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CASE STUDY

Mathematical model of the territorial bioecological coefficient to evaluate the progress of the sustainable development goal

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ABSTRACT

BACKGROUND AND OBJECTIVES: The geographic location of the department of Atlántico makes it highly vulnerable to climate effects, placing it in an environmental risk zone within the Colombian Caribbean region. This scenario requires the development of initiatives that align with the Sustainable Development Goals, and climate action, ratified at the United Nations Conference on Climate Change. It is imperative for governmental organizations to engage in sustainable development through the execution of initiatives that respond to the climate challenges present in the region. These initiatives are designed to secure the survival, promote economic growth, and enhance environmental sustainability for the residents of every municipality in the departments. The objective of this study was to create a territorial bioecological coefficient model designed to measure advancements in development objectives and goals grounded in natural factors. Additionally, the model aims to assess environmental elements and ecosystem resources while considering the impacts of climate change, particularly within the Department of Atlántico, Colombia.
METHODS: This model will allow for more effective anticipation of climate adaptation strategies, correlating the sustainable development goals with the progress established by the United Nations. The integration of these components will lead to more cohesive planning that aligns with global objectives, thereby optimizing both resources and efforts. This will facilitate the identification of priority areas for climate action and promote collaboration between different actors. Additionally, the model will support the tracking and evaluation of progress in achieving climate resilience, encouraging accountability and the adaptation of strategies to meet emerging challenges, which will ensure a holistic response to climate change and its consequences.
FINDINGS: This innovative approach addresses a significant gap, as there is currently no specific mathematical model to measure this coefficient. This tool would play a critical role in assessing ecosystem services and resources, supporting the design of territorial strategies that are tailored to climate change, consistent with sustainable development goals, and reinforcing local resilience, thus encouraging sustainable development. This approach promotes the adoption of sustainable territorial strategies in the face of climate change, which implies strategic coordination between academia, the productive sector, grassroots organizations, territory and local government. A non-compliance rate has been identified at the municipal and local level of sustainable development goal-13, with a percentage of climate actions of 85.60 percent in Usiacurí, 86.23 percent in Puerto Colombia and 84.50 percent in Suan.
CONCLUSION: The territorial bioecological coefficients model developed for the Atlantic is presented as an innovative tool that allows the evaluation of ecosystem resources and progress towards the sustainable development goals. This method fosters the integration of sustainable regional strategies as a response to the impacts of climate change.

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INTRODUCTION

Sustainable development (SD) is characterized by its primary purpose of improving the quality of life of all people around the world, including regions, countries, cultures, etc., considering both current and future generations (Dernbach and Cheever, 2015; Husamah *et al*., 2022; Li *et al*., 2024; Mensah, 2019). SThe concept of SD includes various objectives designed to support communities, and it is imperative for every country to ensure that its citizens can fulfill their needs sustainably (Fábregas Villegas *et al*., 2024; Jauhari *et al*., 2025; Onoshakpokaiye, 2023; Teweldebrihan and Dinka, 2024). The realization of this objective hinges on key factors, including economic growth and equity, social development, the preservation of natural resources (environmental protection), and the establishment of good governance along with the execution of State policies (Chan *et al.,* 2021; Eilks, 2015; Jiménez-Bedoya *et al*., 2024; Liu *et al*., 2021). There are 17 sustainable development goals (SDGs). SDG-13 focuses on climate action, SDG-6 on clean water, SDG-7 on clean energy, SDG-11 on sustainable cities, SDG-14 on marine life, SDG-15 on terrestrial ecosystems, and SDG-17 on partnerships to achieve these goals (UN, 2015). Regarding SDG-13, extensive research has demonstrated its relevance to climate change and its appropriate use for teaching in various subjects (Gómez, 2018; Hroub et al., 2025; Morote and Olcina, 2023; Rocasolano, 2019; Turró-Noa, 2023). Further exploration of climate change has highlighted that other research investigates its repercussions on different ecosystems, such as water systems, agricultural practices, and land use in regions that are at risk (Imalda and Hidayat, 2024; Jiménez-Bedoya *et al*., 2024; Teweldebrihan and Dinka, 2024). Citing some studies, Gupta and Vegelin (2016) analyzed whether the SDGs prioritize the concerns of the poor and their ecological problems or whether the SDG agenda risks being stifled by the ecological and developmental interests of the rich, focusing on economic growth at the expense of other aspects. Behera *et al.* (2024) examined the crucial role of renewable energy use, green finance, and political stability in achieving SDG-13 by reducing carbon dioxide (CO_2) emissions in emerging economies from 1990 to 2021. There is a prevailing assumption that the risks of climate change cannot be effectively mitigated unless CO_2 emissions are decreased, as they significantly contribute to its global consequences. Meanwhile, Liu *et al.* (2023) investigated how carbon sequestration services in ecosystems support progress on the SDGs. Numerous studies highlight the importance of sustainable development, particularly in areas with varied environmental and socioeconomic conditions (Nkaizirwa *et al*., 2021; Nketiah *et al.,* 2024; Tu *et al*., 2017). These articles explore various strategies focused on the environment, society and economy, with the aim of consolidating sustainability (Eilks, 2015). Their analysis highlights how professional, technical, educational initiatives linked to teaching and learning and technological initiatives play a fundamental role in promoting SD (Gündüz, 2017). Aligned with SDG-4 (Nkaizirwa *et al*., 2021), these educational methods strive to ensure that, by 2030, students develop the theoretical and practical skills necessary to promote environmental sustainability. This encompasses sustainable lifestyles (SDG-15), human rights and culture of peace (SDG-16), gender equality (SDG-5), zero hunger (SDG-2), global citizenship and appreciation of cultural diversity (SDG-11) (Wang, 2016). A key element highlighted is international cooperation (SDG-17), which drives strategic alliances to achieve global goals (Maashi *et al*., 2022). Collaborative efforts across regions and the sharing of knowledge are essential for addressing common sustainability issues. They enhance public policies and global understanding of local issues, fostering equitable climate actions (SDG-13). From the science, technology, engineering and mathematics (STEM) perspective, climate change serves as a key strategy to integrate sustainability into the SDGs (Álvarez-Ariza and Olatunde-Aiyedun, 2024). This method allows regions to address the challenges of climate change, presenting environmental solutions in a manner that is both innovative and resilient. Through project-centered methodologies, collaboration between disciplines is promoted and techniques are implemented that develop an ethical and critical awareness of sustainability, strengthening the skills of future generations (Gökel and Dağlı, 2017). A significant element involves refining assessments of sustainable pro-environmental attitudes and behaviors, as gaining insight into how people view and respond to environmental issues is critical for developing effective interventions (Nkaizirwa *et al*., 2021). Previous studies highlight the

