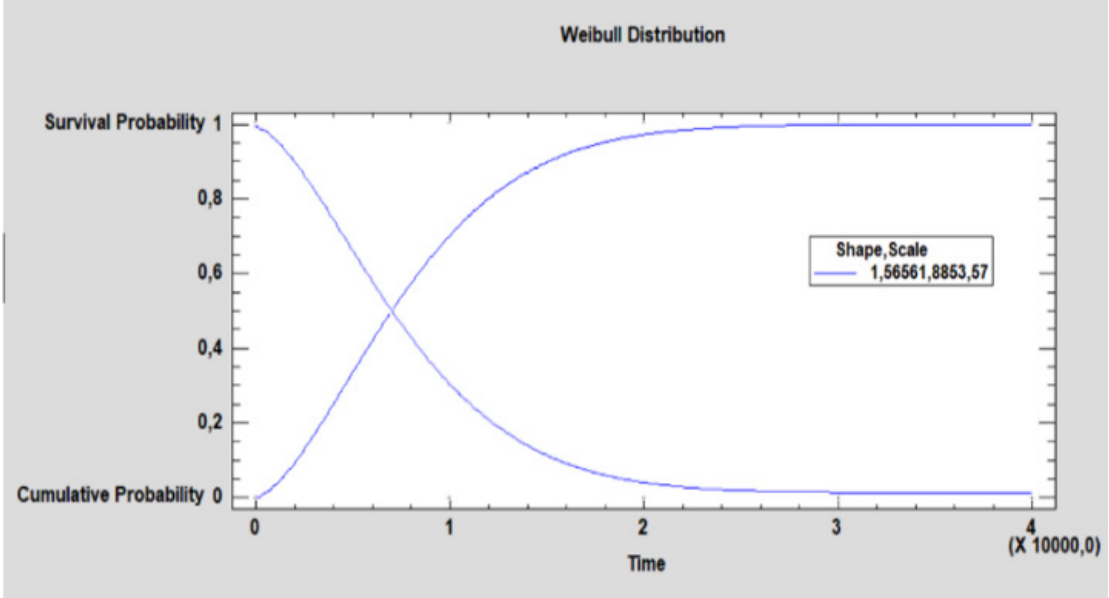

Figure 5. Reliability vs Unavailability curve Weibull analysis **Source:** authors, 2023.

In this way the reliability within a time "t" governed by parameters of this distribution is estimated as can be seen in the figure 4. To estimate the reliability of the feeder within 5 variables "t" that can take any desired value, for this case the variable "t" takes as first value the hours corresponding to 1 month and the following in jumps of 6 months to perform a semiannual analysis of the feeder behavior with respect to reliability and unavailability for a period of 2 years of estimation (see figure 5).

For example, in table 1the output indicates that the probability of obtaining an unavailability less than or equal to 730.0 hours is 0.0198994 for the fitted Weibull distribution.

The curves in function to the Weibull distribution for the reliability and unavailability of the Feeder, where the survival function indicates the probability of obtaining a value greater than or equal to that shown on the X-axis and the cumulative function indicates the probability of obtaining a value less than or equal to that shown on the X-axis.

Table 1. Reliability and unavailability using the 2-parameter Exponential distribution.

t [months]	t [hours]	Unavailability	Reliability
1	730	2,16435E-05	0,999978
6	4380	0,396056	0,603944
12	8760	0,670236	0,329764
18	13140	0,819943	0,180057
24	17520	0,901685	0,0983147

3.2. Monte Carlo algorithm to calculate and evaluate the reliability indexes in the feeder using the Exponential Distribution method

The objective of the designed program was to perform a reliability analysis, presenting at the end the global indexes for each modeled element of the feeder. Where through different components the basic structure of the Monte Carlo methodology is molded, this method is executed under the conditions of a sequential scenario with system state transition sampling. The main structure of the algorithm implemented for the Monte Carlo simulation is shown in figure 6.

The input parameters will be the evaluation time in months, the number of interactions needed according to the proximity to the actual value required (1000 interactions are recommended) and finally the projected power of the feeder in the specified time, these data will help to set the limits to which the data obtained in the process modules 2 and 3 set in Figure 7 should be adjusted.

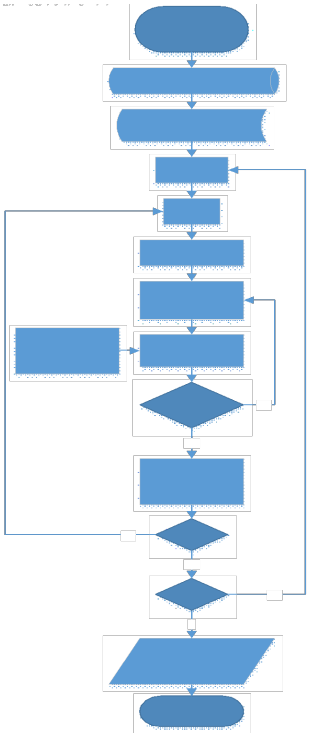

Figure 6 General structure of the implemented Algorithm. **Source:** authors, 2023.

The random variables applied to the MTTR and MTTF times with an exponential distribution of two parameters as analyzed in the previous chapter, are generated from the expression *"Exprnd"* this syntax of the Matlab language generates a random number "n" from an exponential distribution where "i" will be the value of the mean assigned by the researcher, in case of obtaining the variables of the distribution is used:

$$n = exprnd(i;\beta;\gamma)$$
$$N_{MTTR} = exprnd(\mu;\beta;\gamma)$$
$$N_{MTTF} = exprnd(\lambda;\beta;\gamma)$$

In the results window are printed the indexes to evaluate the reliability FMIK and TTIK which indicate both the failure frequency and the duration time, these indexes take the accumulated value for a time t specified by the researcher and a number of interactions that is recommended from 100 to 1000 because when using an exponential distribution, the values tend to have a greater margin of error due to the exponential accumulation of the variables after n interactions (see figure 7a).

To evaluate and estimate the reliability of the feeder, 5-time values ranging from 730 to 17520 hours, equivalent to 24 months of operation, are established as input parameters to perform the simulation under the same parameters analyzed with the Weibull distribution and to make a comparison, each one is evaluated with 1000 interactions (closer approximation to the real value), which results in the table 2.

Using 1000 interactions what is achieved is to reduce the margin of error due to the exponential accumulation of variables in the established model, it should be considered that for the results to be reliable they must have a margin of error of 5% and the convergence between the accumulation of data after n interactions results in n=1000.

From the survival and cumulative probability functions it is possible to plot the curves that describe the behavior of the feeder in terms of reliability and unavailability concepts (see figure 7b).

