SHORT ARTICLE

Oceanographic factors as modulators of biodiversity in the La Guajira upwelling system: a systematic review

Factores oceanográficos como moduladores de la biodiversidad en el sistema de surgencia de La Guajira: una revisión sistemática

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ABSTRACT

In the northern part of Colombia is the department of La Guajira, a marine-coastal area influenced by different oceanographic and atmospheric processes that give it unique characteristics. Various investigations have focused on describing the oceanography of La Guajira, in which the environmental variables respond differently according to the climatic season; however, there are few works that contrast the oceanographic processes of the area of interest with the biodiversity. The objective of this systematic review was to determine the main environmental factors that modulate the oceanography of La Guajira and to establish whether the authors link them with aspects of biodiversity. To achieve this, a search was carried out for scientific articles related to the climatology and oceanography of La Guajira, for which three world-renowned databases were consulted: Scopus, ScienceDirect, and Web of Science. Finally, it was concluded that, although several investigations have analyzed the behavior of the Caribbean Sea and the way in which its temperature, salinity and chlorophyll vary at different scales, few investigations have focused on relating these characteristics with the biodiversity of the zone; a key aspect to take into account if we think that species and ecosystems respond to the way the climate and the ocean behave.

KEYWORDS: La Guajira, upwelling, oceanography, biodiversity.

RESUMEN

En la zona norte de Colombia se encuentra el departamento de La Guajira, un área marino costera influenciada por diferentes procesos oceanográficos y atmosféricos que le atribuyen características únicas. Diversas investigaciones se han centrado en describir el comportamiento oceanográfico de La Guajira, en la cual las variables ambientales responden de manera distinta de acuerdo con la época climática; sin embargo, son pocos los trabajos que contrastan los procesos oceanográficos del área de interés con la biodiversidad. La presente revisión sistemática tuvo como objetivo determinar los principales factores ambientales que modulan la oceanografía de La Guajira, y establecer si los autores los vinculan con aspectos de biodiversidad. Para lograrlo se realizó una búsqueda de artículos científicos relacionados con temas de climatología y oceanografía de La Guajira, para lo cual fueron consultadas tres bases de datos mundialmente reconocidas: Scopus, Sciencedirect, y Web of Science. Finalmente, se

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concluyó que, a pesar de que varias investigaciones han analizado el comportamiento del mar Caribe y la manera en la que su temperatura, salinidad y clorofila varían a diferentes escalas, pocas investigaciones se han enfocado en relacionar estas características con la biodiversidad de la zona; un aspecto clave para tener en cuenta si se considera que las especies y los ecosistemas responden a la manera en la que se comporta el clima y el océano.

Palabras clave: *La Guajira, surgencia, oceanografía, biodiversidad.*

Introduction

La Guajira is a peninsula located in the northern part of Colombia (Fig. 1), characterized by being an area of desert and xerophytic ecosystems, which is also highly influenced by the Caribbean upwelling system, driven by the Northeast Trade Winds (Martínez, Goddard, Kushnir, & Ting 2019) and the Caribbean Low-Level Jet (CLLJ) (Muñoz, Busalacchi, Nigam, & Ruiz-Barradas, 2008; Wang, 2007; Andrade & Barton, 2005).

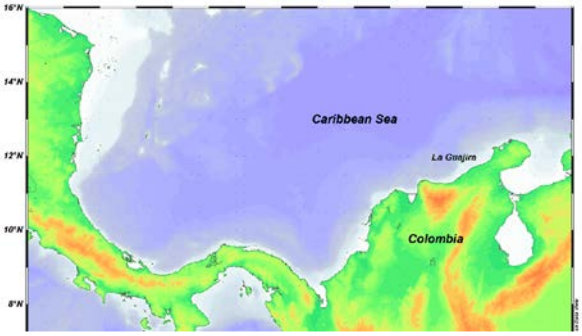

Figure 1. The department of La Guajira and its adjacent marine area

Additionally, it is influenced by the movement of the Intertropical Convergence Zone (ITCZ), which is responsible for precipitation in the area, ranging between 218 mm and 532 mm per year (Toro-Tobón, Alvarez-Flórez, Mariño-Blanco & Melgarejo, 2022). The sea surface temperature (SST) ranges from 20 °C to 30 °C, with an average of 25 °C (Rueda-Roa & Muller-Karger, 2013, Chollet *et al*., 2012). These attributes lead to an upwelling of organic matter that attracts a diversity of species such as fish, marine reptiles, and sharks (Andrade & Barton, 2005; Vásquez & Sullivan, 2021).