need to update assessment tools to better understand the relationship between human actions and the environment. This will help prioritize interventions and promote sustainability. Additionally, they emphasize the training of leaders in various sectors using digital tools and hybrid learning methodologies (Gökel and Dağlı, 2017; Tu *et al*., 2017). By merging digital platforms with direct engagement, these strategies successfully enhance the teaching sustainability and land use planning. The examples presented demonstrate how these methodologies strengthen local governments and communities, promoting fundamental knowledge about environmental management and equity principles adapted to specific contextual realities, which improves decision-making in public policies and community practices (Nkaizirwa *et al*., 2021). In summary, this study underscores the significance of interdisciplinary and innovative methods for achieving sustainable development, encouraging global cooperation and the application of cutting-edge technology to confront challenges at both the international and local levels. The events of 2010 in the south of the Department of Atlántico, Colombia, showed how the waters of the Magdalena River and the Canal del Dique flooded municipalities such as Santa Lucía, Repelón, Candelaria and Manatí due to torrential rains, lack of infrastructure maintenance and government neglect (Llanos Henriquez, 2017). The failure of the Canal del Dique and the inundation of numerous areas stem from a combination of factors, including insufficient state actions and the neglect of maintenance activities in management strategies since 2004. These phenomena caused poverty, economic losses in the agricultural sector, diseases and population displacement, aggravating the proliferation of informal settlements in Barranquilla. As highlighted in the "Third Report of the Citizen Corruption Monitor," the escalation of poverty has resulted in increased social, environmental, and economic risks, largely stemming from the rampant exploitation of ecosystem resources. The Departmental Risk Management Plan for Atlántico points out the absence of policies for mitigating disaster risk and adapting to climate change. The lack of institutional commitment, limited citizen participation and the absence of an integrated platform prevent efficient use of resources. Furthermore, there are currently no metrics available to assess fiscal commitments and initiatives in these domains. A significant challenge lies in the absence of quantitative and bioecological indicators that would aid in tracking threats and risks, particularly within territorial planning plans (TPP). It is essential that this information be accessible to guarantee equity and facilitate decision-making that ensures the sustainability of the territory. Considering the constraints inherent in sustainability research and the data collected, it is essential to develop a territorial bioecological coefficient (TBC), referred to as (CBioET) in Spanish. This coefficient will facilitate the assessment of compliance and advancement concerning the SDGs. To achieve this, it is important to employ suitable tools and methodologies that can effectively identify, measure, or evaluate the sustainability, adaptability, vulnerability, and risks faced by both the territory and its inhabitants, particularly in the context of climate change. This measure aims to provide a comprehensive understanding of how land use practices can align with the natural capacity of ecosystems to sustain life. By integrating various factors, the TBC offers a nuanced perspective that goes beyond traditional sustainability indices. It underscores the importance of considering both biological and physical elements in assessing the sustainability of a region, particularly in relation to human influence (Nketiah *et al.,* 2024). Considering the relevance of the SDG, especially SDG-13, related to climate actions, and the problems associated with climate change, from the economic, social and environmental perspective, this study aimed to develop a TBC model that will serve to quantify progress in development objectives and goals, based on nature, as well as to evaluate environmental components and ecosystem resources in the context of climate change. The study has been carried out in the Department of Atlántico, Colombia, in the period between 2020 and 2023.

MATERIALS AND METHODS

In Colombia and in the municipalities of the Atlántico department, population growth is driving a trend towards spatial expansion of human communities. In the affected areas, the existing natural cover is significantly compromised as a result of urban infrastructure development. Consequently, evaluating this growth with suitable instruments is vital to reduce its impacts. Therefore, in a qualitative

way with some statistical elements (Cohen *et al.*, 2018), it is necessary to develop a territorial bioecological indicator that evaluates the level of compliance and progress in the 17 SDGs and their 169 targets, as established by the United Nations. It employs instruments to evaluate sustainability, adaptive capacity, vulnerability, and climate-related risks, taking into account regional characteristics. A TBC is needed to determine compliance through methodologies linked to climate risks. The proposed mathematical model evaluates SDG-13 progress, adapting to territorial conditions to accurately measure development in response to climate change. For a detailed examination of ecological sustainability, the variables identified are crucial as they address significant components of natural ecosystems and human impacts on the landscape. One such variable is 1) *Vegetation cover*, which plays a key role in determining the condition of ecosystems and their potential to provide vital services, such as carbon absorption, water cycle management, and biodiversity protection. 2) *Water cover:* Water is a crucial resource for life and human well-being. This variable evaluates the availability and quality of water bodies, which is vital for the sustainability of any territory. 3) *Linear cover:* It includes areas such as roads, highways, and other linear infrastructures that divide and fragment the surrounding landscape. It is important to analyze their impact on ecological connectivity and energy and nutrient flows. 4) *Urban cover:* Urban growth has a direct effect on territorial sustainability, as it alters natural patterns of land use, increases demand for resources, and generates greenhouse gas emissions. Evaluating this variable is essential for the sustainable management of urban development. Each of these coverages serves as a crucial component for evaluating the relationship between natural environments and human activities, enabling a comprehensive assessment of the territory's bioecological condition. The document outlines sampling techniques for validating the mathematical model of the TBC, primarily focusing on the analysis of satellite imagery and the segmentation of the territory into quadrants. The techniques used are as 1) *Satellite photographs and cartography:* High-resolution satellite images obtained through tools from the Colombian Institute Agustín Codazzi (IGAC) were used to observe and analyze vegetation, water, urban and linear coverage. These images provided a quantitative basis for measuring environmental impact in different years. 2) *Division into quadrants:* The area was segmented into quadrants, each measuring 10 m² per pixel, allowing for an accurate assessment of the coverages being analyzed. Each quadrant was subdivided into four parts to obtain a detailed percentage analysis of the different coverages (1/4 = 0.25%, 2/4 = 0.50%, 3/4 = 0.75%, 4/4 = 1.00%). 3) *Vester methodology:* A matrix was employed in this methodology to rank essential problems, classifying them according to their level of causality, which included weak, medium, strong, and very strong categories. This allowed key environmental problems in the territory to be identified and assigned a relative weight in the analysis. 4) *Percentage analysis:* An approach based on predictive percentages was implemented to assess the level of coverage for each area in the distinct quadrants. This method facilitated the identification of changes in land cover, comparing data from different periods to measure sustainability and the impact of urban growth. By employing these techniques, the mathematical model was validated through the provision of accurate and trustworthy quantitative data, which is vital for calculating the TBC. The validation of the mathematical model for the TBC was carried out using a structured approach in several stages. First, a direct observation of the territory was carried out, using diagnostic tools to identify the ecological and social variables. Following that, a mathematical equation was formulated to encompass critical variables such as vegetation, water, linear elements, and urban land use. The model combined quantitative and qualitative approaches, weighting the variables according to their importance in the territory. The model was validated by temporally comparing data from different years, using satellite images and percentage analysis, applying it to three municipalities in the Atlantic (Usiacurí, Puerto Colombia and Suan). The numerical findings indicated variations in environmental impact and forecasted the future sustainability of the region.

Data collection

This article is dedicated to a holistic cycle in the municipalities of Usiacurí, Puerto Colombia and Suan, geographical areas that host natural ecosystems in the Department of Atlántico (Fig. 1).