The results window also prints the FMIK and TTIK indices for the times evaluated in Table 1, with these data it is possible to calculate the availability of the feeder for these time periods (see Figure 7c). From the goodness tests it is determined that the exponential distribution is the one that best fits the distribution represented by the failure history, on the other hand, it is required to compare the results obtained by the implemented algorithm in terms of reliability and unavailability in a given time, for this reason the Weibull distribution is used since they are distributions widely used in the context of reliability.

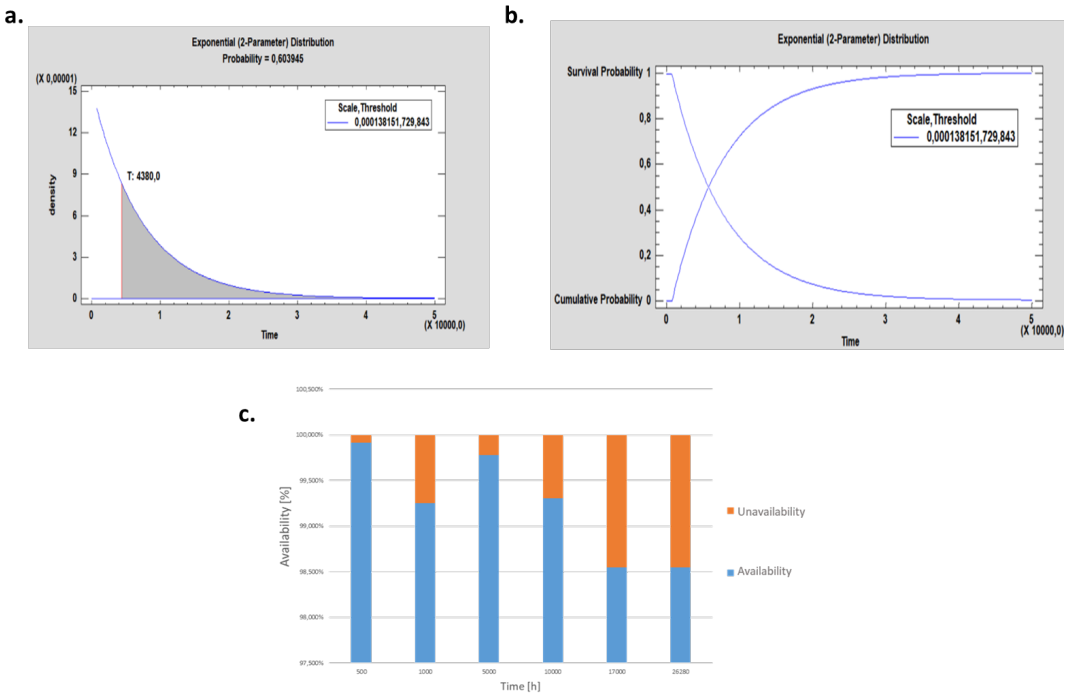

Figure 7. (a) Exponential density function with t=4380, (b) Reliability vs. unavailability curve exponential analysis 2 parameters and (c) Estimated feeder availability and unavailability results. **Source:** authors, 2023.

The statistical summary makes the comparison between the distributions generated for both models, among the main differences we have the variation coefficient that in case of the exponential distribution tends to be higher due to the size of the sample (1000 numbers) generated from random numbers according to the Monte Carlo methodology. The skewness and kurtosis remain within the allowed ranges this means that the results do not possess a significant variance that impairs the confidence of the results, these show that for the Weibull distribution the generated data tend to be close to the mean in a leptokurtic way, i.e.; the kurtosis is greater than 0, for the exponential distribution the data tend to have a skewness of 2. 18 as expected since the exponential distribution is positively skewed and has a kurtosis of 8.058 which indicates that it has a peak characteristic of this type of distribution.

Table 2. Comparison between Weibull and Exponential Distribution (2 parameters) for the distribution feeder.

Time		Weibull distribution		Exponential (2 parameters)	
t [months]	t [hours]	Unavailability	Reliability	Unavailability	Reliability
1	730	0,019899	0,98010	2,1645E-05	0,99997
6	4380	0,2827	0,7173	0,39605	0,60394
12	8760	0,626002	0,37399	0,67023	0,32976
18	13140	0,843629	0,15637	0,81994	0,18005
24	17520	0,94559	0,05441	0,90168	0,09831

4. CONCLUSIONS

The conditions and characteristics of the distribution feeder are evaluated with a record of events between 2020-2021, where the interruptions that affected the continuity of the electric service for the feeder are verified. In 2020 there were a total of 9.13 failures (FMIK) and a total interruption time (TTIK) of 13.34 hours per year. In the year 2021, due to the preventive and corrective maintenance work of the company in charge, there is a decrease for both the FMIK index of a total of 7 interruptions and an interruption time (TTIK) of 4.85 hours per year, which translates into better management and performance, but even so, the feeder does not comply with the "Quality of Energy Distribution and Commercialization Service" regulations established by the Ecuadorian regulatory body ARCERNNR 002/20.

Therefore, according to the analysis performed in the previous sections, two types of distributions have been established for which the failure times have been adjusted correlatively, using the Weibull distribution the results suggest a reliability of 5.44% in 17520 hours, the correlation factor of these data is 0.97, unlike the exponential distribution (2 parameters) which suggests a reliability of 9.83% in 17520 hours, a slightly more accurate value because this distribution has a factor r^2 slightly higher than the Weibull distribution.

By implementing the MATLAB computational software to design an algorithm capable of estimating in a period of time the reliability indexes FMIK and TTIK, it is concluded that the feeder has a high percentage of availability with a total of 98% in an estimation for 2 years with the current characteristics and with a load growth of 2 to 5%, these factors are important and should be taken into account when making expansion designs or redesigns of the feeder.

In spite of this, the indexes exceed the limits established by the Ecuadorian standard ARCERNNR 002/20 in the evaluated time, the feeder will have a higher probability of complying with the limits established for the "quality and service control" for an operation time of up to 7000 hours, that is, 9 months approximately, after which preventive and corrective maintenance maneuvers will have to be carried out.

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METHODOLOGY FOR SUSTAINABILITY ANALYSIS FOR THE ENERGY SECTOR: THE CASE OF LPG AS REPLACEMENT FOR FIREWOOD IN RURAL HOUSEHOLDS IN COLOMBIA

Metodología para el análisis de la sostenibilidad del sector energético: el caso del GLP como sustituto de leña en los hogares rurales de Colombia

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Abstract

In this paper we provided a sustainability analysis for the LPG energy sector in Colombia using different methodologies: analysis of primary and secondary sources of normative documents; programmatic and regulatory framework of LPG; a study on the current tax burden of fuel gas subsidies; scenarios for the expansion of LPG subsidies; a socio-environmental sensitivity analysis; identification of relevant territorial factors to make prioritization recommendations in the replacement of firewood by LPG in specific areas; LPG emissions estimations as a strategy for replacing firewood in rural homes and the analysis of the economic sustainability of the business using different indicators. The research begins with a brief introduction which describe and highlights the importance of analyzing studies of natural gas and LPG in Colombia. The first section briefly exposes the theoretical and conceptual framework that supports the research. The second section presents the methodology used for each of the analysis topics. The third section shows some of the results achieved during the investigation and the main conclusions. Finally, we provide a series of reflections and insights for sustainability research where the dialogue of knowledge and multidisciplinary is encouraged.

