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A Fuzzy Logic Technique for the Environmental Impact Assessment of Marine Renewable Energy Power Plants

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Abstract: The application of fuzzy logic to environmental impact assessment (EIA) provides a robust method to address uncertainties and subjectivities inherent in evaluating complex environmental systems. This is particularly relevant in ocean renewable energy projects, where predicting environmental impacts is challenging due to the dynamic nature of marine environments. We conducted a comprehensive literature review to identify the types of impacts currently being investigated, assessed, and monitored in existing marine energy conversion projects. Based on these foundations, we developed both traditional and fuzzy mythologies for EIA. The fuzzy logic methodology approach allows for the incorporation of uncertainties into the assessment process, converting qualitative assessments into quantifiable data and linguistic levels and enhancing decision-making accuracy. We tested this fuzzy methodology across four types of ocean energy devices: floating, submerged, fixed to the ocean floor, and onshore. Finally, we applied the methodology to the EIA of a marine energy project in the Cozumel Channel, Quintana Roo, Mexico. The results demonstrate that fuzzy logic provides a more flexible and reliable evaluation of environmental impacts, contributing to more effective environmental management and sustainable development in marine renewable energy contexts.

Keywords: fuzzy logic; environmental impact; ocean renewable energy

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1. Introduction

The utilization of renewable energy generation technologies is becoming increasingly prevalent, largely due to the numerous environmental, economic, and social benefits they offer. These include the reduction in greenhouse gas emissions, the creation of employment opportunities, and the potential for providing electricity to isolated communities. Additionally, renewable energy sources do not face the same limitations as fossil fuels in terms of depletion [1–3].

In recent years, there has been a notable focus on the development of technology for the conversion of energy from the ocean. Solar, wind, and gravitational energy co-occur in the ocean, giving rise to phenomena such as waves, tides, thermal gradients, and currents, which possess potential or kinetic energies that can be captured and converted [4–6].

One of the most significant challenges to the utilization of ocean energy is the assessment of the potential impacts that the devices and arrays of devices may have on surrounding marine and coastal ecosystems. The occurrence and magnitude of such impacts, as well as the socioeconomic implications, vary according to the type, operation, and extent of each device. With regard to the potential impact on ecosystems, this will depend on the functioning of the ecosystem itself, its resistance and resilience, as well as the response of the ecosystem to previous anthropogenic pressures [7–11]. In order to identify and quantify the environmental impacts (EIs) generated by a project or human activities, an EIA is conducted.

Such evaluations are of a preventative nature and thus must be conducted prior to the commencement of the project in question. Consequently, EIAs necessitate the acquisition of primary data from environmental monitoring networks, which are then transformed into environmental indicators. These indicators facilitate communication with the general public and decision-makers [12–15].

In accordance with the General Law for Ecological Balance and Environmental Protection in Mexico, any activity or civil works project may be carried out without the presentation of an EIA. These evaluations serve as an instrument of environmental policy, with the objective of identifying, predicting, and interpreting the environmental impacts that a project or activity would produce. Additionally, they aim to prevent, mitigate, and restore any damage to the environment. Furthermore, they regulate the works and activities with the objective of reducing or even avoiding any negative effects on the environment. Additionally, they guarantee the sustainability of the projects, considering the economic feasibility and the social benefit [16,17].

Despite the importance of EIAs, there is a paucity of marine renewable projects that include them and even fewer that report some type of monitoring during the operational phase of the devices. Furthermore, there is no consensus on the criteria that should be employed to conduct the evaluations. Consequently, each development must commence anew, implementing its own principles and criteria. This practice significantly hinders the establishment of a universal basis for EIA that can be applied to ocean energy converter projects [14].

It is, therefore, essential that the environmental implications and consequences of obtaining energy from marine sources be properly assessed with respect to the ecological status of the coastal and marine zones. This will necessitate an analysis of the current condition of the ecosystems in question, with a view to maintaining or enhancing the composition, structure, and function of said ecosystems. As a result of greater understanding and knowledge of EIs, there will be greater certainty and support in the development of marine energy systems in Mexico and globally. This will also lead to greater certainty about their long-term sustainability [9,14].

In this context, the application of fuzzy logic represents a powerful tool for EIA due to its ability to handle uncertainty and complexity in environmental systems. Fuzzy logic enables the integration of vague or subjective data into models that can yield meaningful insights, facilitating decision-making under uncertain conditions. This approach has been particularly valuable in human-centric systems and environmental modeling, as discussed by Hagras (2018) [18]. Fuzzy inference systems, as outlined by Chen and Pan (2021) [19], have shown promise in representing complex interactions between variables and improving the robustness of decision-making processes. Moreover, the work of Zhang and Zhan (2021) [20] highlights how fuzzy decision-making methods can be applied effectively in complex systems, making them ideal for environmental impact assessments in the marine context [18–20].

In this regard, the objective of this study is to present a quantitative framework that provides a methodology for the elaboration of EIAs in different ocean energy conversion projects and to establish a flexible framework that can be adapted to different types of devices and ecosystems. This flexibility allows the methodology to incorporate the specific characteristics of each project and ecosystem, enabling its use across diverse marine energy deployments.

Furthermore, there is no consensus on the criteria for EIA in marine energy, which leads each project to develop its own principles and criteria. This makes it challenging to create a standardized framework that can be generally applied to ocean energy projects. By addressing this gap, this study provides an innovative step toward establishing a more consistent approach that is adaptable to various marine energy systems. As a result, it contributes to the long-term sustainability and better understanding of the EI of ocean energy, both in Mexico and globally.