The study units and data collection techniques are carried out and presented in a descriptive, comparative,

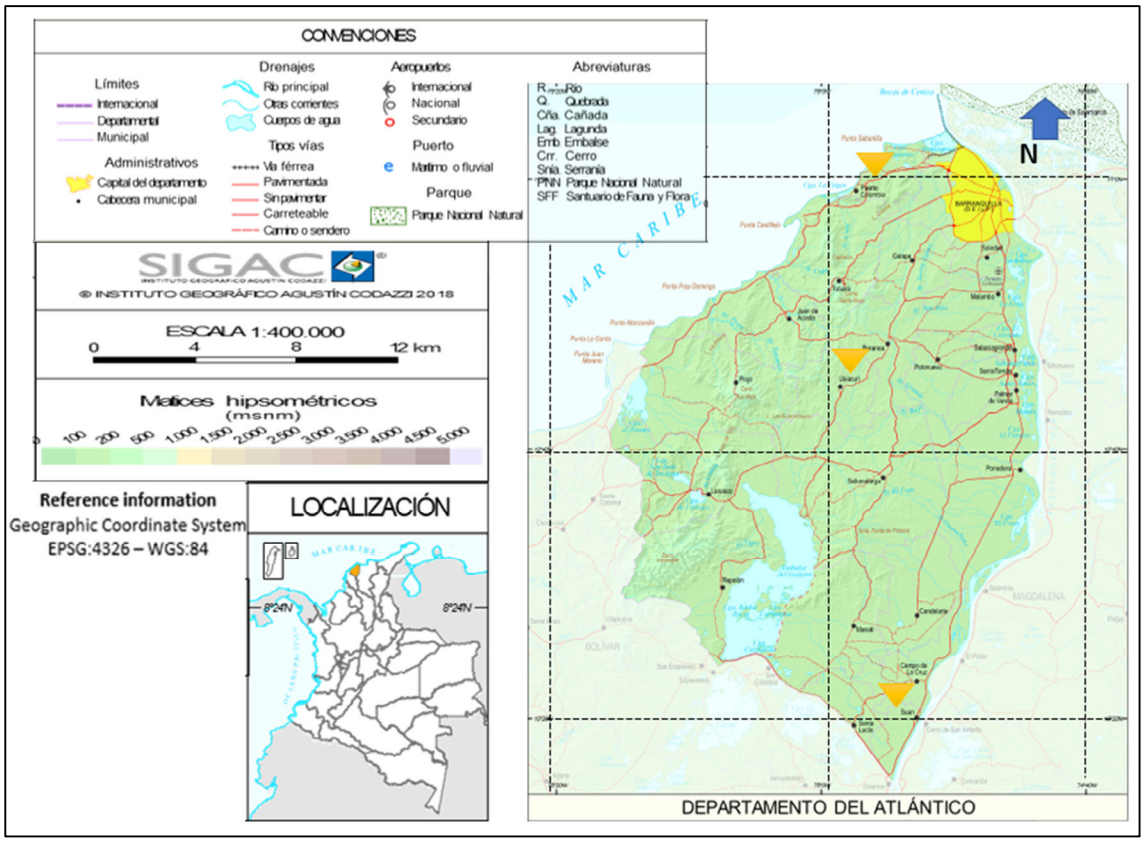

Fig. 1: Geographical location of the study area in the Department of Atlántico, areas of the Municipality of Usiacurí, Puerto Colombia and Suan, using geographic information system (GIS) (IGAC, 2024)

analytical and explanatory manner. Furthermore, it aims to establish a clear framework for the research processes linked to each phase of the analysis, making it applicable to any field or region that is to be studied at local, regional or global level. This approach, which is based on the multifactorial-systematic theory, anticipates the explanatory process of the holistic spiral. In this context, the researcher goes beyond mere speculation regarding the reasons behind events, actively working to synthesize information and experiences in order to generate knowledge that is both significant and applicable. It should be noted that grounded theory uses only qualitative analysis techniques (Hurtado, 2000).

Data analysis

In the analysis of the results, the premise put forward by Amartya Sen is considered, which highlights the external characteristics inherent to the environmental components in the context of sustainable human development. This process is carried out without factoring in human influence, which shapes regions and territories in relation to their economic, social, environmental and climatic systems. Conversely, Maslow posits that internal conditions are unique to specific communities and individuals, making them essential for driving behavioral change within a given territory. These conditions are closely tied to the survival needs and behaviors of the population, influencing sustainability in each region under examination (Maslow, 1943). This implies that the desire to change or modify behaviors to improve environmental conditions depends on people, who must adapt to climate change by implementing plans, programs and projects necessary to carry out actions that improve the quality of life.

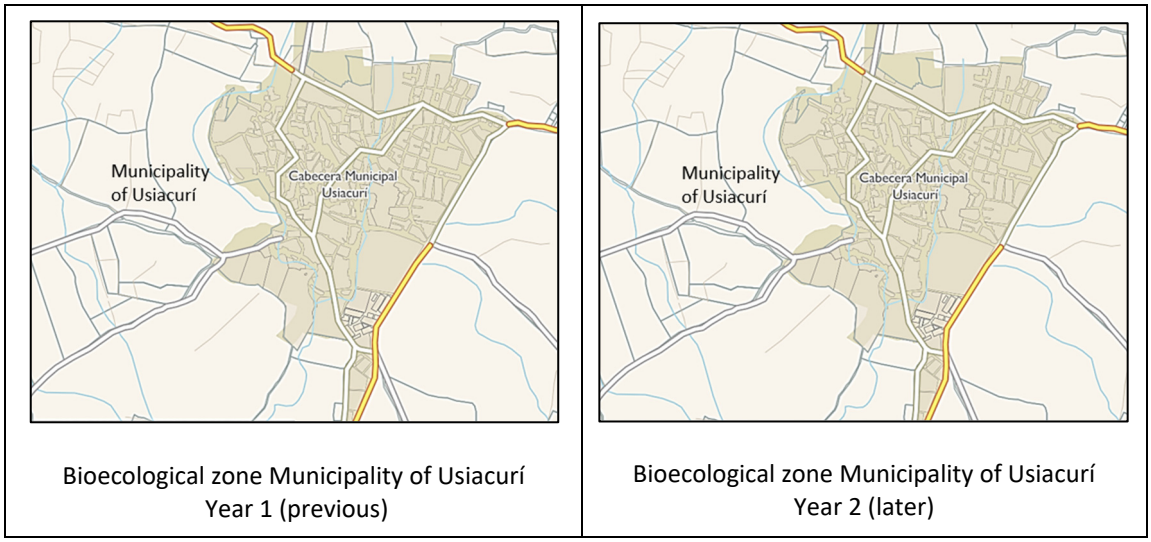

Fig. 2: Photograph taken from the GIS of the Usiacurí Municipality area (IGAC, 2024)

Table 1: Percentage analysis of temporality in the different coverages (Hroub *et al.*, 2025; IGAC, 2024; UN, 2015)

Initial value (year 1)	Temporary value (year 2)
$C.V_1$ = Plant Coverage	$C.V_2$ = Plant Coverage
$C.L_1$ = Linear Coverage	$C.L_2$ = Linear Coverage
$C.H_1$ = Water Coverage	$C.H_2$ = Water Coverage
$C.U_1$ = Urban Coverage	$C.U_2$ = Urban Coverage
$C.V_1 + C.H_1 + C.L_1 + C.U_1 = V1$	$C.V_2 + C.H_2 + C.L_2 + C.U_2 = V2$
$V1 - V2 = Y\%$	

RESULTS AND DISCUSSION

Mathematical model of the territorial bioecological coefficient (TBC)

The development of TBC is based on a qualitative approach (Hurtado, 2000), which allows to numerically explain a quantitative condition for government decision-making. This coefficient aids in recognizing ongoing events and forecasting potential future occurrences by utilizing an index that measures the level of advancement in bioecological elements. It is tailored to align with the environmental attributes of the region as well as the plans, programs, and projects aimed at the area's development. The methodological design was developed using the adapted model proposed by Schavino and Villegas (2010), which encompasses the following stages:

Stage 1: Recognize the variables related to temporality and ecological sustainability through vegetation, water, linear areas, deserts and urban coverage, using cartography and satellite photographs of the study area (Fig. 2), as used by Pérez-Aristizabal *et al*. (2025).