Key words: *sustainability, energy transition, methodology, energy sector, LPG, firewood, cooking fuel.*

Resumen

Presentamos un análisis de sostenibilidad para el sector energético de GLP en Colombia utilizando diferentes metodologías: análisis de fuentes documentales primarias y secundarias de documentos normativos; marco programático y regulatorio del GLP; un estudio sobre la carga tributaria actual de los subsidios al GLP; escenarios para la expansión de los subsidios al GLP; un análisis de sensibilidad socio-ambiental; identificación de factores territoriales relevantes para hacer recomendaciones de priorización en la sustitución de la leña por el GLP en áreas específicas; estimaciones de emisiones de GLP como estrategia para reemplazar la leña en hogares rurales y el análisis de la sostenibilidad económica del negocio utilizando diferentes indicadores. Se presenta una breve introducción en donde se destaca la importancia de este tipo de investigaciones en Colombia. La primera sección resume el marco conceptual que respalda la investigación. La segunda sección presenta la metodología utilizada para cada uno de los temas de análisis. La tercera sección muestra algunos de los resultados logrados durante el desarrollo de la misma. Finalmente, se proporcionan una serie de reflexiones e ideas para la investigación de sostenibilidad fomentando el diálogo del conocimiento y la multidisciplinariedad.

Palabras clave: *sostenibilidad, transición energética, metodología, sector energético, GLP, leña, combustible para cocción.*

1. INTRODUCTION

T Natural Gas and LPG are currently fundamental energy sources for the Colombian energy matrix, therefore researching the sustainability of the processes associated with the exploration, production, distribution, and consumption of gas in the country is essential to generate prospects for regional sustainable development within the general framework of a global energy transition.

Since the 1990s, Colombia began a transformation in the energy matrix as a result of the discovery of mega gas fields in the north of the country. Natural gas was promoted through different public policies that improved the infrastructure and competitiveness for its distribution and commercialization in areas of the national territory [1].

In 1993, before the implementation of the gas massification plans, 30% of households in Colombia used electricity for cooking, 38% used natural gas or LPG, 21% firewood and 11% used other fuels such as kerosene, gasoline or cooking oil. By 2020, 86% of homes use natural gas or LPG, 10% firewood, 3% electricity and other fuels represent 1%.

Natural Gas -GN- is the main fuel for cooking in urban areas given the technical facilities provided by gas connections. 80% of households in the municipal capitals have a connection to Natural Gas and use it as cooking fuel.

In rural areas where there is no possibility of massive connection to gas pipelines, LPG has been positioned as one of the most important cooking fuels. For the year 2020, the Quality-of-Life Survey (ECV) estimated that 21.9% of households in Colombia used LPG as the main fuel for cooking. While in rural areas this percentage was 43.3%, making it for the first time the most used fuel in the rural sector [2].

In addition to the importance of gas for millions of urban and rural homes, in the thermal, industrial, and commercial sector, gas is an essential factor for productivity. The industrial and thermal sector consumed around 53% of the country's Natural Gas in 2021.

The industrial sector is the main driver of demand in the country and, according to UPME projections, it is expected to continue to be so until 2033, when thermal consumption for electricity generation is expected to grow [3]. Between 2025 and 2030, the UPME has projected an average growth rate of 0.40% for Natural Gas and 2.44% for LPG. In the medium growth scenario, the demand for Natural Gas would reach 1,300 GBTUD per year by 2035, while the demand for LPG would reach 42,000 GBTUD. In this scenario, the deficits between the national supply and the demand for NG can be reached as soon as 2026 if there is no increase in national production. Which could mean the loss of national energy autonomy and put millions of homes at risk due to price increases subject to international volatility.

1.1. Sustainability and energy transition: analysis reference frameworks

Sustainability is a concept that emerged as a social, economic, and environmental ideal in the late 1970s [4]. The concept became relevant worldwide after the publication of the Brundtland Report, also known as the Report: "Our Common Future" where an explicit definition of sustainable development was given. Henceforth, the term ceases to simply belong to the academic community and the history of ecological thought and begins to form part of public opinion and common sense. However, sustainability and sustainable development remain disputed concepts and their precise meaning depends on different attitudes and ideologies towards social, environmental, and economic problems [5][6].

Despite this, we can speak of a hard core of sustainability and sustainable development in two key aspects 1) The notion of complexity and interdependence of real systems, which implies the interrelation between the economic, social, and environmental dimensions and 2) The notion of inter and intra generational justice, which means the search for conditions so that future societies can develop [7]. These coordinates of sustainability and sustainable

development imply seeking development models that allow future generations their own development, understanding the complexity of the relationships between the economic, social, and ecological dimensions.

The definition of sustainability that guided the research was based on the idea of The Natural Step Foundation called "System Conditions" [5][8] which establishes that the principles of sustainability will aim at:

- Eliminate the human contribution to the systematic increase in the concentrations of substances from the lithosphere in the ecosphere.
- Eliminate the human contribution in the systematic increase of substances produced by society in the ecosphere.
- Eliminate the human contribution to the systematic degradation of the physical conditions of the biosphere.
- Eliminate the human contribution in conditions that systematically impede the ability of people to meet their needs.

This definition provides the framework for a more precise understanding of sustainability as it focuses on reducing the damage caused by human activity. In this way, sustainability is understood as the ability for human activities to be channeled into the principles.

One of the main implications of this definition is that it allows us to understand sustainability as a long-term process in which it is possible to take different paths that lead towards these principles. This long-term process is particularly important when analyzing the sustainability of energy systems. Given that the energy transition is one of the central concerns of the organizations, institutions and actors that promote the different visions of sustainability, understanding the transition as a long-term process with different possibilities of action within a framework of complex relationships between the social, economic and environmental dimension is essential to avoid establishing roadmaps that are impossible to meet with absolute criteria that may even be detrimental to the principles of sustainability themselves.

One of its main components of this long-term path of sustainability is the so-called energy transition. Given that one of the main motivations within the sustainable development and sustainability agenda is the reduction of GHG due to adverse climatic effects on different human activities. The change in the energy matrix towards a diversified matrix with less participation of fossil fuels is one of the priorities worldwide [9][10].