The use of fuzzy logic is proposed as a means of reducing the degree of uncertainty and intrinsic subjectivity of these evaluations, as well as representing scenarios that are more closely aligned with reality, thereby facilitating decision-making.

The paper is divided into the following sections.

- Materials and Methodology: This section details the methodology applied to conduct an EIA based on a bibliographic review of ocean energy devices, categorized by their position in the water column. It also outlines the integration of traditional EIA with fuzzy logic, identifying the relevant environmental components and criteria used for the assessment. Furthermore, the multi-criteria analysis methodology is described, along with the process for implementing fuzzy logic, which is divided into three phases:
    1. Approximate Assessment
    2. Detailed Assessment
    3. Corrective Measures
- Results: This section presents the results from the three phases of fuzzy logic, providing insights into how the methodology was applied and the outcomes for each phase of the assessment.
- Case Study: The case study is conducted in the Cozumel Channel, where the previously explained methodology is applied using a vertical axis helical turbine as the energy conversion device. The area is described, and the results from the fuzzy logic assessment are presented. This section also includes an analysis of the environmental impacts specific to the location and provides recommendations based on the findings.
- Corrective Measures: Based on the results from the case study and the fuzzy logic analysis, this section presents the recommended corrective measures to mitigate environmental impacts identified during the assessment.

2. Materials and Methods

The methodology applied in this study integrates traditional EIA practices with fuzzy logic techniques, creating a comprehensive framework for evaluating the EI of marine energy conversion devices. This approach not only adheres to established EIA principles but also introduces a flexible and nuanced system to address the inherent complexity and uncertainty in these assessments. The methodology consists of several clearly defined components, which are outlined below:

1. Device Classification: Marine energy devices are categorized based on their position within the water column. This classification ensures that the methodology is adaptable to diverse technologies and their specific interactions with the environment.
2. Identification of Environmental Components: Relevant environmental components were identified through a thorough literature review, focusing on aspects most commonly analyzed in EIA processes for marine energy projects. These components include marine ecosystems, water quality, and species biodiversity, among others.
3. Criteria Definition Using Standardized Frameworks: To ensure consistency, the study employed Conesa's (1997) [21] standardized matrix for defining evaluation criteria.

This matrix uses predefined indicators such as intensity, magnitude, and duration to systematically categorize potential EIs.

4. Multi-Criteria Analysis Framework: The methodology incorporates a two-stage multi-criteria analysis:
5. Traditional EIA Analysis: The first stage applies conventional methods, evaluating the significance of impacts based on the criteria and indicators defined by the standardized framework.
6. Fuzzy Logic Integration: The second stage enhances the traditional analysis by employing fuzzy logic. This involves the use of linguistic variables, membership functions (trapezoidal functions), and fuzzy inference systems to handle uncertainties and subjective judgments, offering a more precise and adaptable assessment.
7. Application and Validation: The combined framework was applied to a hypothetical ocean energy project to demonstrate its adaptability and effectiveness across different device types and ecosystems. This application highlights the framework's ability to provide robust, consistent, and scalable evaluations.

To ensure transparency and comprehensibility, the following sections of the manuscript will provide an expanded explanation of each methodological step. This detailed presentation will clarify how the various components of the methodology are interconnected and how they collectively contribute to the assessment of Eis.

By explicitly presenting these steps, the study aims to provide a clear and replicable framework for future research and application in the field.

2.1. Devices Classification

The diversity of ocean energy devices is substantial, with the potential EI varying based on factors such as the power source, construction materials, and operational principles. To address this complexity, we adopted the classification proposed by Mendoza et al. (2019) [14], which categorizes devices not by their energy source but by their position within the water column. This approach enables a clearer understanding of the interactions between the devices and their surrounding environment, grouping them into four main categories: floating devices, submerged devices, devices situated on the seafloor, and onshore devices. This classification is shown in Figure 1.

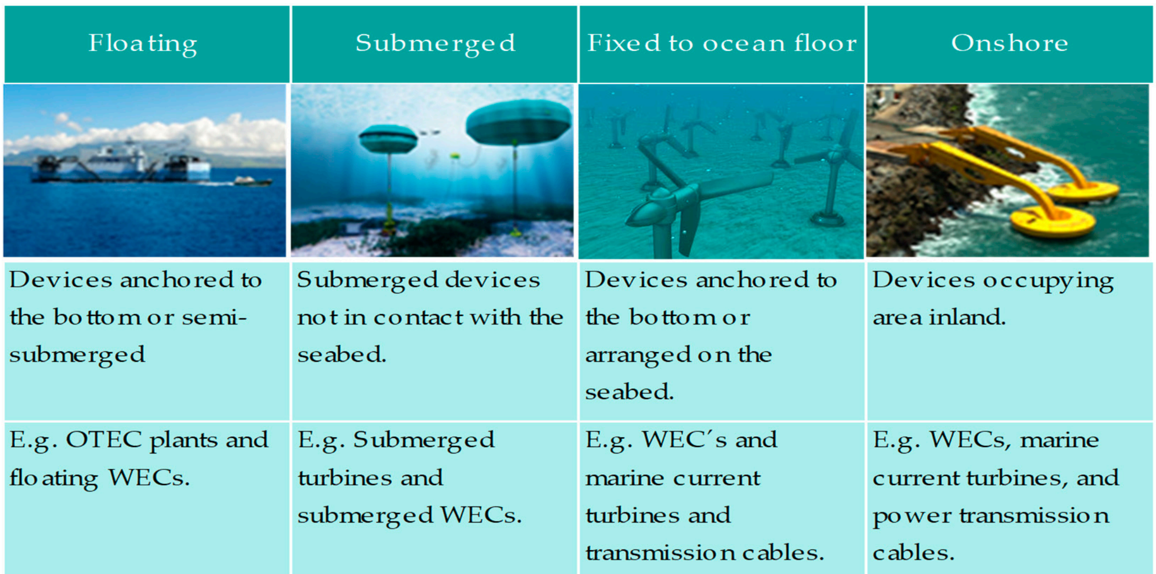

Figure 1. Types of devices according to their position within the water column.