There are few studies in this area that address marine biodiversity or its relationship with climatology or oceanography, among which Muller-Karger (2023), Ayala, Gutiérrez, and Montoya (2022), Dorado-Roncancio, Medellín-Mora, Mancera-Pineda and Pizarro-Koch (2022), Invemar (Eds. 2010), Páramo *et al*., (2003) and Bernal *et al*., (2016) stand out, as it is a zone in which mainly social, cultural, and economic aspects are addressed (Bonet-Morón & Hahn-De-Castro, 2017; Colorado & Moreno, 2017).

In this sense, it is relevant to discuss not only social issues but also climatological and oceanographic topics in the area, as their variation over time could jeopardize indigenous populations and the associated biodiversity (Vásquez & Sullivan, 2021). Therefore, this study aimed to identify research trends in the maritime area of La Guajira through a bibliometric analysis, and based on this, determine the main environmental factors that modulate the oceanography of La Guajira and establish whether authors link it to aspects of biodiversity or not.

Study area

The region of La Guajira, in oceanographic and ecological terms, is characterized by the presence of a seasonal upwelling system with low productivity (Gómez & Acero, 2020). Consequently, there is high variability in oceanographic and atmospheric structure. Using satellite reflectances and standardized empirical orthogonal functions, Bastidas-Salamanca, Ricaurte, Santamaría del Ángel, Ordóñez, Murcia and Romero (2017) identified 9 oceanographic regions in the Colombian Caribbean with high variability in the annual cycle, one of which was named the La Guajira System. This system was described by Murcia, Ricaurte, Ordóñez and Bastidas-Salamanca (2017) as an area of high oceanographic dynamism, where the main fertilization mechanism is advection rather than Ekman transport. This advection varies depending on the dominant season, either through mesoscale eddies from the east transporting nutrients from the Gulf of Venezuela or from the west through continental discharges from the Magdalena River carried by the Caribbean counter-current.

The area is inhabited by different indigenous groups, including the Wayúu, Koguis and Arzarios, known for their culture and tradition, with a total population exceeding 1 000 000 inhabitants, according to the Chamber of Commerce of La Guajira (Cámara de Comercio de La Guajira, 2017). The economy is centered around the mining of salt, gas, and coal, as well as agriculture involving the cultivation of sesame, rice, sorghum, cotton, cassava, sugarcane, and tobacco. Additionally, there are some tourism activities. However, La Guajira is the third poorest department in Colombia, following Chocó and Vichada (Otero-Cortés, 2013).

Methodology

A search for scientific articles related to climatology and oceanography in La Guajira, Colombia was conducted. The search was performed using three databases available at Nueva Granada Military University: Scopus, ScienceDirect, and Web of Science (WoS). The information was obtained based on the search criterion of articles published in the last 20 years (2003 to 2021) related to the biodiversity, ecology, oceanography, and climatology of the region (Fig. 2).