The current energy transition is part of a history of technological transformations that have occurred since the 18th century that have been linked to changes in the use of primary energy. Robert Ayres has theorized about three great technological transformations and a fourth transformation still underway that have produced the great changes within modern societies, allowing continued economic expansion [11].

In a similar scheme but more focused on the proper energetic transitions and not only energetic-technical ones, but it is also possible to establish the existence of three transitions. The first coincides with the transition from the use of traditional biomass fuels to coal, the second with the emergence of oil and its derivatives, the third with the positioning of natural gas and the fourth with the entry of renewable energy sources [12]. The technological transformation that is currently taking place is facing a series of important challenges, particularly in the energy transition towards renewable energies, that is, the transition from a fossil civilization [13] to a renewable energy civilization. Table 1 summarizes the main challenges facing the energy transition on the global stage.

In the research we have consider these challenges and what they represent for a global south country like Colombia. As said before, the energy transition as a long-term process towards sustainability means that the public policy must adapt to the conditions given in a certain space and time, because of that, we concluded that the use of LPG as a replace for woodfire in rural areas was worth considering as a possible alternative for reaching SDG goals particularly SDG number 7: Affordable and clean energy.

Table 1. Challenges of the energy transition

Challenge	Implications
Political	International cooperation and coordinate action to mitigate climate change in a short period of time [9] [14][15].
Geopolitical	Weak incentives to achieve transitions, creation of new interest for key raw materials [14].
Economic	Possible burst of the "carbon bubble" as investments shift from fossil fuels to other sectors [16].
Inequality Gap	Technological backwardness in global south countries [17].
Infrastructure, capacity, and logistics	Difficulty for the replacement of fossil fuels in key areas

2. MATERIALS AND METHODS

The research project "GEOLOGICAL HABITAT, PROSPECTIVITY, SOCIO-ENVIRONMENTAL AND ECONOMIC SUSTAINABILITY OF WET GAS (LPG) IN COLOMBIA AS A FUEL OF ENERGY TRANSITION" had the objective of carrying out a geological study within the commercial hydrocarbon production basins to establish a series of scenarios prospects for wet gas (LPG) reserves in Colombia, all articulated to a perspective of environmental, social, and economic sustainability and sustainable development. To develop the research on the social, environmental, and economic sustainability of LPG as a transition fuel, we started from the analysis of the theoretical and conceptual framework that focused on the study of the concept of sustainability and energy transition and how the five lines of research were articulated with these concepts. At the same time, progress was made in the necessary analyzes of the five lines of research for which the study of the regulatory framework and public policy in each of the themes was essential.

The analysis of the regulatory and public policy framework allowed feedback on the research lines (Subsidies, Socio-environmental Sensitivity, Avoided Emissions and Socioeconomic Sustainability) to the extent that it allowed the identification of challenges and limitations within public policy at the national level and the challenges demanded by the changes and the roadmaps proposed at the international level by different organizations.

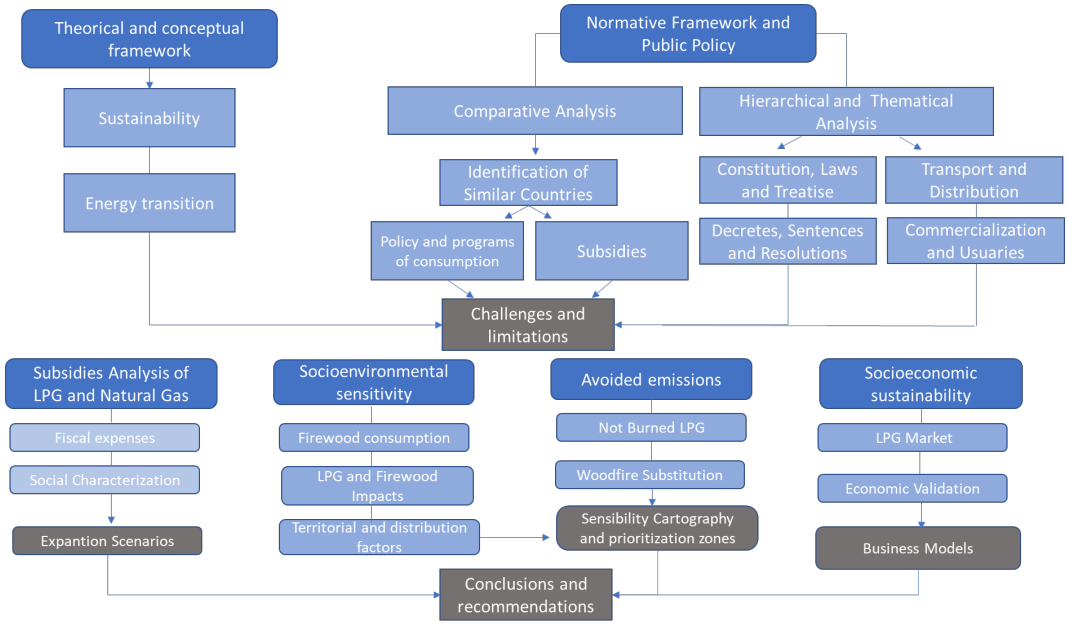

Figure 1. Methodology used in this research. **Source:** authors, 2023.

2.1. Methodology for the analysis of Subsidies

For the analysis of NG natural gas and LPG wet gas subsidies, the expenses in Natural Gas and LPG subsidies in the period 2017-2021 were evaluated. This evaluation was accompanied by a socioeconomic characterization of the users of Natural Gas and LPG, to try to determine if the subsidies are being efficient in their allocation. For this, the following variables within households were considered:

- Household has a network connection to natural gas
- Household uses LPG as the main fuel for cooking
- Household uses firewood as the main fuel for cooking
- Household stratum
- Total household income
- Household per-capita income

The determination of the LPG subsidy expansion scenarios considered the vital minimum determined by the UPME, as well as empirical consumption averages in households measured in surveys. For the determination of the price of LPG, prices were taken as a reference.

2.2. Methodology for the analysis of socio-environmental sensitivity

The analysis of socio-environmental sensitivity to the use of firewood for cooking food in homes, is carried out to prioritize those territories where the substitution of this fuel for a more efficient, less polluting, and harmful to the health of the population becomes more urgent and therefore, guarantee greater access to clean energy.

To carry out this analysis, we started from the analysis of the quantitative and spatial consumption of firewood in the country, the impacts that the use of this energy source generates and the identification of those that are most relevant. For each of the most relevant socio-environmental impacts, indicators are identified that reflect territorial sensitivity to said impact.

The sensitivity indicator corresponds to a condition of the territory, the population or the dwelling that has the potential to cause or maximize unwanted effects of cooking with firewood. These correspond to territorial factors. Then, a weighted aggregation of the territorial factors is carried out, with which the integrated sensitivity index is obtained, which, as well as the individual indicators, is specialized in maps.