2.2. Environmental Components Identification

From the literature review (see Appendix A), five key environmental components that may be affected by ocean energy devices were identified. Each component is further divided into relevant subcomponents. Table 1 presents these components along with their description and associated subcomponents.

Table 1. Environmental components and subcomponents.

Components	Description	Subcomponents
Hydrological	Changes that can be generated in the distribution of wave energy and water circulation.	- Current direction - Wave energy - Water turbulence
Geomorphological	Changes in erosion and accretion patterns, in relation to the distance from a device or arrangement of devices.	- Far-field sediment transport and properties - Local sediment transport and properties
Biological	Any interaction that affects the ecosystem and its components.	- Collision risk - Changes in behavior - Noise and vibration - Electromagnetism - Population density - Ecological connectivity - Creation of new habitats
Chemical	Interactions that generate changes in the natural chemistry of the water.	- Water quality - Nutrients distribution
Sociocultural	Changes in the economic value and appreciation of the site for the population.	- Scenic value (visual impact) - Impact on fishing - Tourism - Mental health

2.3. Criteria Definition

For this study, the action criteria proposed by Conesa (1997) [21] were applied. This is a standardized tool commonly used in EIA. It provides a systematic approach to categorizing the potential impacts of a project based on predefined criteria. Each indicator in the tables is associated with a specific impact value, which allows for the classification of environmental effects into levels. These criteria utilize a series of indicators to assess the level of environmental impact in each category, offering a comprehensive evaluation of the project's sustainability and environmental responsibility. The indicators are presented in Table 2.

2.4. Multicriteria Analysis

The multicriteria analysis was conducted using the importance assessment matrix proposed by Conesa (1997) [21], an updated version of the well-known Leopold matrix. This matrix provides an initial approach to conducting the EIA by avoiding descriptive and approximate evaluations of potential impacts. Its utility lies in its ability to offer a comprehensive characterization of the impacts, enabling a deeper understanding of their nature. Moreover, the matrix's principles are well-established within the scientific community, ensuring that the interpretation of results remains accessible to scientists and experts alike [21,22].

Table 2. Impact evaluation criteria proposed by Conesa (1997). The criteria, their description, and their values are shown.

Criteria	Description	Value	
Nature	Refers to the favorable or harmful nature of the impact	Favorable Harmful	−1 +1
Intensity (*I*)	Level of destruction	Low Medium High Very high Total	1 2 5 8 12
Extension (*EX*)	Affected spatial area	Punctual Partial Extensive Total Critical	1 2 4 8 12
Moment (*MO*)	Time from the start of the action and the beginning of the effect in the environment	Long term Medium term Short term Critical	1 2 4 10
Persistence (*PE*)	Permanence of the impact over time	Brief Temporary Permanente	1 2 4
Reversibility (*RV*)	Possibility of returning to the initial condition by natural means	Short term Medium term Irreversible	1 2 4
Recoverability (*RC*)	Possibility of returning to the initial condition through the application of corrective measures	Short term Medium term Mitigatable Irrecoverable	1 2 4 8
Synergy (*SI*)	Reinforcement of two or more simple effects	Non-synergistic Synergistic Very synergistic	1 2 4
Cumulative (*AC*)	Progressive increase in the manifestation of the effect	Simple Cumulative	1 4
Effect (*EF*)	Evaluate the cause–effect relationship	Indirect Direct	1 4
Periodicity (*PR*)	Regularity of the manifestation of the effect	Irregular Periodic Continuous	1 2 4

It is proposed that an impact matrix be developed for each stage of the device's life-cycle. Each matrix will include columns representing environmental subcomponents and competencies, while the rows will represent the criteria outlined by Conesa (1997) [21]. This arrangement allows for the representation of the effects each action has on environmental components. Once the matrix is completed, the importance formula will be applied.

$$I = -NA(3IN + 2EX + MO + PE + RV + SI + AC + EF + PR + RC) \quad (1)$$

where

I = Impact,
NA = Nature; the sign of the "nature" variable (positive or negative) depends on whether the impact is positive or negative.

IN = Intensity; *EX* = Extension; MO = Moment; *PE* = Persistence; *RV* = Reversibility; *SI* = Sinergy; *AC* = Cumulative; *EF* = Effect; *PR* = Periodicity; *RC* = Recoverability. The description and values of the criteria can be found in Table 2.

The significance of an impact is quantified on a scale from 0 to 100. Accordingly, the intervals outlined in Table 3 can be used to qualitatively categorize the impacts based on the quantitative results.

Table 3. Impact importance values.

Importance of the Impact	
No interaction	0
Very low	1 to 13
Low	14 to 24
Moderate	25 to 49
High	50

2.5. Fuzzy Logic Technique

As has been previously mentioned, EIAs are essential tools to identify, prevent, and mitigate the potential impacts caused by human activities. These assessments are of a preventative nature and must be carried out before the project begins. In Mexico, in accordance with the General Law of Ecological Balance and Environmental Protection (LGEEPA), any activity or civil works project may be carried out without the presentation of these evaluations [22–24].