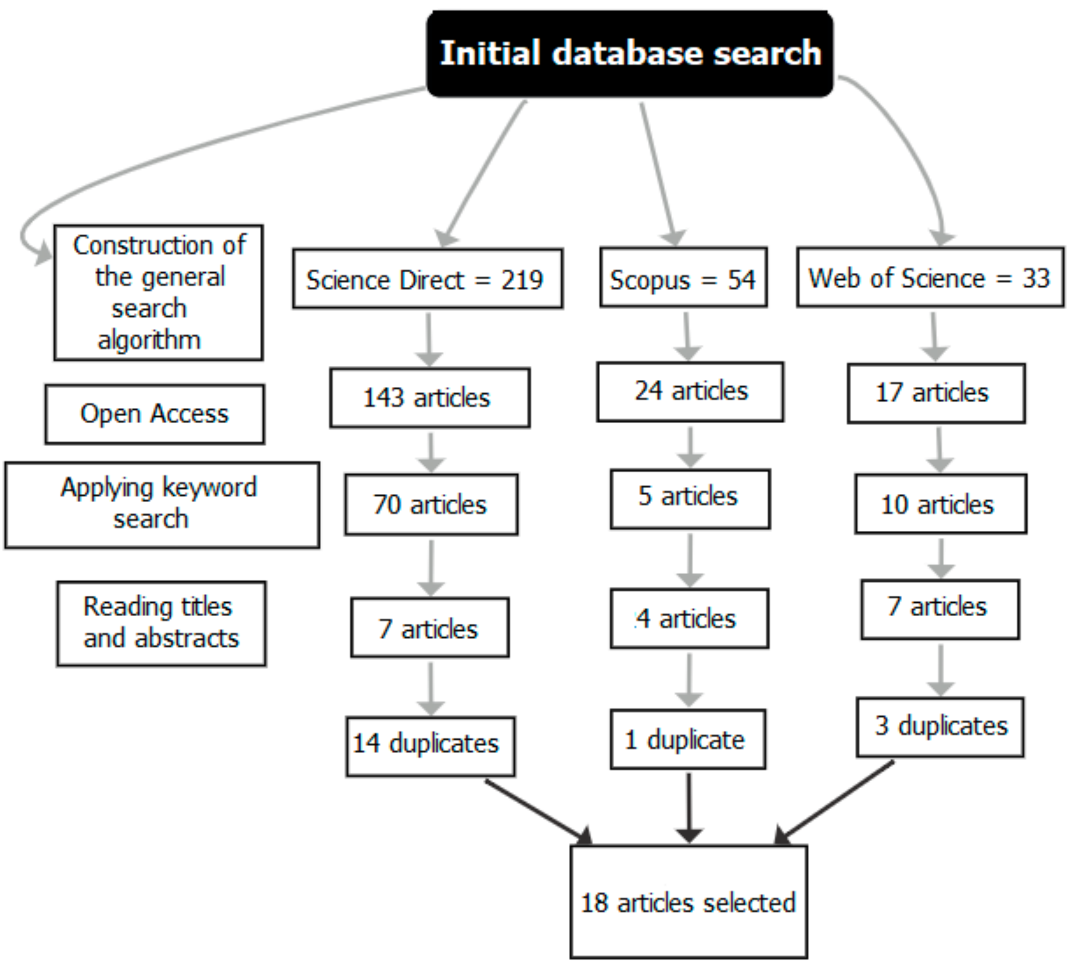

Figure 2. Flowchart of the filtering process applied to the documents found in the databases before the systematic review

The database search followed the following search algorithm: Caribbean Sea OR Guajira AND oceanographic, Guajira AND upwelling, Guajira AND Caribbean Jet, Guajira AND Climatology. The selection of documents was based on those that strictly met the search algorithm, and were available in English and Spanish. Duplicate documents in each database were not considered. Subsequently, a matrix was created with the selected articles, allowing for a comparison of publication years, databases, and topics addressed. Additionally, a bibliometric analysis of the selected articles in the Scopus database was conducted using the VOSviewer software, a freely available tool for analyzing and visualizing scientific literature through bibliometric networks.

Results and discussion

Bibliometric Analysis

The systematic search yielded a total of 306 publications related to climatological and oceanographic processes in the Colombian Caribbean and La Guajira. After applying the selection criteria, a total of 85 publications were obtained from the three selected databases. Finally, these publications were carefully reviewed to assess their relevance to the objective of this study, resulting in the selection of a total of 18 publications (Table 1).