Consequently, the fundamental numerical computations will be executed to determine the primary indicator required for assessing the sustainability of various coverages. This assessment will rely on the presence or absence of the different environmental factors evaluated through the implementation of telemetric plans and the count of observed quadrants, as illustrated in Table 1.

Referring to Table 1, Y percent (%) = (V1-V2) the first identified index of bioecological sustainability that, through the suggested methodology, must be expressed in percentage terms to facilitate the interaction with the other indicators and variables of the analysis method , the bioecological coefficient is identified. At this point in the process, an analysis takes place to establish an indicator that illustrates population growth as outlined in the following:

A review of the TPP for the selected municipality

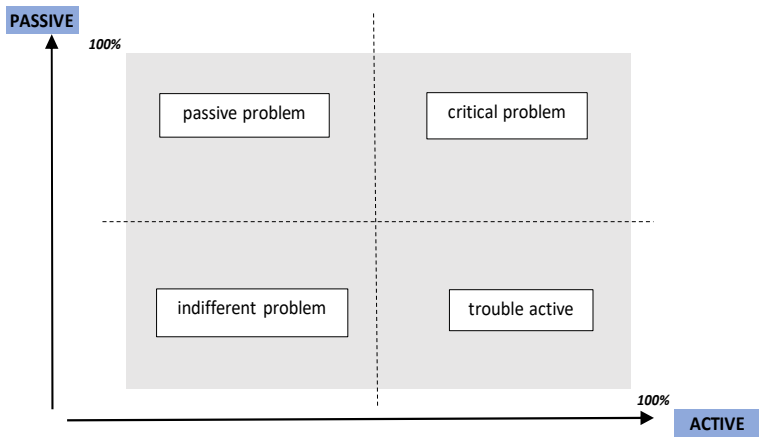

Fig. 3: Analysis of identified problems (Suberi, 2022)

Table 2: Vester methodology value scale (Suberi, 2022)

Scale of value	Description
0	Not causal
1	Weak causal
2	Causal media
3	Strong causal
4	Very strong cause

is undertaken to evaluate the progress made in its development and to determine the extent of its ecological sustainability. This analysis is carried out based on the projection of the population growth of the area, considering the population of the initial period and the current population within the framework of the study. Therefore, the population at the end of period "n" is expressed using Eq. 1 (Betzholtz *et al*., 2025).

Growth "n" = population index (Year 1) – population index (Year 2) (1)

Following the acquisition of the necessary factors and variables, the percentage analysis of the impacts of climate change is initiated. Problems are identified and sorted into categories of critical, indifferent, passive, and active using the Vester matrix. Critical problems for each environmental element are selected to formulate indicators and propose solutions (Fig. 3).

In order to determine how to prioritize projects and programs, as well as to develop an action and improvement plan, this system is evaluated according to the in accordance with the assessment outlined in Table. 2.

An environmental identification registry (EIR) is created to align with the ecological and environmental sustainability aspects of the territory. This process includes an exhaustive analysis of the diagnoses of water, soil, culture, air, social aspects and biodiversity. A percentage-based assessment of the needs will be performed, utilizing the environmental quality index (EQI) specific to the study area. This process will enable the development of a table that details territorial needs, following the principles of the Maslow triangle (Maslow, 1943). The results will be presented in a calculation table (Table 3), which will allow obtaining the percentage assessment necessary for representation in a spider diagram, where the various components of ecological sustainability will be compared.

Stage 2: Implement the variables derived from the percentage analysis of each SDG objective, as follows:

- 17 SDGs are equivalent to 100%, which means that each SDG has a percentage weight of 5.88%.
- The SDGs comprise a total of 169 goals. A percentage analysis is carried out for each of these

Table 3. Percentage analysis by element (Suberi, 2022)

Percentage average environmental diagnosis				
A	Water diagnosis			11.11%
B	Air diagnosis			11.11%
C	Soil diagnosis			11.11%
D	Flora diagnosis	11.11%	Biodiversity Diagnosis	22.22%
	Fauna diagnosis	11.11%		
E	Diagnosis education	11.11%		
F	Housing diagnosis	11.11%	Socioeconomic Diagnosis	44.44%
G	Health diagnosis	11.11%		
H	Employment diagnosis	11.11%		
Total				0 – 100%

Table 4: Correlation of relative weight of goals and SDG13 (Hroub et al., 2025; UN, 2015)

	GOAL	Relative weight by territorial importance
SDG-13 Climate actions	13.1 Increase resilience and adaptation capacity to climate risks and natural disasters in all territories at local, regional and global levels.	0.71
	13.2 Integrate climate change-related actions into local, national and global policies, strategies and plans	0.71
	13.3 Education, awareness-raising and human and institutional capacities should be promoted to improve climate change mitigation, adaptation to its effects, minimization of its impacts and the implementation of early warnings.	0.71
	13.a Developed countries party to the United Nations Framework Convention on Climate Change must honour their commitment to mobilize a total of US$ 100 billion annually from a variety of sources by 2020. This financing is crucial to address the needs of developing countries in terms of taking concrete mitigation measures and ensuring transparency in their implementation. It is also essential that the Green Climate Fund be put into operation and that it be capitalized as soon as possible.	0.41
	13.b Promote the creation of mechanisms to improve planning and management capacity in relation to climate change in the least developed countries and small island developing States, paying special attention to women, youth and local and marginalized communities.	0.41
	RELATIVE WEIGHT OF SDG 13 GOALS	2.95

goals, resulting in a rating scale of 0.59%. This percentage will be compared with the goals set in SDG 13, multiplying 0.59 by 5, given that this SDG has five goals. Thus, the relative weight of the SDG 13 Goals translates into 2.95%.

• The homologation analysis is carried out in accordance with the existing environmental elements.

• The existing environmental elements in the territory are considered.

• An index of importance of basic ecological needs (water, air, soil, flora, fauna, education, housing, health and employment) is prepared.

• It is formulated from a percentage analysis using qualitative and quantitative techniques by bioecological component, identifying the existing problems in the analyzed territory.

• An index of importance of basic needs is also prepared, which considers both qualitative and quantitative factors.