Finally, we proceeded to identify the territorial factors for the distribution of LPG in cylinders, which were crossed with the integrated sensitivity map to obtain as a result the map of priority areas for a program to replace firewood with LPG.

2.3. Methodology for the analysis of emissions

The calculation of avoided emissions consists of two components:

- Calculation of possible emissions avoided using the portion of wet gas that is currently burned in the country's production fields.
- Calculation of possible emissions avoided by the eventual replacement of firewood that is currently used in homes for cooking food with LPG.

To perform the first calculation, the gas information associated with the country's production fields was processed, those with gas composition information were filtered, and finally the portion corresponding to wet gas of the gas that is currently flared was obtained. Taking the volume of the portion of wet gas that is burned, the calculation of the emissions that it generates was made, and therefore those that could be avoided if it were not burned in the Teas.

For the second calculation, we start from the volume of firewood used for cooking in rural homes, the emissions are calculated and compared with the emissions generated by LPG that would have been required to do the same job. The difference between the emissions of firewood and LPG emissions correspond to the possible emissions avoided with the substitution of firewood.

2.4. Methodology for the analysis of economic sustainability

For the development of this economic sustainability analysis, the LPG market in the country was reviewed,

which includes the offer from the point of view of gas availability based on the statistics of production data published by the National Hydrocarbons Agency (ANH). The data used corresponds to the gross production of the fields.

The demand study was carried out by sector, which has grown in recent years driven by the policies of mass use of LPG (for example, in the rural sector due to programs to replace firewood with this fuel).

After reviewing the business models that are used in the industry from different points of view, they were basically summarized in two: a first model in which the field operator is in charge of the processing and commercialization of gas products, and a second model in which the operator delivers the gas to a third party to take charge of its processing and marketing. Both have advantages and disadvantages.

For the economic analysis of the LPG business in the country, the existing regulation on the subject was reviewed and that focuses on the mass use of it, grants incentives and subsidies, which has a direct impact on demand. The country's offer was reviewed, based on the associated gas production data at the country level and an economic valuation exercise was carried out for a selected area.

3. RESULTS AND DISCUSSION

In this section we illustrate the results of the investigation by showing some graphic examples and some of the general conclusions of the research. It should be mentioned that these examples are purely illustrative of the results of the work and do not represent the bulk of the work carried out during the investigation.

3.1. Graphic results

The Table 2 summarizes the results of allowances. The final product was a series of expansion scenarios for the LPG subsidy in the country.

The Figure 2 constitutes the result of applying the sensitivity equation through an image rasterization process. The map represents the territorial sensitivity to the cutting of firewood given the possible effects that this activity could generate on the environment and the population.

The map shows that the most sensitive areas are concentrated in Córdoba, Antioquia, Nariño, Cauca, Tolima, Boyacá, Norte de Santander and with medium sensitivity, important areas are observed in the Amazon, Orinoquía, Chocó, the Caribbean region and Bolívar, among others.

The following equations represent the calculation of the CO2 emissions that would be avoided if LPG was not burned in the production fields. According to the calculations around 21 million tons of CO2 could be avoided. Other results, concerning public policy, normative frames and socioeconomic sustainability were discussed and presented in the research but are not presented here due to the length it will demand.

$$Total\ LPG_q = 921.34\ mpc$$

$$1pc = 0.0283$$

$$921{,}340{,}000\ pc = 26{,}089{,}400\ mc$$

$$1mc\ of\ LPG = 264{,}172\ gallons$$

$$LPG_q = 26{,}089{,}400\ mc\ X\ 264{,}172 \frac{gallons}{mc}$$

$$LPG_q = 6{,}892{,}101{,}818.2\ gallons$$

$$CO_2 emissions = 21{,}029{,}181{,}067.0816\ Kg\ CO_2$$

$$CO_2 emissions = 21\ millon\ tons\ CO_2$$

An important output of the research was to formulate a series of conclusions regarding the production, consumption and distribution of LPG in Colombia associated with the replacement of firewood as cooking fuel in rural areas. Here we present some of the most important conclusions derived from the investigation.

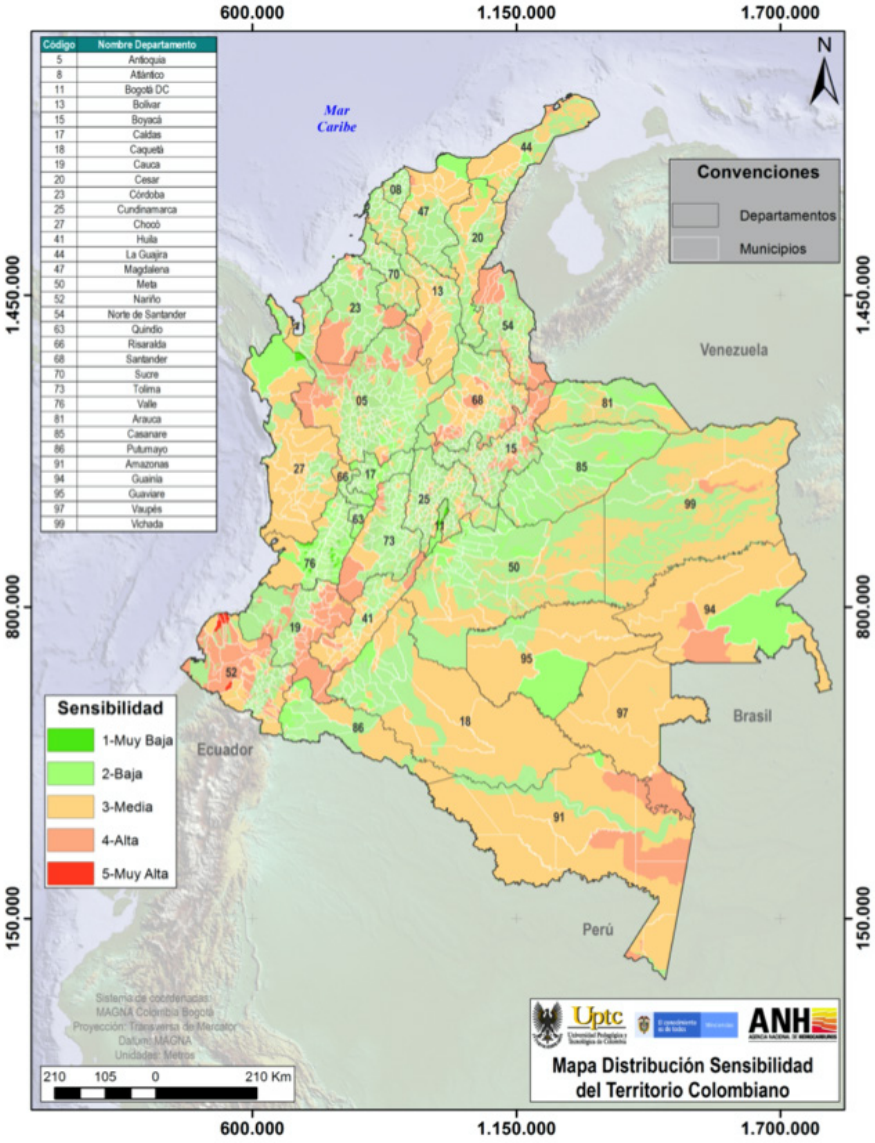

Figure 2. Socio-environmental sensitivity results. **Source:** authors, 2023.