Table 1. Selected articles after the filtering process

Author	Year	Title of the Publication	Data base
Alonso del Rosario, J. Vidal, J.; Blázquez, E.	2021	The Upwelling of the Colombian Caribbean Coasts: Remote Sensing, Morphology, and Influence on the Lake Maracaibo	Scopus
Torregroza-Espinosa, A. Restrepo, J.; Escobar, J. Pierini, J.; Newton, A.	2021	Spatial and temporal variability of temperature, salinity and chlorophyll-a in the Magdalena River mouth, Caribbean Sea	ScienceDirect
Orfila, A.; Urbano, C.; Sayol, J.; González-Montes, S. Cáceres-Euse, A.; Hernández, I.; Muñoz, A.	2021	On the Impact of the Caribbean Counter Current in the Guajira Upwelling System	WoS
Correa-Ramírez, M.; Rodríguez, A.; Ricaurte-Villota, C. Paramo, J.	2020	The Southern Caribbean upwelling system off Colombia: Water masses and mixing processes	Scopus
Alonso del Rosario, J; Vidal, L.; Blázquez, E.	2019	On the prediction of upwelling events at the colombian caribbean coasts from modis-SST imagery	Scopus
Montoya-Sanchez, R.; Devis-Morales, A.; Bernal, G.; Poveda, G.	2018	Seasonal and intraseasonal variability of active and quiescent upwelling events in the Guajira system, southern Caribbean Sea	ScienceDirect
Beier, E.; Bernal, G.; Ruiz-Ochoa, M.; Barton, E.	2017	Freshwater exchanges and surface salinity in the Colombian basin, Caribbean Sea	WoS
Bastidas-Salamanca, M.; Ordóñez-Zúñiga, A.; Ricaurte-Villota, C.	2016	Events of wind intensification and relaxation in the Bay of Santa Marta (Colombian Caribbean): Oceanographic implications	Scopus
Santos, F.; Gómez, M.; Varela, R.; Ruiz☐Ochoa, M.; Días, J.	2016	Influence of upwelling on SST trends in La Guajira system	WoS
Bernal, G.; Osorio, A.; Urrego, L.; Peláez, D.; Molina, E.; Zea, S.; Montoya, R.; Villegas, N.	2016	Occurrence of energetic extreme oceanic events in the Colombian Caribbean coasts and some approaches to assess their impact on ecosystems	ScienceDirect

Author	Year	Title of the Publication	Data base
Alonso del Rosario, J. Blázquez, E.; Isaza-Toro, E.; Vidal, J.	2015	Internal structure of the upwelling events at Punta Gallinas (Colombian Caribbean) from modis-sst imagery	ScienceDirect
Sarmiento-Devia, R.; Vásquez, Á.; Mejías, M. Dávila, P.; Franco-Herrera, A.	2014	Variabilidad intra-anual del régimen climático en sectores de surgencia en el sudeste del Mar Caribe, usando ERA Interim.	WoS
Jouanno, J.; Sheinbaum, J.	2013	Heat Balance and Eddies in the Caribbean Upwelling System	WoS
Ruiz-Ochoa, M.; Beier, E.; Bernal, G.; Barton, E.	2012	Sea surface temperature variability in the Colombian Basin, Caribbean Sea	ScienceDirect
Lonin, S.; Hernández, J. Palacios, D.	2010	Atmospheric events disrupting coastal upwelling in the southwestern Caribbean	WoS
Arévalo-Martínez, D. Franco-Herrera, A.	2008	Características oceanográficas de la surgencia frente a la ensenada de Gaira, departamento de Magdalena, época seca menor de 2006	ScienceDirect
Andrade, C.; Barton, E.	2005	The Guajira upwelling system	ScienceDirect
Páramo, J.; Quiñones, R.; Ramírez, A.; Wiff, R.	2003	Relationship between abundance of small pelagic fishes and environmental factors in the Colombian Caribbean Sea: an analysis based on hydroacoustic information	WoS

For the search conducted in the Scopus database, the bibliometric analysis included the representation of keyword co-occurrence in the VOSviewer program (Fig. 3).