Stage 3: In this phase, the climatic variations within the studied region will be defined using the Territorial Planning Plans (PPT) alongside telemetry data from

the chosen municipal areas. An initial baseline will also be established to characterize the bioecological components under investigation. The previous PPTs will be chosen and through their historical analysis in the different plans, programs and projects, the ecological resilience of the area in question can be evaluated. Based on the gathered indicators, an analysis is conducted utilizing a homologation table to assess the advancement of the 17 municipal SDGs. This evaluation informs decisions regarding the direction of the PPT for upcoming terms, allowing for necessary reorganizations or enhancements (Table 5).

The construction of the TBC was determined through Eq. 2 (IGAC, 2024), where the sum of the telemetric variables, population growth and the sum of indicators of the Vester matrix, the environmental identification registry and the relative weight of the goals of the SDG, gives us the first percentage analysis of compliance with SDG-13, using Eq. 2 (Hroub *et al*., 2025; IGAC, 2024; UN, 2015):

$$\mathrm{TBC} = \frac{[\mathrm{V1} - \mathrm{V2}]\% + \mathrm{IVe}\% + \mathrm{EIR}\% + \mathrm{Crp}\% + \mathrm{PODS}\%}{5} \quad (2)$$

Where:

V1 -V2: Photographic or cartographic method (telemetry)

IVe: Vester homologation indicator

EIR: Environmental identification registry

CrP: Population growth

PODS: Percentage of the relative weight of each SDG

In order to analyze the application of the mathematical formula within the municipality of Usiacurí, a comprehensive summation of the indices for each analyzed element is performed. Based on this information, the corresponding indicator is substituted to calculate the TBC, using Eq. 3 (IGAC, 2024; Suberi, 2022):

Telemetric temporality difference:

$$V1 - V2 = Y\% = 0.103\,\% \quad (3)$$

To obtain the Vester percentage index, proceed as Table 6.

For the final consolidation by IRE Municipality of Usiacurí, the following result is established for each environmental element analyzed.

The results are obtained using Eq., 4 (IGAC, 2024; Suberi, 2022):

$$\mathrm{IER}\,(\mathrm{average}) = 1.75 + 0.44 + 2.24 + 1.66 +$$

Table 5: Percentage analysis of SDG progress (Hroub *et al*., 2025; UN, 2015)

Studied area	TBC (%)	Analyzed (%)	Progress in territorial SDG management
Department Area of the Atlantic	To find the percentage value	SDG relative weight of the 169 SDG targets of 100% of the total	Percentage analysis required, actions to be developed to improve the sustainability of the area studied.

Table 6 : Consolidation of clothing indices for each element (Suberi, 2022)

Vester index by environmental element			Percentage analysis of vesting by element
IVe (Flora)			6.66
IVe (Fauna)			6.25
IVe (Water)			6.25
IVe (Air)			6.66
IVE (Floor)			6.66
IVe (Education)	6.66	IVe (Socioeconomic)	$\frac{6.66 + 6.25 + 5.00 + 6.66}{4} =$ 6.14%
IVe (Housing)	6.25		
IVe (Health)	5.00		
IVe (Employment)	6.66		
Total, IVe average			6.438%

Table 7: Environmental Identification Registry (IGAC, 2024; Suberi, 2022)

Environmental elements	Relative percentage weight identified
IER (Flora)	1.75
IER (Fauna)	0.44
IER (Water)	2.24
IER (Floor)	1.66
IER (Air)	2.41
IER (Socioeconomic)	1.89
IER (average)	1.73

Table 8: The percentage values of compliance with TBC for each municipality analyzed (Hroub et al., 2025; IGAC, 2024; UN, 2015)

TBC of the Municipality of Usiacurí	TBC of the Municipality of Puerto Colombia	TBC of the Municipality of Suan
14.403%	13.77%	15.5%

Table 9: The percentage factor of non-compliance with SDG-13 would be the difference of 100% (Hroub *et al*., 2025; UN, 2015)

TBC of the Municipality of Usiacurí	TBC of the Municipality of Puerto Colombia	TBC of the Municipality of Suan
(85.60%)	(86.23%)	(84.50%)

$$2.41+1.89=\frac{10.39}{6}=1.73 \quad (4)$$

Population difference in the temporality studied as $CrP=0.26\ \%$

The percentage weight of the 17 SDGs is 5.88%, giving an equal percentage to each SDG analyzed as $\mathrm{PODS}=5.88\%$.

By replacing the results obtained, using Eq., 5 (IGAC, 2024; Suberi, 2022):

$$\text{Total TBC}=0.103\%+6.43\%+0.26\%+1.73\%+5.88\%=14.403\% \quad (5)$$

The result obtained is divided by the number of variables found, which in the case of TBC is 5, depending on the number of items analyzed, using Eq., 6 (IGAC, 2024; Suberi, 2022):

$$\text{TBC}\left(\text{Municipality of Usiacurí}\right)=\frac{14.403}{5}=2.880 \quad (6)$$

The utilization of the equations and the examination of the variables pertinent to TBC yields results that offer valuable insights into directing the administrative management systems and municipal governance across the various territories studied. This analysis helps to clarify the necessary plans, programs, and projects that should be prioritized for implementation at the municipal level (Table 8).

According to the information presented in Table 9, it has been found that the analyzed territories do not meet all the goals defined by SDG-13. The percentage analysis indicates 85.60% for Usiacurí, 86.23% for Puerto Colombia and 84.50% for the Municipality of Suan (Table 9).

The considerable difference observed between the territories analyzed and the fulfilment of the SDG - 13, which focuses on “Climate Action”, raises a crucial debate on the challenges faced by the local community in its fight against climate change. The non-compliance with the evaluated indicators in the relevant areas highlights a notable divide between international targets and the current realities experienced locally. This discrepancy highlights the urgent need to adopt concrete and effective measures to address territorial ecological damage at local, national and global levels. It is essential to analyze and identify the causes of non-compliance with the SDGs, in particular SDG 13, in the territories under study. If suitable measures are not executed in a timely fashion, this non-compliance could lead to a significant environmental crisis. Moreover, the elements leading to this non-compliance could involve insufficient technical, human, and financial resources, ineffective policy frameworks, and a low