Table 2. Results of allowances

Variables	Q1	Q2	Total
Households	792,000	790,000	1,582,000
Kg allowances per month	6	4.8	
Average price LPG (Kg)	3,304	3,304	
Cost	15,702,718,861	12,530,452,425	28,233,171,286

4. CONCLUSIONS

Within the international regulatory framework to which Colombia belongs, there are different incentives for the increase in the consumption, production, and distribution of LPG. Among them, the reduction of GHG emissions, the increase in energy efficiency, the reduction of deforestation, among others.

Within the national regulatory and programmatic framework, there are incentives to increase the consumption, production, and distribution of LPG. In accordance with laws, government plans, CONPES, resolutions and decrees.

LPG is an excellent fuel for the energy transition as it contributes to the three fundamental pillars of public policy in the energy sector:
- Improves accessibility to energy, through the substitution of firewood for cooking in rural homes.
- It contributes to the reduction of greenhouse gases, since it generates 25% less CO2 than firewood, 24% less than coal, 8.5% less than diesel and 3.1% less than gasoline.
- Contributes to the improvement of energy efficiency, especially in the residential sector, with the replacement of a fuel with very low efficiency such as firewood (3-15%) by LPG, which has efficiencies between 35-50%.

The growing demand for LPG in the country in recent years is largely due to the mass use programs promoted by the national government, such as the firewood substitution plan and subsidies granted by the government for sectors of the population with lower income.

Even though LPG was defined as an essential public service in Law 142 of 1994, this is the only public service that does not have a subsidy that covers the most vulnerable population in the entire country. The subsidies established for LPG are focused on a defined group of municipalities.

The design of subsidies for fuel gas in Colombia has disproportionately benefited Natural Gas to the detriment of LPG, which has meant that the poorest households in the country do not have access to clean and efficient fuels for cooking.

The current allocation by strata of the Natural Gas subsidy is inefficient to the extent that it allocates resources equally to households with very different incomes, since the allocation method is stratification. By establishing alternative forms of subsidy targeting, it would be possible to release resources for the LPG subsidy.

The use of firewood for cooking in homes generates multiple socio-environmental impacts, among which the most important are:
- The loss of vegetation cover and biomass and therefore the affectation of biodiversity.
- The increase in the demand for women's time for unpaid work and leisure, and the decrease in the time available to children for study and leisure.
- The impact on health from the smoke from burning firewood, mainly due to particulate matter, which mainly generates respiratory problems, especially in women, but also in children.

The environmental sensitivity indicators for the three most important impacts of the use of firewood for cooking in homes are:
- The presence of sensitive ecosystems, associated with the affectation of ecosystems.
- The multidimensional poverty index, associated with the increase in the demand for time in unpaid work for adults and children.
- Cooking food in a closed room, associated with health impairments from wood smoke.

The socio-environmental sensitivity analysis for the country yields approximately 1 million hectares in high sensitivity, around 5 million in medium sensitivity and a little less than 5 million in low sensitivity. The most sensitive areas are concentrated in Córdoba, Antioquia, Nariño, Cauca, Tolima, Boyacá, and Norte de Santander, and with medium sensitivity, important areas are observed in the Amazon, Orinoquía, Chocó, the Caribbean region, and Bolívar, among others.

Two fundamental distribution factors for LPG cylinders are accessibility and population density. In terms of accessibility, it is considered that the areas that belong to the SIN and the mixed areas are relatively easily accessible, so a program to replace firewood with LPG can be implemented. From the population point of view, the criterion included in UPME (2022) of serving municipalities that have a rural population greater than the urban one is included.

Regarding the LPG that is currently burned in production fields, the largest volumes correspond to the Caño Limón, Chichimene and Pauto Sur fields and in terms of basins, those with the highest volumes of LPG burned in total correspond to the Middle Magdalena Valley. and Eastern Plains followed by the Upper Magdalena Valley and the Piedmont Zone. In Catatumbo there are no reports of gas flaring and in the Lower Magdalena Valley the amount of gas flaring is very low.

The energy generated by the fraction of humid gas that is currently burned in the country's production fields amounts to 604 PJ, which corresponds to 5.8 times the energy generated by firewood for cooking food in homes per year in Colombia.

The presence of gas in the production of hydrocarbons has begun to stop being seen as a problem, and now it is a business opportunity that is evaluated within the technical, economic and commercial parameters (demand), which allow determining the feasibility of treating it. as a product that generates value for the company.

There are several examples in the country that prove that the gas business is viable. Companies that previously burned or reinjected the associated gas in the production of crude have decided to send it to a gas plant to obtain an economic benefit from it through the different products that can be extracted. Each case is different, and it is a matter of detailed analysis of the possibilities that the business individually can promise.

5. REFLECTIONS ON SUSTAINABILITY RESEARCH

Finally, we propose a series of reflections for research on sustainability linked to energy resources within the framework of the global energy transition.

In the first place, sustainability research must necessarily be multidisciplinary, it must combine diverse methodologies and it must present quantitative and qualitative analyzes with the aim of accounting for complex systems and the interrelationships between society, economy, culture, and the environment. The integration of knowledge also implies an epistemological position where there is no epistemic privilege or a privileged inclination towards the "hard sciences", quantitative methods and numerical results. Human and social sciences, qualitative methods and conceptual results should be considered as equally valid results. Linked to this, it is necessary to recognize that sustainability research lacks an absolute foundation and that the different visions of the concept of sustainability and its interpretations in the short, medium, and long term influence the studies, methodologies, and results.
Another of the key elements that we have identified in the research is the need for a long-term vision to propose pragmatic solutions within the different social, economic, technological, logistical constraints, etc. This is of particular importance within the energy transition, since it is a civilizational change of great relevance, comparable to previous major transformations such as the industrial revolution.

In the methodological aspect, the research found it vitally important to clearly establish the regulatory framework (national and international) that includes aspects of international politics, national legality, and the interaction between these components. It is within the regulatory framework where sustainability research can support clear objectives and public policy recommendations.

The use of social cartography is another of the key elements for the methodology, to the extent that it allows the results of an investigation to be clearly communicated to different actors and decision makers. Finally, the

proposal of a series of public policy recommendations so that decision makers and society in general can participate in the debate is an essential element in research on sustainability within the energy sector.