However, EIAs have key characteristics.

I. Since they predict the effects and impacts of projects on ecosystems, some level of uncertainty is inevitable.
II. Given the complexity of ecosystem components, the EIAs must be conducted by multidisciplinary groups, which introduces a certain degree of subjectivity.
III. The complexity of the ecosystems requires the use of both quantitative (numerical) and qualitative (linguistic) variables in the EIA process.
IV. Most terms used in EIAs are linguistic, meaning the significance of an impact is classified using labels like “irrelevant”, “moderate”, or “critical”.

This complexity makes it challenging to develop mathematical models that can adequately represent ecosystems. However, fuzzy logic presents a promising solution. This mathematical tool allows for the consistent treatment of both types of variables, reducing the uncertainty and subjectivity common in traditional EIAs. Fuzzy logic techniques provide clear methodologies and models, offering more realistic scenarios of a project’s EI.

The fuzzy logic methodology consists of three main phases.

Phase 1: Approximate Assessment

This phase evaluates the project’s environmental impact. This may be regarded as an extension of the traditional evaluation methodology, given the similarities in their development processes. It involves the following steps:

I. Creation of a hierarchical tree with at least two levels defined by the user: the environment and its components. Each component is assigned an importance value (Unit of Importance (UIP)). This step involves defining the environmental components and their importance.
II. The project’s activities are also organized hierarchically, with at least two levels: project and project actions.

III. An impact matrix is used to determine how each action affects each environmental component. This step calculates how each action affects each environmental component.

IV. The significance of each impact is characterized. Impacts are characterized in terms of linguistic variables, defined for both the inputs and outputs of the model. These variables are assigned by the users, who also establish the linguistic labels of the associated fuzzy sets.

V. Definition of membership functions. To model the linguistic variables, membership functions are used to describe the degree to which a value belongs to a fuzzy set. In this context, trapezoidal functions are applied, which are ideal for representing terms like "low", "moderate", "high", or "critical". These functions are defined as follows:

$$\mu_A(\times) = \begin{cases} 0\ if\ x\ \le a, \\ \frac{x-a}{b-a}\ if\ a < x \le b, \\ 1\ if\ b < x \le c, \\ \frac{d-x}{d-c}\ if\ c < x \le d, \\ 0\ if\ x > d. \end{cases} \quad (2)$$

where a, b, c, and d are parameters that define the limits and shape of the fuzzy set. These functions allow for assigning a degree of membership to each value of a variable, facilitating the integration of both qualitative and quantitative data.

VI. Calculation of approximate impact. Once the fuzzy sets are defined, the approximate impact importance (IMP) is calculated using the following formula:

$$IMp = \sum_{i=1}^{n} f_i w_i g_i(x_i) + \sum_{i=1}^{n} (1 - f_i) w_i g_i (1 - x_1) \quad (3)$$

where

$g(x) = x^r$ is a monotonic function from [0, 1] to [0, 1] with $g(0) = 0$ and $g(1) = 1$. When $r > 1$, smaller values of x are undervalued, while if $r < 1$, the low values of x are overvalued; that is, r determines the rate at which the importance grows.

w_1 represents the weight of each variable so that $\sum_{i=1}^{n} w_i = 1$. Higher weights are assigned to the most relevant variables.

f_i is a parameter related to each variable, with $f_i = 1$ if the output increases with the input and $f_i = 0$ otherwise.

The "nature" variable (Equation (1)) is not an input to the IMP approximate reasoning function but is used to process the output. If the impact results in damage to the environment, "nature" is set to -1; if the impact is beneficial, it is set to +1.

VII. Defuzzification (centroid method). To convert the fuzzy results into a crisp value, the centroid method was applied. This method calculates the center of gravity of the membership fiction curve:

$$\mu C = \frac{\int_a^b \mu A(x) x\, dx}{\int_a^b \mu A(x)\, dx} \quad (4)$$

where

μC represents the crisp value of the impact.

$\mu A(x)$ is the membership function for the fuzzy set.

This process helps us to derive a more tangible, actionable value from the fuzzy impact assessment.

VIII. Linguistic Approximation and Consistency. Once the impact importance value has been established, a linguistic approximation is conducted. In this step, a label is assigned to the output variable, and the consistency between the fuzzy sets representing the impact importance and the fuzzy sets linked to the linguistic labels of the importance variables is calculated.

Then, the overall importance of the activity's effect on the environment is assessed to determine whether the project is environmentally compatible. To accomplish this, fuzzy indicators are computed using a method known as computation with words (CWW).

This methodology is based on fuzzy arithmetic, where fuzzy importance and indicators related to linguistic variables are used as input. The input values depend on the indicator being calculated, the level within the action hierarchy, and the environmental factors relevant to the project.

Phase 2: Detailed Assessment

This phase corresponds to the Quantitative Assessment phase of the traditional method. The objective of this phase is to determine the Total Impact Value of the project and calculate metrics such as the Total Magnitude by Factor, Net Environmental Quality by Factor, and Total Impact Value by Factor.

This phase aligns with the Quantitative Assessment phase in traditional EIA methodologies. The objective of this phase is to determine the Total Impact Value (TIV) of the project by quantitatively evaluating the significance of each environmental impact. This step builds upon the results obtained in the previous phase, where impacts were categorized using fuzzy logic.