level of environmental consciousness. Recognizing these causes is essential to formulate effective strategies that meet the particular needs of each territory. In short, the active participation of the local community and environmental education are key aspects to improve compliance with SDG 13 in the territory analyzed. Involving citizens in climate change mitigation and adaptation actions can be decisive in facing climate challenges and promoting SD in the area. Emphasizing the necessity of enhancing cooperation among local governments, non-governmental organizations, the private sector, and civil society is crucial (UN, 2015). Cooperation between different sectors is essential for the formulation and implementation of comprehensive policies and climate action programs that address the underlying causes of non-compliance and promote SD in the Department of Atlántico. This scenario not only represents a challenge but also provides an opportunity to strengthen the resilience of communities and foster SD in the region. Failure to comply with SDG 13 (climate action) poses a critical challenge for the territories under study, as it could aggravate the climate crisis if timely measures are not taken. As stated by the UN (2015), it is vital to engage in multi-sector collaboration to effectively confront the fundamental causes of this challenge, which include resource scarcity, inadequate policies, and and a lack of environmental consciousness. Comparatively, authors such as Gupta and Vegelin (2016) have highlighted that the integration of inclusive and participatory policies can be decisive in moving towards sustainable development, which coincides with the need to involve local communities in climate mitigation, restoration and adaptation. In addition to emphasizing the significance of ecosystem services in advancing the SDGs, the enhancement of environmental education, as discussed in the text, aligns with their findings by fostering transformative changes in local practices. Finally, strategies must be adapted to the particularities of each territory, an idea that reinforces the need for a territorial approach, such as that proposed by Behera *et al.* (2024) in their analysis of the links between renewable energy and SD in emerging economies. This plays a significant role in promoting and realizing the SDGs fairly, while acknowledging different territorial contexts, and aids in decision-making through the application of a TBC mathematical formula relevant to multiple scientific disciplines. It is essential to redefine the ecological security index and the concept of territorial ecological sustainability, taking into account the environmental, ecological and social particularities of each municipality and the areas where the SDGs are sought to be implemented through a territorial bioecological index. This study suggests that the concept of "territorial bioecological coefficient (TBC)" refers to the extent of utilization, alteration, diminishment, rehabilitation, and sustainable management of natural resources. It emphasizes the importance of preserving current ecological standards while ensuring that the foundational natural environment remains secure. for future generations. This concept, according to the author of this study, is based on Maslow's human conditions. Considering hierarchical structures in relation to human, biological, and physiological needs necessitates an understanding of the livelihoods of the communities and inhabitants in the region where the formula is utilized. To address these premises, it is crucial to establish a TBC that evaluates the degree of compliance with social, economic, political, technical, financial and cultural conditions, in order to monitor progress towards the SDGs. The use of simple, clear and precise methodologies is proposed, which reflect the regional reality and the achievement of the 169 goals of the SDGs. The goal is to integrate natural sciences, including physics, chemistry, and biology, with social sciences to enhance the visualization of advancements in territorial plans, programs, and projects through a mathematical model. This will allow governments to make appropriate decisions related to climate change mitigation and adaptation, incorporating these strategies into environmental risk management systems, regardless of administrative changes during government periods. Utilizing a mathematical framework will support the analysis of how the administrative policies of different mayors can be organized to acquire the necessary resources aimed at improving the living standards of their residents. The term "territorial bioecology" arises from the identification of territorial variables evident from the sustainability of the area studied, integrating the components that are part of this mathematical model on climate change. A comprehensive strategy was crafted for three separate areas, confirming the results within diverse environmental settings and evaluating their specific geographical and geospatial

conditions in maritime, river, and savanna landscapes. In these territories, indicators and coefficients can be validated without taking into account periods of governance, analyzing the population's capacity to adapt to climate change and the potential risks of not carrying out actions that improve living conditions. The development and evaluation of the TBC, established in this research, enables an exhaustive and critical analysis of its relevance, applicability and potential impact on progress towards the SDGs. This instrument provides a credible means to tackle the distinct issues of environmental sustainability in at-risk areas such as the Department of Atlántico in Colombia, where the consequences of climate change are particularly severe. However, success in its implementation is conditional on the ability to overcome the environmental, social, economic and political limitations inherent to the local and national context. The TBC is characterized as a novel methodological approach that integrates biotic, abiotic, and socioeconomic factors within a specific analytical structure to evaluate the sustainability of territories. As highlighted by recent studies in environmental management of environmental sustainability (Unceta, 2014) and territorial analysis methodologies (Wang and Bao, 2021), this integration allows identifying discrepancies and opportunities in economic, environmental and social management, contributing to the strengthening of adaptation capacity of territories to climate threats. Furthermore, TBC enhances the relationship between scientific understanding and policy creation, ensuring a seamless integration of local factors with the global commitments outlined in the 2030 Agenda. It is crucial to consider the criticisms raised regarding the generalized applicability of the SDGs, which often do not reflect the particularities of the most vulnerable regions. Insufficient contextual adaptation and the lack of concrete tools for sector-specific implementation have contributed to a disparity in goal attainment. Specifically, in the Atlantic area, the deficiencies in both technical capabilities and human resources within municipalities reveal the importance of adopting approaches such as TBC, which enable a more localized and relevant analysis. A notable aspect is the identification of structural barriers that hinder sustainable development. These include lack of financial resources, institutional weakness and administrative fragmentation, especially in small and medium-sized municipalities. Moreover, the restricted awareness among authorities and communities concerning the extent of climate impacts complicates the process of making effective and timely decisions. In this context, TBC not only faces technical challenges inherent to its application, such as obtaining reliable data and building local capacities, but also the need to generate political will to integrate this type of tools in territorial planning. The findings indicate that the implementation of the SDGs is impeded by political and cultural differences, as well as the Congreso of the Republic of Colombia's insufficient interest. This underlines the need for a legislative framework that prioritizes climate action and ensures adequate resources. Moreover, the application of satellite telemetry alongside accessible technological resources in territorial evaluation is identified as a crucial strength of TBC, allowing for precise evaluations of ecological and social circumstances. These data, historical and current, allow for more effective territorial planning based on evidence. The development of mathematical models that incorporate bioecological and socioeconomic variables is also highlighted as a key tool to evaluate and monitor progress towards the SDGs. Creating these models demands an interdisciplinary approach that combines insights from the natural, social and technological sciences. In addition, ensuring that these models are both interpretable and functional for local decision-makers is of utmost importance. The use of tools such as satellite images and the aforementioned percentage analyzes reinforce the viability of TBC to generate territorial diagnoses that combine objective quantification and qualitative observations. Studies such as those by Wang and Bao (2021) have shown how telemetry can provide valuable data for territorial planning, while Wackernagel and Rees (1996) highlight the importance of visual indicators in sustainability assessment. This enables the assessment of changes in environmental factors such as water, soil, and vegetation, as well as the evaluation of the effects of human activities on these ecosystems. For example, population growth and urbanization stand out as factors that decrease territorial sustainability. The dialogue surrounding the reallocation of the significance of the SDGs, tailored to the specific needs and capacities of different territories, holds considerable relevance. In regions such as the