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CHARACTERIZATION OF MELIPONICULTURE IN THE PROVINCE OF CIENFUEGOS, CUBA

Caracterización de la meliponicultura en la provincia de Cienfuegos, Cuba

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Abstract

The research was carried out in the province of Cienfuegos, with the objective of characterizing the management system and state of health of the *Melipona beecheii* stingless bee hives. In order to evaluate the state of meliponiculture in this territory, all persons keeping colonies of *M. beecheii* bees were surveyed. In five municipalities of the province of Cienfuegos, 22 meliponiculturists were identified. The total number of people who are dedicated to the cultivation of the Melipona species do not carry out the activity professionally; they reveal another occupation. The level of schooling reflects that 59.08% have an intermediate level, 22.72% finished high school and 18% have a higher level with an average age of 42 years. Different models for the manufacture of *Melipona beecheii* hives were identified, showing a living space per hive of maximum capacity and good health.

Key words: *melipona beecheii, meliponiculture, health.*

Resumen

La investigación se desarrolló en la provincia de Cienfuegos, con el objetivo de caracterizar el sistema de manejo y estado de salud las colmenas de abejas sin aguijón *Melipona beecheii.* Para evaluar el estado de la meliponicultura en este territorio fueron encuestadas todas las personas con tenencia de colonias de abejas *M. beecheii.* En cinco municipios de la provincia de Cienfuegos fueron identificados 22 meliponicultores. El total de personas que se dedican al cultivo de la especie Melipona no realizan la actividad de manera profesional, revelan otra ocupación laboral. El nivel de escolaridad refleja que el 59,08 % tienen nivel medio el 22,72% concluyeron la secundaria y el 18 % cuentan con nivel superior con una edad promedio de 42 años. Fueron identificados diferentes modelos para la fabricación de colmenas de *Melipona beecheii,* mostrando un espacio vital por colmena de máxima capacidad y buen estado de salud.

Palabras clave: *melipona beecheii, meliponicultura, salud.*

1. INTRODUCTION

Melipona beecheii Bennett belongs to the group of "stingless bees" and is known in Cuba as the "earth bee". It is, together with *Apis melífera Linnaeus,* the only two species of social bees living on the island, where they are bred and managed by humans to use their products or services in the pollination of agricultural crops.

In the last decades, although the breeding of meliponae has aroused more interest every day, proof of this is the growing participation of professionals and students in scientific events, the publication of articles, as well as the appearance of journalistic news on television or web pages alluding to meliponiculture, with the will to increase and stimulate its management in all regions of Cuba. On many occasions, outdated or erroneous information is handled or published; papers are presented in scientific events that are never published or research results are published in journals with very little international circulation [1].

In the mid-2000s, projects led by the Agrarian University of Havana began to be developed in Cuba, with the aim of showing results on the state of meliponiculture in the western region of the country [2].

In the province of Cienfuegos, there are insufficient references of studies that provide elements on good management practices and biological characteristics of the species *Melipona beecheii Bennett.* In this context, some research is reported, such as the study of morphometric characters to identify the similarities and differences between *Melipona beecheii* bee populations in the municipality of Cienfuegos [3].

Brood population and food reserves in rational hives of *Melipona beecheii Bennett* as basic factors for their health. Important biological parameters of *Melipona beecheii Bennett* have been little studied in Cuba and even less in relation to health. Their determination favors the promotion of the species on the basis of a correct management, especially in rational hives. [4].

2. MATERIALS AND METHODS

The study area covered five municipalities in the province of Cienfuegos, where the survey technique was used in the diagnostic process and evaluation of results. It allowed to know the needs of the meliponiculturists, their aptitudes and attitudes, years of experience, among other variables.

Due to the lack of any registry that controls the meliponicola activity in the province, the population and sample do not coincide. The hives that were identified were classified according to the type of housing as rustic or natural, according to the method used by [2].

Additionally, the dimensions (length, width and height) were taken using a tape measure and the volume of the lodges was calculated from the formula (Volume = Length × Width × Height). The thickness of the wood and the diameter of the entrance structure were measured using a caliper.

The data obtained were subjected to a Kolmorov test and a descriptive statistical analysis with the Statgraphics Plus version 5.1 package.

3. RESULTS AND DISCUSSION

100% of meliponiculturists belonged to the male sex, for a total of 22 meliponiculturists identified. The age range was diverse, showing the predominance of older people, with 64.70 % of them over 50 years of age, with an average age of 42 years; a situation similar to that reported in the Yucatan Peninsula where it is argued that the use of meliponiculture resources is in the hands of older people, due to cultural deterioration in Mayan communities and the migration of young people to the cities of the country and abroad, causing the abandonment of traditions and even their rejection [6].

According to the results obtained on the level of schooling of the respondents, five melipon farmers have a high school degree (22.72%), three (36.36%) have a technical

high school degree, three have a pre-university degree (22.72%) and three (18.18%) have a university degree.

According to the occupational occupation, the sample was very heterogeneous, 20 of the people who carry out this work have another trade or profession (90.9%). It should be noted that none of those surveyed had a professional activity in Meliponiculture. The professions found were: beekeeper, policeman, Ministry of the Interior (MINIT) officer, electronics technician, small farmer, agronomy student, agricultural worker, custodian, bricklayer, self-employed, driver, heavy equipment operator and sailor [1].

In the literature consulted, there is little detailed information on the professions of the people involved in stingless bee cultivation, although there are mainly groups of peasants and native settlers, as in Costa Rica, where [7] states that it is mainly in the hands of indigenous groups. In Mayabeque province obtained very heterogeneous results in terms of labor occupation [2], while [9] in Pinar del Río Province, reported that 63 % of the sample is made up of beekeepers, 17 % are agricultural workers and the remaining 20 % is distributed in other categories.

On average, the producers have had their colonies for 11.5 years, less than the average of 16 years reported by [9] for Pinar del Río and similar to the results obtained by [5] in Mayabeque province.

Fifty percent of the producers started the activity because of the influence of other producers, 27.27% because of family tradition and the rest referred to other motivations. The total number of colonies found in the province of Cienfuegos was 785. In spite of the fact that in Cienfuegos the meliponiculture activity has been going on for a few years, the study confirmed that the largest number of hives identified in Cuba is concentrated in this territory. Being the meliponiculturists of the town of Juraguá, Popular Council belonging to the municipality of Abreu, province of Cienfuegos; those who concentrated the largest number (400).

The organization and management system of the group of beehives (160) and meliponaries, due to their performance in meliponiculture, was located in the Horquita Agricultural Enterprise; the only known experience of Meliponiculture associated to a state enterprise in Cuba. The rest of the producers have between 1 and 45 hives.