In this phase, several key metrics are calculated to provide a comprehensive understanding of the project's environmental consequences. These include the following:

1. Total Magnitude by Factor: This metric quantifies the overall impact of each factor on the environment, incorporating both the severity and likelihood of the impact. It reflects the cumulative effect of all actions associated with the project on a specific environmental component.
2. Net Environmental Quality by Factor: This metric assesses the net effect of the project on environmental quality, considering both positive and negative impacts. It is calculated by subtracting the negative impacts from any positive effects.
3. Total Impact Value by Factor: This metric aggregates the individual impacts of each factor, enabling a holistic evaluation of the overall environmental effect of the project. It combines both the quantitative results from the Total Magnitude and the qualitative input from fuzzy logic, offering a more robust and nuanced perspective on the project's sustainability.

The calculation of these metrics is crucial for providing decision-makers with a clear understanding of the project's potential environmental risks and benefits. By integrating both quantitative data and fuzzy assessments, this phase helps ensure that the environmental implications of the project are thoroughly evaluated, allowing for informed decisions regarding project development and the need for potential mitigation measures.

Phase 3: Corrective Measures

This phase involves estimating the importance of individual impacts, aiming to keep their importance within acceptable limits. Following the application of the fuzzy logic, a set of corrective actions can be recommended to support project approval. To achieve this, the fuzzy indicator Mean Importance is used. This indicator provides a quantified measure of the overall environmental impact, helping to identify areas where mitigation efforts should be focused. Based on the results, appropriate corrective actions can be recommended, such as altering project activities, improving technology, or enhancing environmental monitoring, to reduce the impact and make the project more environmentally compatible.

The methodology described was applied to the EIA of an ocean energy conversion project, and the results of this analysis are presented in the following section.

3. Results

3.1. Phase 1: Preliminary Assessment

To identify the environmental components, the hierarchy illustrated in Figure 2a was utilized. A literature review was conducted, and experts from INECOL and UNAM were consulted to assign UIP values to each environmental factor [22,24]. The project actions were identified using the hierarchy displayed in Figure 2b.

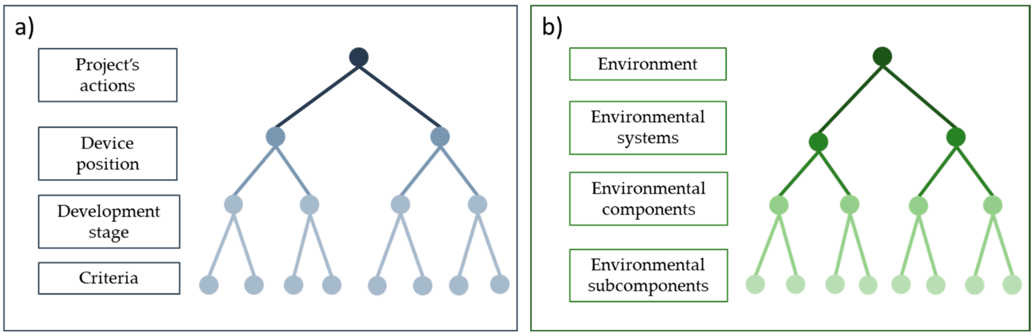

Figure 2. Environmental components hierarchy (modified from Duarte (2000) [22]). (**a**) Hierarchy of environmental components (**b**) hierarchy of project actions.

Then, the same percentage of importance units was assigned to the impacts of each factor; see Table 4.

Table 4. Environmental factor hierarchy.

		Importance Units (100)
Environment		80
	Hydrological	20
	Geomorphological	20
	Biological	20
	Chemicals	20
Sociocultural		20
	Perception	10
	Economy	10

The linguistic variables used to calculate the importance of impacts are displayed in Table 5. This table was developed based on the computation with words system methodology, utilizing fuzzy arithmetic as described by Duarte (2000) [22].

The "Weight" column indicates the degree of alignment between the fuzzy set generated from approximate reasoning and each of the labels assigned to the output variable. This alignment was interpreted as the likelihood that the result of the approximate reasoning corresponds to the semantic meaning of the associated linguistic label.

The variable "Importance" is defined within the range of [−1, 1] to account for both positive and negative impacts. Additionally, "Importance" generally increases in relation to all input variables, except for "Moment", since an impact is considered more significant if it occurs sooner. The "Extension" variable is expressed as a percentage of the affected area. In Figure 3, the graphical representation of the linguistic definition of variables is shown.

To construct the fuzzy sets, linguistic variables were assigned to each input and output. A set of descriptive labels was created to characterize the relevant variable, with each label linked to a fuzzy set defined over the universe of discourse, which had a range of [0, 1]. The following criteria were applied:

1. The relative importance of each criterion was determined using the Conesa methodology.
2. Each fuzzy set corresponds to a trapezoidal fuzzy number.

3. Adjacent fuzzy sets have a consistency of 0.5, while non-adjacent sets have a consistency of zero.
4. The sum of the membership degrees of the labels equals one, with each label having at least one value where its membership degree exceeds zero.
5. The trapezoidal fuzzy numbers are defined as follows:

$$\begin{gathered} CD_1 = T(a_i, b_i, c_i, d_i) \qquad i = 1, 2, \ldots p \\ a_i = \begin{cases} 0 & i = 1 \\ (2_i - 3)\Delta & i \neq 1 \end{cases} \qquad b_i = \begin{cases} 0 & i = 1 \\ (2_i - 2)\Delta & i \neq 1 \end{cases} \\ c_i = \begin{cases} (2_i - 1)\Delta & i \neq p \\ 1 & i = p \end{cases} \qquad d_i = \begin{cases} (2_i)\Delta & i \neq p \\ 1 & i = p \end{cases} \\ \Delta = 1/(2p - 1) \end{gathered} \tag{5}$$

where
p = the number of labels $(p > 1)$, and $CD_1 =$ the fuzzy set associated with the label number i.