Atlantic, where climate vulnerability is high, it may be necessary to prioritize objectives such as climate action (SDG-13) or poverty eradication (SDG 1) over others that have a less immediate impact. Nevertheless, this approach brings forth ethical and operational issues. One concern is the possibility of fostering inequalities between regions as a result of uneven resource allocation. On the other hand, the variability in the implementation of the SDGs could hinder the global comparability of progress and the coordination of international efforts. Achieving a balance between local adaptability and global consistency is essential, alongside the promotion of environmental and social equity. The TBC is presented as an innovative methodological tool by integrating biotic, abiotic and socioeconomic components and the elements of water, air, soil, flora, fauna, education, housing, health, employment, within a specific analytical framework to evaluate territorial sustainability. As highlighted by recent studies in environmental management of environmental sustainability (Unceta, 2014) and territorial analysis methodologies (Wang and Bao, 2021), this integration allows identifying discrepancies and opportunities in economic, environmental and social management, contributing to the strengthening of adaptation capacity of territories to climate threats. Moreover, TBC enhances the relationship between scientific understanding and policy creation, ensuring a seamless integration of local factors with the global commitments outlined in the 2030 Agenda. It is important to consider the criticisms raised regarding the generalized applicability of the SDGs, raised by the United Nations and especially SDG-13 (climate action), which often do not reflect the particularities of the most vulnerable regions. The lack of contextual adaptation and specific sectoral and specific scientific tools for its implementation has resulted in uneven fulfillment of the goals. In the case of the Department of Atlántico, the technical, financial, economic and human deficiencies in the municipalities highlight the need for approaches such as TBC, which allow an analysis adjusted to local conditions. A significant factor is the acknowledgment of structural challenges that obstruct sustainable development. These include the dependence of municipalities on the central government, lack of their own financial resources, institutional weakness and administrative fragmentation, especially in small and medium-sized municipalities. The research correctly points out that social, environmental, political and cultural differences, as well as the lack of interest in the Congress of the Republic of Colombia, constitute a significant obstacle to the implementation of the SDGs. This highlights the importance of establishing a legislative framework that prioritizes climate action and ensures the appropriate allocation of resources. Utilizing satellite telemetry alongside accessible technology for territorial analysis stands out as one of the most promising elements of TBC. The ability to make accurate diagnoses of ecological and social conditions, using historical and current data, allows planning to be guided more effectively and based on evidence. The development of these models necessitates a collaborative effort that brings together expertise from natural, social and technological sciences. Furthermore, it is essential to ensure that these models are understandable and usable by local decision makers. This allows not only to measure variations in environmental coverage such as water, soil and vegetation, but also to analyze the impacts of human activities on these systems. For example, population growth and urbanization stand out as factors that decrease territorial sustainability. The redistribution of the relative weight of the SDGs based on territorial needs and capacities is a crucial issue, especially in vulnerable regions such as the Atlantic. Here, climate action (SDG-13) and poverty eradication (SDG-1) may require higher priority due to their immediate impact compared to other goals. However, this strategy faces significant challenges. Unequal distribution of resources may exacerbate regional disparities, and inconsistencies in the execution of the SDGs could impede global comparability and international coordination. The balance between local flexibility and global coherence is essential to guarantee environmental and social justice, promoting inclusive and equitable sustainable development. This study also suggests that certain territories could benefit from the application of specific methodologies such as the Vester matrix, widely recognized for its usefulness to identify causes and effects of environmental problems in a systemic way. By utilizing this tool alongside percentage analyses and satellite monitoring, a more accurate determination of adherence to the SDGs could be achieved. Furthermore, the success of TBC also depends on the ability of local communities to take

ownership of the planning and decision-making process. This study highlights how environmental education fosters awareness and civic engagement, while local participation shapes territorial strategies. Integrating education with environmental needs enhances skills, innovation, and resilience, supporting climate actions and SDGs. Projects that prioritize sustainability, including homes tailored to withstand climate variations, contribute to achieving these aims. The study also explores the ethical dilemma of conserving resources for future generations. This concern has been highlighted in works such as those of, who analyze the principles of sustainability, and Wackernagel and Rees (1996) in their formulation of the ecological footprint as a tool to evaluate resource consumption against the planet's regeneration capacity. This strategy is pivotal to the principle of sustainability, indicating a need to balance immediate demands with the safeguarding of natural assets. To address this dilemma, the development of mathematical mechanisms is proposed that allow calculating the sustainable use of environmental resources, ensuring their availability for future generations. Likewise, the integration of measurement instruments such as the ecological footprint and additional sectoral indicators could augment the TBC, delivering a wider understanding of environmental dynamics and their influence on territorial sustainability. However, its implementation requires overcoming technical barriers and guaranteeing the participation of key actors, from local governments to communities. This TBC model goes beyond current methodologies by taking into account key differences: In terms of the Territorial Approach, while many ecological indices have a global or national focus, the TBC emphasizes a detailed analysis at the territorial or regional level. This facilitates the evaluation of how well a specific region can accommodate certain human activities without jeopardizing its ecological sustainability over the long term. Other indices, such as the Ecological Footprint, tend to generalize the environmental impact more, which can omit local particularities. In the case of Bioecological Integration, the TBC not only measures the impact of human activity in terms of emissions or resource consumption, but also how these activities directly affect biodiversity, nutrient cycles, and site-specific ecological flows. Conversely, a significant number of sustainability indices concentrate predominantly on metrics like greenhouse gas emissions, energy consumption, or resource efficiency, frequently failing to account for the complex interactions within bioecological systems. In relation to the social and cultural components, another differentiating aspect of the TBC is that it can include social and cultural variables that are deeply intertwined with the use of the territory and respect for ecosystems. In areas where indigenous communities reside, the TBC might include the ways in which traditional knowledge supports the sustainability of the land. Conventional ecological indices can overlook these cultural factors and their contribution to sustainability. Regarding the dynamic adjustment to local conditions, the TBC is developed at the territorial level and can dynamically adjust to the changing conditions of that specific ecosystem, taking into account its resilience, the ecosystem services it provides, and the environmental pressures to which it is subjected. Typically, global or national sustainability indices lack flexibility and are based on general metrics that do not consistently represent the unique characteristics of specific geographic area. Compared to similar models, there is no information at the regional and national level. At the international level, the ecological security index models of Wang and Bao (2021) and the Ecological Footprint of Wackernagel and Rees (1996) are used as a reference for comparison. This evaluation enhances the viewpoint on sustainability management and ecological security at multiple scales. Below, we outline significant attributes of the three models (Table 9):

This TBC takes into account different aspects to those reported by (Imelda and Hidayat, 2024; Jiménez-Bedoya et al., 2024; Teweldebrihan and Dinka, 2024) who have been concerned about specific ecosystems such as water, agriculture and territory, since it focuses on four coverages: water, vegetation, urban planning and linear (roads, paths, etc.). In conclusion, the achievement of TBC and similar instruments hinges on a unified strategy that merges scientific understanding, political determination, and community engagement. This combination is essential to meet the challenges of climate change and move towards genuine sustainability, as it becomes a crucial challenge regarding bioecological sustainability as well as the need to overcome structural barriers that hinder sustainable development, the lack of financial resources, administrative fragmentation

Table 10: Comparison of TBC with other existing ecological models

Criterion	Ecological security model (Wang and Bao, 2021)	TBC	Ecological footprint
Approach	Ecological security in large urban agglomerations (Beijing-Tianjin-Hebei). Considers air quality, water resources and soil protection.	Evaluation of land use in municipalities of Colombia, considering ecological coverage (vegetation, water, infrastructure, urban development).	It measures human demand on natural resources at a global level, without a focus on ecological security.
Variables considered	Land use, water bodies, air quality, biodiversity, urban expansion. It also evaluates infrastructure to mitigate environmental disasters and maintain ecological stability.	Territorial coverage (vegetation, water, urban and linear), social and economic factors (education, housing, employment). Considers anthropic and abiotic elements.	Resource consumption and carbon emissions. It does not assess ecological security variables or territorial infrastructure.
Scale and applicability	Large urban regions. Seek balance between economic development and environmental conservation. Consider infrastructure planning for sustainability.	Local and regional territories (municipalities of the Department of Atlántico in Colombia). Provides detailed overview of local environmental impact.	Global application, although it can be used at different scales. Designed to measure the aggregate impact of humanity on the planet.

and poor institutional capacity, especially in small and medium-sized municipalities. The situation is further complicated by the narrow understanding of authorities and communities regarding the impacts of climate change and the urgency of these issues, hindering the effective implementation of tools such as the TBC. Other challenges of this project are the training of local capacities for the correct use of this mathematical model. Additionally, a strong political will is required to embed the TBC within territorial planning at local, regional, and various other areas of the country, aiming for improved implementation of the model.