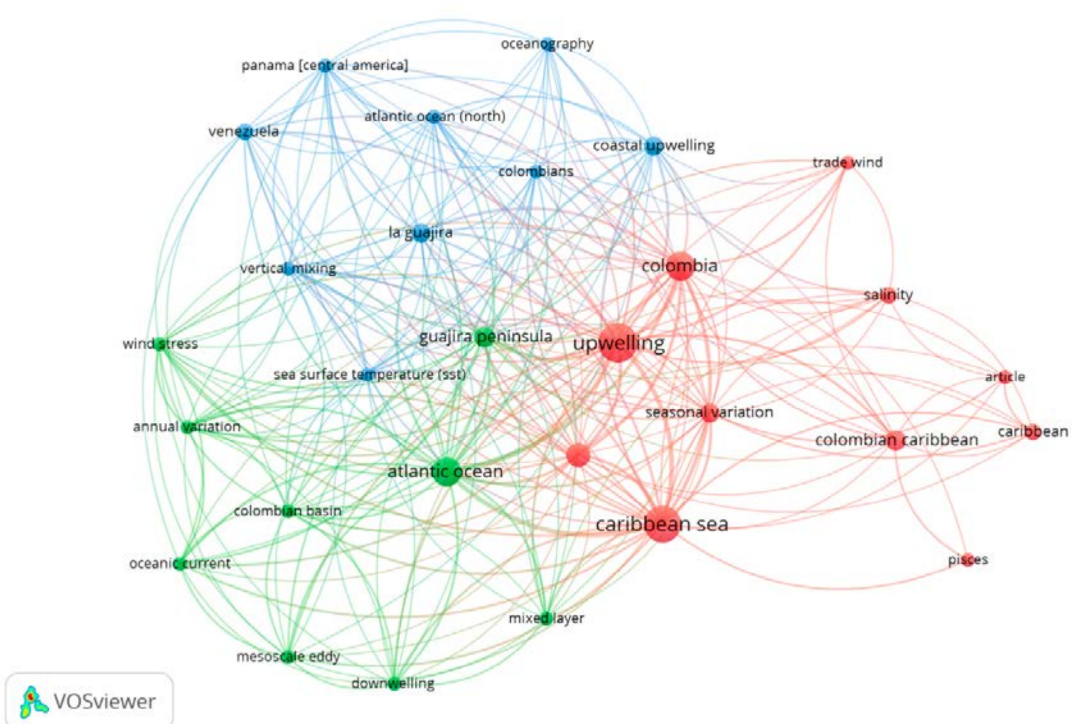

Figure 3. Keyword co-occurrence network, part of the bibliometric analysis of the results from Scopus

In this graph, the nodes (colored circles) represent the selected feature (keywords). The location and size of the nodes have meaning; for example, a larger-sized node represents a greater presence of that keyword, indicating that it has been more extensively researched than others among the articles found in the database. For this specific search, the largest nodes correspond to "upwelling," "Caribbean Sea," and "Colombia," which refer to the study area.

Additionally, three colors are identified in the figure (green, blue, and red). This color grouping is called a cluster and corresponds to a set of nodes that have been commonly investigated, representing large grouped themes that can be studied simultaneously. For the Scopus database, excluding words associated with geographical areas, the blue cluster encompasses themes of coastal upwelling, vertical mixing, and sea surface temperature; the green one includes wind stress, annual variation, circulation (eddies and currents), and the mixing layer, and the red one includes winds, salinity, seasonality, and fish. From this graphical analysis, it is possible to identify the predominance of studies in physical topics associated with oceanography and meteorology, and few or almost none associated with biological aspects, representing an initial indication of research opportunities.

It is important to note that the Scopus database includes scientific articles published in indexed journals and does not include gray literature (reports, theses, books, event proceedings), which may potentially contain research contributing to oceanographic, climatic, and biodiversity knowledge that is beyond the scope of this analysis.

Oceanographic Factors Modulating Biodiversity

La Guajira Upwelling Process

Upwelling is an oceanographic phenomenon where the interaction of coastal winds and currents causes the rise of deep waters, bringing nutrients from the ocean floor to the surface, where they are utilized by photosynthetic organisms. Therefore, this upwelling process of productivity favors different pelagic species (Andrade & Barton, 2005). This process generally occurs on the western edges of continents; however, there are specific conditions in certain other areas that allow this phenomenon to happen (Albuquerque *et al*., 2014).

In addition to its importance in maintaining the oceanic food web and, consequently, establishing areas of high biodiversity (Arévalo-Martínez & Franco-Herrera, 2008), on a large scale, it can even regulate local, regional, and global thermal balance (England *et al*., 2014; Jouanno & Sheinbaum, 2013). In the case of the La Guajira upwelling, it is driven by the Trade Winds, the CLLJ, and the Caribbean Current (Alonso del Rosario *et al*., 2019). The Caribbean upwelling system has been studied in two main areas: the western basin (La Guajira, Colombia) and the eastern one (Cariaco, Venezuela). Oceanographic behavior is different in the two areas, and sea surface temperature (SST) and salinity values vary notably (Montoya-Sánchez, Devis-Morales, Bernal & Poveda, 2018). Also, in both coastal upwelling zones, fish production is very uneven (Gómez & Acero, 2020).