Table 5. Linguistic definition of variables.

Variable	Range	Weight	Labels	Fuzzy Number
Intensity	[0, 1]	3/13	Low Medium High Very High Total	(0.0, 0.0, 0.11, 0.22) (0.11, 0.22, 0.33, 0.44) (0.33, 0.44, 0.55, 0.66) (0.55, 0.66, 0.77, 0.88) (0.77, 0.88, 1.0, 1.0)
Extension	[0, 100]%	2/13	Local Partial Vast Total	(0, 0, 1.4, 2.9) (1.4, 2.9, 4.3, 5.7) (4.3, 5.7, 7.1, 8.6) (7.1, 8.6, 100, 100)
Moment	[0, 1]	1/13	Long Term Medium Term Immediate	(0.0, 0.0, 0.2, 0.4) (0.2, 0.4, 0.6, 0.8) (0.6, 0.8, 1.0, 1.0)
Persistence	[0, 1]	1/13	Brief Temporal Permanent	(0.0, 0.0, 0.2, 0.4) (0.2, 0.4, 0.6, 0.8) (0.6, 0.8, 1.0, 1.0)
Reversibility	[0, 1]	1/13	Short Term Medium Term Non-Reversible	(0.0, 0.0, 0.2, 0.4) (0.2, 0.4, 0.6, 0.8) (0.6, 0.8, 1.0, 1.0)
Recoverability	[0, 1]	1/13	Short Term Medium Term Recoverable Irrecoverable	(0.0, 0.0, 0.14, 0.29) (0.14, 0.29, 0.43, 0.57) (0.43, 0.57, 0.71, 0.86) (0.71, 0.86, 1.0, 1.0)
Synergy	[0,1]	1/13	Simple Synergic Very Synergic	(0.0, 0.0, 0.2, 0.4) (0.2, 0.4, 0.6, 0.8) (0.6, 0.8, 1.0, 1.0)
Accumulation	[0, 1]	1/13	Simple Accumulative	(0.0, 0.0, 0.33, 0.66) (0.33, 0.66, 1.0, 1.0)
Cause–Effect	[0, 1]	1/13	Indirect Direct	(0.0, 0.0, 0.33, 0.66) (0.33, 0.66, 1.0, 1.0)
Periodicity	[0, 1]	1/13	Irregular Periodic Continuous	(0.0, 0.0, 0.2, 0.4) (0.2, 0.4, 0.6, 0.8) (0.6, 0.8, 1.0, 1.0)

Table 5. *Cont.*

Variable	Range	Weight	Labels	Fuzzy Number
Importance	[−1, 1]		Critical −	(−1, −1, −0.846, −0.692)
			Severe −	(−0.846, −0.692, −0.538, −0.385)
			Moderate −	(−0.538, −0.385, −0.231, −0.077)
			Compatible	(−0.231, −0.077, 0.077, 0.231)
			Moderate +	(0.077, 0.231, 0.385, 0.538)
			Severe +	(0.385, 0.538, 0.692, 0.846)
			Critical +	(0.692, 0.846, 1.000, 1.000)

3.2. Phase 2. Detailed Assessment

The data used for the approximate reasoning function IMP were obtained from the previously conducted literature review. These data were obtained using the crisp methodology, applying linguistic labels corresponding to the potential values of the variables. Then, the following formula was applied to calculate the average importance:

$$imp = \frac{1}{q} \sum_{k=1}^{q} x_k \tag{6}$$

where q represents the number of vectors, as previously described.

The fuzzy rules, along with data normalization and fuzzy analysis, were developed using the Python 3.13.0 programming language. By applying the fuzzy methodology, it becomes possible to model the inherent uncertainty associated with the variables typically used in the classical EIA methodologies. This approach allows for more consistent results by accounting for a range of potential impacts and importance values with varying degrees of occurrence.