Among all the producers, only those belonging to Juraguá rented their colonies for pollination in the various crop units belonging to the Ministry of Agriculture (MINAGRI) in their locality. This action could have a double impact; contributing to an increase in crop yields due to its incidence on crop pollination, and to a greater availability of food for meliponines.

The range of rental prices for a melipona colony fluctuates between 200 and 250 CUP per month, which reveals the potential interest of this activity. [10], affirm that greater advantages can be obtained in the pollination service in crops of the agricultural company where the hive is located.

The colonies studied were in different housing systems, 635 (80.89 %) in systems with drawers or supers, 23 (2.92 %) in tree trunks and 14 (1.78 %) in rustic boxes, all of them in simple systems.

The colonies of M. beecheii are able to occupy the entire volume of the rational housing with food reserves (the pollen pots surrounding a portion of the brood chamber and the rest of the housing occupied by the well-organized honey reserve pots).

Regarding the housing systems of the colonies, the highest percentage (80.89%) corresponds to technified designs, belonging to the breeders of Juraguá, Empresa Agropecuaria de Horquita and San Fernando de Camarones; more experienced producers who have consulted Nogueira-Neto's studies. The rest of the hives are personal confections, manufactured without any technical criteria and which exceed, in most cases, the appropriate dimensions for the species.

Only the meliponiculturists belonging to Juraguá, Horquita and San Fernando de Camarones (3), increase the number of colonies by dividing the hives or artificial multiplication (76%), and the rest of the meliponiculturists do not multiply them artificially and do not know the methodology to do it, this perpetuates the extraction of the colonies from the environment with the damages that it causes. This situation has changed little since the observations of [11], who refers that in Cuba the colonies of these bees are being domesticated and located near the houses of farmers who, without any training or preparation, use wild colonies for this purpose, which is why they are disappearing from natural areas.

This situation coincides with that reported by [5], in Mayabeque. Referring to the average yield of honey harvested, 15 respondents obtained 1400 ml of honey/ hive, with a minimum of 500 ml and a maximum of 2500 ml. Studies by [12] in San Jose de las Lajas, Mayabeque province in this aspect reported higher honey yield/hive, with an average production record of 1 066 ml of honey per hive, a minimum of 330 ml and the maximum of 2 250 ml.

The results of the research affirmed that ten (45.45%) use honey mainly for medicinal purposes, ophthalmic problems and flu-like conditions; nine (40.90%), as food, five (18.18%), with dual purpose three (13.63%), do not know about the use of honey. This high percentage of those who use honey for medicinal purposes is due to the curative properties of various ailments that popular tradition attributes to this product, among which according to [9], are ocular cataract, pterygium, infectious and traumatic conjunctivitis, wounds and ulcers of the eye, hard-to-heal skin sores, hemorrhoiditis, skin blemishes, laryngitis, sinusitis and bronchitis.

Of the meliponiculturists identified, six (27.27 %) harvest honey between October, three (13.63 %) in any month of the year, three (13.63 %) in December and March, two (2.09 %) in October, one (4.54 %) in December, one (4.54 %) in March and another (27.27 %) stated that they do not castrate honey due to lack of knowledge.

In general, meliponiculturists harvest honey in the last quarter of the year, coinciding with the flowering season, when they obtain the highest yields in the country, obtaining 41.79% of *Apis mellifera* honey, according to data from 1992-2010 [13]. In relation to floral species, [2] state that colonies of the Cuban variety of *Melipona beecheii Bennett* (1831), in its natural state, visit a wide diversity of plants.

The meliponiculturists surveyed recognized a total of 19 botanical species of meliponicultural interest, although the degree of knowledge ranges from one (1) to ten (10) species, with an average of 1.81, showing a scarce knowledge of the area's meliflora and, therefore, of the food base on which these bees depend. The above is supported by the reports of [14] and [5] who state that the main plants of the melliferous flora in Cuba reach 54 species, grouped in 34 botanical families. Regarding the main contribution of these bees to man and nature, 9 (40.91 %) responded affirmatively during the study with the correct answer (pollination), one respondent (5.88 %) attributed the importance to honey and the remaining four (23.53 %) stated that they did not know the answer.

In this aspect, [15] reported higher results and pointed out that only 12% of the respondents considered pollination as a contribution of bees to man and nature. In the five municipalities where melon growers were identified, the total number of producers (22) reported not having received any training in topics related to the biology and management of this species. Only 5 producers (22.73%) have consulted specialized bibliography and writings on the internet, 7 (31.82%) through the exchange with producers and family members with more experience in the activity.

Table 2 shows the dimensions of the rustic hives, obtaining as a result that the parameter with the least variability is the diameter of the taphole, which shows a mean value of 1.05 cm, a structure of generally uniform dimensions in the species; similar values were obtained by [16] in Matanzas and [16] in Yucatán, who reported mean values for this parameter of 1 and 1.15 cm, respectively.

The dimensions and thickness of the wood of the hives do not conform to the recommended designs for the rearing of the Melipona beecheii bee species and do not coincide with the measurements reported by [18] in Yucatán.

The disproportionate number of hives made by meliponiculturists in Table 2 shows that stingless beekeepers build their hives without taking into account any technical element, negatively influencing colony development and inadequate conditions for efficient thermoregulation, an extremely important factor to consider for the multiplication of meliponine colonies. Providing adequate conditions for this activity can determine the success or failure in the acclimatization of a colony to a new housing [16].

Figure 1 shows the interior of a hive and corroborates the use of inadequate dimensions of the hives inspected during the study, a situation that can generate alterations in the colonies, difficulties in thermal regulation, excessive energy expenditure for the colony during its development, which can lead to its death [17].

Table 2. Descriptive statistics of the dimensions of rustic accommodations.

Indicators	Statistics					
	X	Min.	Max.	D.S	C.V %	E.E. (±)
Length (cm)	39,38	17,00	82,00	18,27	45,30	2,558
Width (cm)	19,62	6,00	54,00	6,62	22,58	0,9265
Height (cm)	20,23	10,00	40,00	11,04	37,76	1,546
Diameter of the entrance (cm)	1,05	0,9	1,2	0,070	6,67	0,0099
Wood thickness (cm)	1,86	1,0	2,6	0,307	16,51	0,0430
Volume of the hive (dm3)	29,99	12,15	79,71	14,23	47,47	1,99

Figure 1. Colony housed in a rustic hive of inadequate dimensions: note that half of the space is left over. **Source:** author, 2023.

4. CONCLUSIONS

The total of people who are dedicated to the cultivation of the Melipona species do not carry out the activity professionally, they reveal another work occupation. The level of schooling reflects that 59.08% have an intermediate level, 22.72% finished high school and 18% have a higher level with an average age of 42 years. Different models for the manufacture of *Melipona beecheii* hives were identified, showing a living space per hive of maximum capacity and good health.

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