Some authors consider that, compared to other coastal upwelling processes, La Guajira's is weak and has low productivity due to a mixing process occurring in the Panama-Colombia Gyre (Correa-Ramírez *et al*., 2020). There, the influence of the mouth of the Magdalena River causes dilution of the nutrient-rich Caribbean Sea by freshwater, leading to a reduction in salinity values and nutrient concentration, thereby contributing to the low productivity of this upwelling system (Beier *et al*., 2017). However, another author suggests that the upwelling process is strong thanks to the mouths of the Magdalena and Orinoco Rivers and the outlet of Lake Maracaibo. Additionally, there is an aeolian contribution of dust from the La Guajira desert, which also enriches the Caribbean waters (Andrade & Barton, 2005).

The upwelling in La Guajira is strong during the months of December to March and July, as these are the dry seasons and wind intensity is high. In the rainy season from October to November, the winds weaken, as does the upwelling (Andrade & Barton, 2005; Montoya-Sánchez *et al*., 2018). This aligns with Alonso del Rosario *et al*. (2019) and Alonso del Rosario *et al*. (2015), who consider that the upwelling in the zone is mainly coastal, not evident in the open sea, and strongly influenced by the ITCZ. When this is located to the south (December to April-May), the Trade Winds predominate, the CLLJ intensifies, and so does the upwelling. On the other hand, it weakens around June-August when the ITCZ is located to the north, and the rainy seasons occur.

Thus, it is determined that the Caribbean region is strongly influenced by the Trade Winds that induce the CLLJ, even though two upwelling episodes occur around the La Guajira Peninsula during the year. The first is the strongest and occurs from October-November to March-April. The second occurs between May and July, when the ITCZ is in the northern zone and is much weaker (Alonso del Rosario *et al*., 2021).

Temperature

Ruiz-Ochoa *et al*. (2012) found that the influence of the La Guajira upwelling was observed throughout the evaluated period (1985-2009) but was more intense between December and February. During this period, the temperature ranged between 25.5 °C and 29.5 °C, with no difference between La Niña and El Niño years. This aligns with Lonin *et al*. (2010), Bastidas-Salamanca *et al*. (2016) and Santos *et al*. (2016), who found that during the first three months of the year, SSTs fluctuate between 25 °C and 28 °C, associated with the upwelling process. In the weakened upwelling season, SSTs rise above 28 °C. However, Alonso del Rosario *et al*. (2019) found different values. These authors suggest that during upwelling processes, the temperature varies from 22 °C to 23 °C, and when upwelling weakens, the temperature fluctuates between 28 °C and 29 °C. This discrepancy may be associated with the studies being conducted in different years, during which the El Niño or La Niña phenomena occurred, which led to different values being measured.

Chlorophyll

Chlorophyll values are usually measured in the sea through satellite images from spectroradiometers. Chlorophyll is associated with higher primary productivity, indicating greater nutrient availability for the first links in the marine food chain (Roberts *et al*., 2017). For example, Orfila *et al*. (2021) found that between June and October, when the wind is weakened, chlorophyll values were close to 3 mg m^{-3}. However, Arévalo-Martínez and Franco-Herrera (2008) found that during the dry season when the winds are strong, the Caribbean waters have SSTs between 21 °C and 24 °C, salinity between 36.5 and 37.2, and chlorophyll values of 0.59 mg m^{-3}. Therefore, the months of higher productivity correspond to the rainy season, between June and October. In contrast, when the ITCZ is located to the north, chlorophyll concentrations decrease during April and May (Orfila *et al*., 2021).

The Colombian Caribbean is influenced by river discharge, causing variations in salinity, temperature, and chlorophyll values. Torregroza-Espinosa *et al*. (2021) found that at the mouth of the Magdalena River, salinity has values close to 28, the average temperature is 27.6 °C, and chlorophyll values are 1.5 mg m^{-3}. This aligns with the mixing processes described by Correa-Ramírez *et al*. (2020), which cause the oceanographic conditions in this area to be different compared to areas without river mouths, affecting upwelling processes.

Salinity

In the Panama-Colombia Gyre zone, freshwater dilution from rivers and runoff occurs throughout the year, causing salinity values to decrease (Torregroza-Espinosa *et al*., 2021). In contrast, to the north of La Guajira, salinity increases from December to May due to upwelling processes, as a result of which values can reach around 36.5 (Sarmiento-Devia *et al*., 2013). When the El Niño phenomenon is present, the increase in salinity values occurs in the dry season from December to February. In La Niña periods, when the rainy season begins (between September and November), dilution processes are elevated near the La Guajira coastal zone (Beier *et al*., 2017), and consequently, salinity decreases.