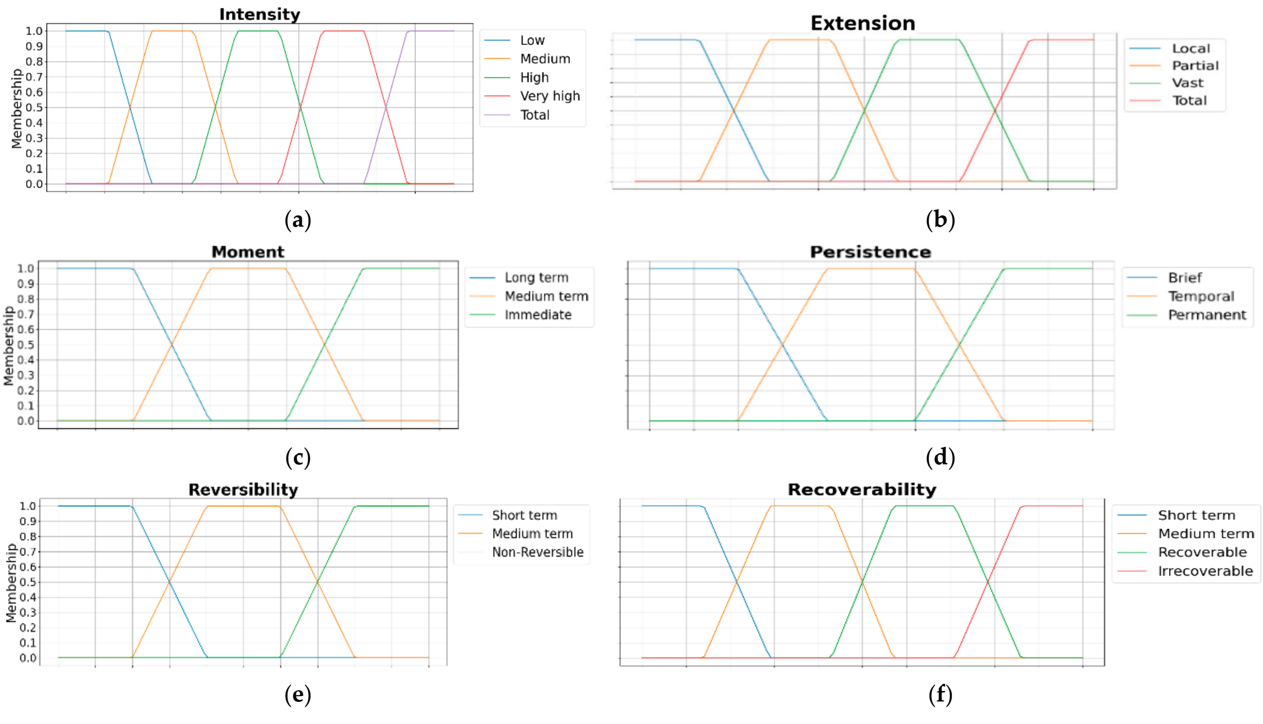

Figure 3. *Cont.*

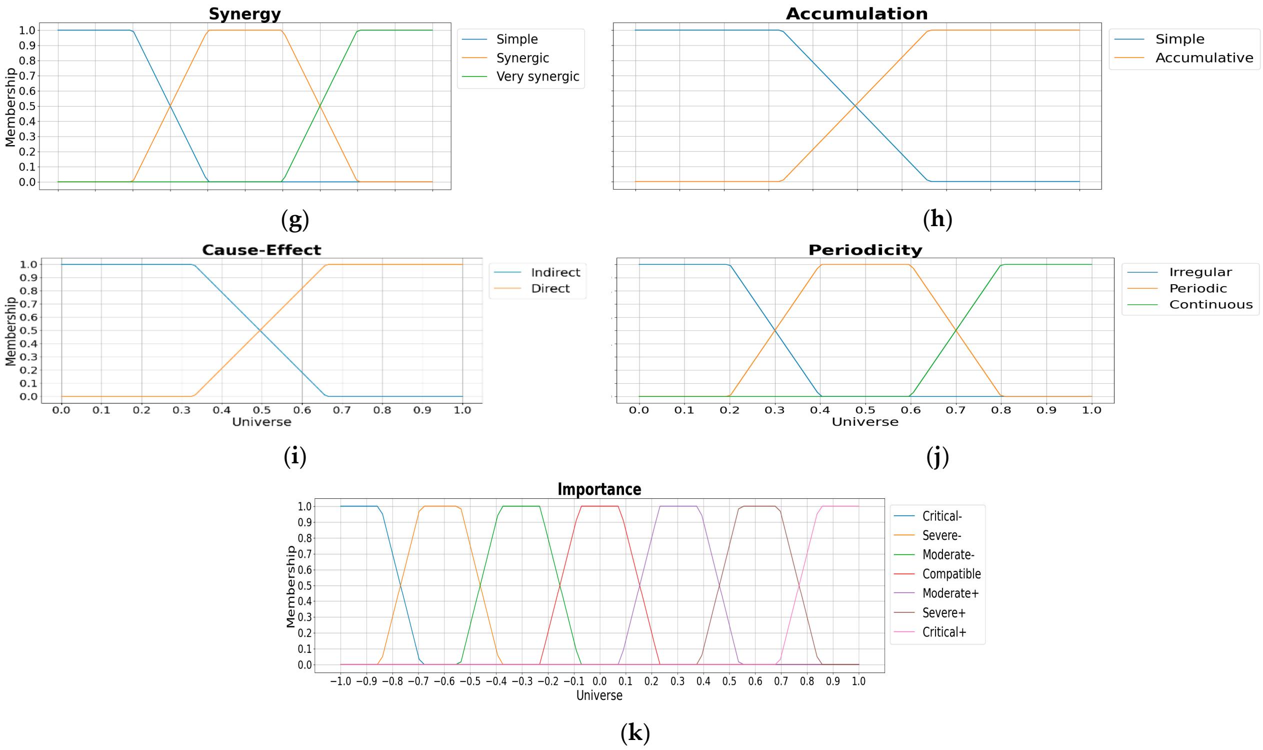

Figure 3. Graphical representation of linguistic definition of variables (trapezoidal function).

Using the aforementioned components and variables, 151 rules were generated, which correspond to the conditions established at the beginning of the evaluation process. It was noted that the stages with the most significant EIs occur during construction and operation, particularly in the case of floating and submerged devices.

As shown in Table 6, floating devices produce the highest number of activities leading to EIs, especially during the construction phase.

The most severe impacts are observed in biological factors, such as collision risk, behavioral changes, noise and vibration, and electromagnetism. Additionally, significant impacts are seen in geomorphological factors, including sediment transport and properties in the far field, as well as one hydrological factor, i.e., wave energy.

Submerged devices in the operational phase occupy the second position; however, this specific device exhibits the highest number of severe impacts among the seven biological components analyzed.

Following this, devices fixed to the ocean floor were found to have experienced critical and severe effects on biological factors, classified as critical in two geomorphological components—local properties and sediment transport—and in one hydrological component, specifically water turbulence. See Table 7.