CONCLUSION

The findings of this study reveal a crucial link between the TBC and the successful realization of the United Nations' SDGs. It is imperative to engage in research that focuses on developing mathematical frameworks capable of evaluating the territorial and bioecological dimensions that play a vital role in fostering SD worldwide.. The department of Atlántico faces significant challenges derived from climate change, including alterations in weather patterns, pressure on natural resources and limitations in the capacity of authorities to implement effective measures. The lack of community empowerment underlines the urgency of adopting an integrated approach that adapts to the territorial reality and strengthens local resilience. For this to be achieved, both the central government and local authorities need to take a proactive stance in managing the environment and adapting to climate change, ensuring that the implementation of the SDGs is grounded in a thorough comprehension of regional attributes. Therefore, with the TBC, a new vision of analysis of bioecological and territorial elements begins, leading to the management of local and national plans, programs and projects. This study proposes a methodology that links environmental management systems with municipal planning, promoting sustainability in some territories of the department of Atlántico. TBC serves as a crucial instrument in harmonizing the use of natural resources with their preservation, thereby safeguarding the welfare of both present and future generations. The use of satellite images, environmental records and population growth analysis allowed a better understanding of the environmental and urban dynamics of each municipality. The relationship between population growth and the reduction of natural resources justifies the implementation of more effective environmental management strategies. Technologies such as satellite telemetry and the EIR support the evaluation of the current state and the recognition of past trends, both of which are critical for planning proactive strategies in response to extreme events. Finally, it is essential to develop strategies that optimize decision-making from the central government, together with local initiatives that encourage community participation. The implementation of a comprehensive plan based on the Deming quality cycle will guarantee the success of environmental management programs.

Moreover, prioritizing the expansion and validation of tools such as the TBC in different areas is crucial for reinforcing the effective realization of the SDGs. This study represents a first step towards optimizing environmental management in the context of climate change, providing territories with concrete and effective tools for the execution of regional plans, programs and projects that promote sustainable, equitable and resilient development. To enhance environmental management and SD in the Atlántico department, it is advisable to create a municipal environmental observatory that leverages satellite imagery and environmental data to assess the effects of climate change. In addition, a territorial environmental management system is proposed that links municipal planning with conservation strategies. It is key to encourage citizen participation through environmental education and incentives for sustainable local initiatives. The implementation of circular economy models and climate resilience plans will ensure efficient management of natural resources. It is recommended at the political level to revise the regulatory framework, decentralize the management of environmental issues, and encourage investment in scientific research and technological advancements. It is also essential to integrate sustainability into economic planning, create a climate change adaptation fund and establish indicators to evaluate the progress of the SDGs in each municipality.

SUGGESTIONS FOR FUTURE AREAS OF RESEARCH

The development and validation of the TBC is based on advanced mathematical models that allow its effectiveness to be evaluated in various regional contexts. These models integrate environmental, social and economic variables to offer a complete view of its impact and sustainability. By engaging in comparative studies, the goal is to authenticate and modify the TBC, ensuring it is suitable for diverse environments. In addition, environmental management and adaptation to climate change in the Department of Atlántico are investigated, analyzing local policies aligned with the 17 SDGs. The objective is to improve community practices to face climate and natural resource management challenges. This encompasses the assessment of institutional capacity, the implementation of resilience strategies, and the creation of a regional approach that is customized to the unique features of the Department of Atlántico. In conclusion, these proposals are designed to bridge the recognized gaps, laying a strong groundwork for future research and increasing the effectiveness of environmental policies and global sustainability initiatives. 1) Integrating science and technology into municipal planning through telemetry and satellite data, applying the use of remote sensing and telemetry technologies for the collection of environmental and urban data and evaluating the data that can be used for more effective planning and management of SD. 2) Analyzing historical patterns and research derived from satellite imagery and environmental data to forecast potential challenges and enhance preventive strategies, serving as a guiding framework for current leaders in governance. 3) Improving local strategies and analysing SDG compliance, using methodologies that prioritise the SDGs at the territorial level. It is essential to investigate the allocation of relative weights to the SDGs necessary to progress on local goals, so that the particular priorities and needs of each municipality are reflected. This could involve the development of assessment tools that are adapted to various local, national and global contexts. 4) The creation of assessment tools aimed at validating and broadening the application of instruments like TBC in various regions to evaluate their relevance and efficacy in diverse settings. 5) Promoting community engagement and participation in studies on urban initiatives, in order to investigate how to foster engagement in environmental management and the implementation of the SDGs, evaluating local strategies that have proven effective in involving the population in decision-making and in the implementation of environmental policies. 6) Educational programs and training initiatives aimed at community leaders and local officials focused on natural resource management and climate change adaptation. 7) Case studies from different regions to identify successful practices and lessons learned in the implementation of climate change adaptation and mitigation strategies through TBC. 8) This analysis focuses on the assessment of the Deming Quality Cycle as a framework for integrating quality systems within public administration. It aligns with the execution of the SDGs and emphasizes its application in environmental management. The evaluation aims to highlight how this approach can enhance the effectiveness of both administrative and financial

processes in the delivery of SD initiatives

AUTHOR CONTRIBUTIONS

R. Zapata-Stacey performed the conceptualization, methodology, supervision, writing of the original draft; D. Pinto Osorio assisted to analyse the data and validation; C.A. Rodríguez-Nieto performed the editing, drafting the original draft and review; M. Machado Penso reviewed, visualization and supervised the whole writing.

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CONFLICT OF INTEREST

The authors declare that there are no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, were observed by the authors.

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ABBREVIATIONS

%	Percent
TBC	Territorial Bioecological Coefficient
C.V1	Plant coverage
C.L1	Linear coverage
C.H1	Water coverage
C.U1	Urban coverage
CrP	Population growth
COP26	Conference on climate change
EIR	Environmental identification registry
EQI	Environmental quality index
GIS	Geographic information system
IGAC	Instituto geográfico Agustin Codazz
IVe	Vester homologation indicator
PODS	Percentage of the relative weight of each SDG
SD	Sustainable development
SDG	Sustainable development goal
SDGs	Sustainable development goals
SDG13	Sustainable Development Goals 13-climate action
STEM	Science, technology, engineering and mathematics
TPP	Territorial planning plans
V1	Initial value

V2	Temporary value
V1 -V2	Photographic or cartographic method

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