Biodiversity

Some authors mention the relationship between the oceanographic processes in the area of interest and the abundance and distribution of different species such as the Atlantic herring (Opisthonema oglinum), scaled sardine (Harengula jaguana), and round sardinella (Sardinella aurita). These species have a preference for certain salinity and temperature conditions that are favored by upwelling processes (Páramo *et al*., 2003). Some planktonic organisms usually leave the continental margin to develop in open sea areas, depending strictly on the upwelling processes occurring on the coasts to obtain food in their early life stages (Andrade & Barton, 2005). On the other hand, Bernal *et al*. (2016) mention the importance of understanding these oceanographic processes in relation to coastal ecosystems such as mangroves, reefs, and beaches, to understand how they behave and respond in the face of these processes.

Recently, Dorado-Roncancio *et al*. (2022) analyzed the distribution of copepods between 2013 and 2018, finding that it responds to local oceanographic patterns regulated by dissolved oxygen variability and temperature in the water column. Using data collected on a cruise in 2008, Lozano, Vidal, and Navas (2010) reported spatial differences in the Colombian Caribbean regarding the composition and percentage abundance of phytoplankton species. Meanwhile, Medellín and Martínez (2010), using data from the same cruise, described the distribution of mesozooplankton, indicating that the highest concentrations of biomass and abundance were found in the northeastern and southwestern zones of the Colombian Caribbean, and that they are related to upwellings and continental discharges, as well as the pattern of surface currents and cyclonic circulation events.

The conditions of the seafloor are also relevant to the biodiversity of the Colombian Caribbean. Regarding echinoderms, Benavides-Serrato and Borrero-Pérez (2010) identified a clear bathymetric distribution pattern, with four clusters of stations that could be explained by the structure of water masses, marine currents, and sediment type. For their part, Trujillo, Sosa, and Linero (2009) showed a weak effect of the size of the grains which make up the physical substrate on the spatial distribution of La Guajira's macrofauna.

Currently, there is a growing interest in the potential for renewable energy in the La Guajira area, both on the mainland and in the sea. Studies on wind resources have been conducted along the entire coastal zone of the Colombian Caribbean with high (Gil, Cañón, & Martínez, 2021) and low temporal resolution (Bastidas-Salamanca & Rueda-Bayona, 2021), and for specific locations such as La Guajira (Ochoa, Álvarez, & Chamorro, 2019). However, as mentioned by Garavito-Téllez (2020), these types of projects generate environmental impacts on the biotic environment, including connectivity loss or fragmentation, habitat loss, or collisions with structures, which require special attention from environmental authorities and will require, in the short term, specific studies on biodiversity.

Conclusions

Based on this review, it is evident that there is a comprehensive understanding of how the La Guajira upwelling system functions and behaves. The influence of this upwelling can be identified in terms of variations in salinity, temperature, and chlorophyll during the year. The upwelling is driven by the Trade Winds, the Caribbean Low-Level Jet (CLLJ), and the Caribbean Current. Additionally, it is influenced by the Intertropical Convergence Zone (ITCZ) and its position, which varies during the year in concert with the dry and wet seasons.

Various authors have been able to establish the values of key variables and how they change in the annual cycle using satellite images. The temperature during upwelling processes is cold, ranging between 25°C and 28°C; when upwelling weakens, sea surface temperatures (SST) increase to values above 28°C. Chlorophyll values are generally higher during upwelling processes but can also vary depending on whether it is the dry or wet season. Salinity values are high (36.5 to 37.2) but decrease in the wet season or in areas with river mouths due to the mixing and dilution process.

However, there is a gap in understanding regarding the upwelling and its impact on the biodiversity of the area and the ecosystems associated with it. While some articles briefly mention the importance of the upwelling process for marine diversity, it is crucial to recognize that climate and oceanography modulate how species are distributed. Moreover, many species associated with upwelling zones have high economic value, making it even more imperative to conduct research in this regard.

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Authors' contributions

Conceptualization: A. R., F. B.; Methodology: A. R.; Software: A. R., F. B.; Analysis: A. R., F. B.; Writing - Original Draft Preparation: A. R.; Writing - Review and Editing: A. R., F. B. All authors have read and approved the final published version of the manuscript.

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