Onshore devices, while displaying the fewest severe interactions, show the greatest number of critical interactions. The most significant impacts occur during the construction phase, particularly affecting sociocultural components such as visual impacts, tourism, and mental health. The critical interactions noted during the operational phase relate to two geomorphological components—local properties and sediment transport—as well as a hydrological component, namely, wave energy.

These results are consistent with those derived from the traditional methodology for environmental impact assessments (EIA), as shown in Tables 8 and 9. However, a major difference between the two methodologies is that the traditional approach does not consider the interactive effects between devices and the environment, whereas the fuzzy logic technique indicates moderate to low-impact interactions.

Table 6. Linguistic labels for assessing the significance of impacts on the ocean environment, categorized by device type—floating and submerged—and by stage of development.

	Devices	**Floating**				**Submerged**			
	Stage	**Construction**	**Operation**	**Maintenance**	**Dismantling**	**Construction**	**Operation**	**Maintenance**	**Dismantling**
Hydrologic	Current direction	Compatible	Moderate	Compatible	Compatible	Compatible	Severe	Compatible	Compatible
	Wave energy	Severe	Critical	Moderate	Moderate	Compatible	Moderate	Compatible	Compatible
	Water turbulence	Moderate	Severe	Moderate	Moderate	Moderate	Moderate	Compatible	Compatible
Geomorphologic	Local sediment transport	Compatible	Compatible	Compatible	Compatible	Moderate	Moderate	Compatible	Moderate
	Local sediment properties	Compatible	Compatible	Compatible	Compatible	Compatible	Moderate	Compatible	Compatible
	Far sediment transport	Severe	Severe	Moderate	Moderate	Compatible	Moderate	Compatible	Compatible
	Far sediment properties	Severe	Severe	Moderate	Moderate	Compatible	Moderate	Compatible	Compatible
Biological	Collision risk	Severe	Critical	Moderate	Moderate	Moderate	Severe	Compatible	Compatible
	Changes in behaviour	Severe	Critical	Moderate	Moderate	Moderate	Severe	Compatible	Moderate
	Noise and vibration	Severe	Critical	Moderate	Moderate	Moderate	Severe	Compatible	Moderate
	Electromagnetism	Severe	Severe	Moderate	Moderate	Moderate	Severe	Moderate	Moderate
	Population density	Critical	Critical	Moderate	Moderate	Moderate	Severe	Moderate	Moderate
	Ecological connectivity	Critical	Critical	Moderate	Moderate	Moderate	Severe	Moderate	Moderate
	Creation of new habitats	Compatible	Severe	Compatible	Compatible	Compatible	Severe	Severe	Severe
Chemical	Water quality	Moderate	Moderate	Compatible	Compatible	Compatible	Moderate	Compatible	Compatible
	Nutrients distribution	Compatible	Moderate	Compatible	Compatible	Compatible	Moderate	Compatible	Compatible
Sociocultural	Scenic value	Compatible	Moderate	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	Impact on fishing			Compatible	Moderate	Severe		Compatible	Moderate
	Tourism	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	Mental health	Compatible	Moderate	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible

Table 7. Linguistic labels for assessing the significance of impacts on the ocean environment, categorized by device type—fixed to ocean floor and onshore—and by stage of development.

	Devices	**Fixed to Ocean Floor**				**Onshore**			
	Stage	**Construction**	**Operation**	**Maintenance**	**Dismantling**	**Construction**	**Operation**	**Maintenance**	**Dismantling**
Hydrologic	Current direction	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	Wave energy	Compatible	Compatible	Compatible	Compatible	Moderate	Critical	Compatible	Moderate
	Water turbulence	Moderate	Critical	Compatible	Moderate	Compatible	Compatible	Compatible	Compatible
Geomorphologic	Local sediment transport	Moderate	Critical	Compatible	Moderate	Moderate	Critical	Compatible	Moderate
	Local sediment properties	Moderate	Critical	Compatible	Moderate	Moderate	Critical	Compatible	Moderate
	Far sediment transport	Compatible	Moderate	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	Far sediment properties	Compatible	Moderate	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
Biological	Collision risk	Compatible	Moderate	Compatible	Compatible	Compatible	Compatible	Compatible	Compatible
	Changes in behaviour	Moderate	Severe	Moderate	Moderate	Moderate	Critical	Moderate	Moderate
	Noise and vibration	Moderate	Severe	Compatible	Moderate	Moderate	Critical	Compatible	Moderate
	Electromagnetism	Moderate	Severe	Moderate	Moderate	Compatible	Compatible	Compatible	Compatible
	Population density	Moderate	Critical	Moderate	Moderate	Moderate	Critical	Moderate	Moderate
	Ecological connectivity	Moderate	Critical	Moderate	Moderate	Moderate		Moderate	Moderate
	Creation of new habitats	Compatible	Critical	Severe	Severe	Compatible	Compatible	Compatible	Compatible
Chemical	Water quality	Compatible	Moderate	Compatible	Compatible	Compatible	Moderate	Compatible	Compatible
	Nutrients distribution	Compatible	Critical	Compatible	Compatible	Compatible	Moderate	Compatible	Compatible
Sociocultural	Scenic value	Compatible	Compatible	Compatible	Compatible	Severe	Critical	Compatible	Compatible
	Impact on fishing	Compatible	Moderate	Compatible	Compatible	Compatible	Moderate	Compatible	Compatible
	Tourism	Compatible	Compatible	Compatible	Compatible	Severe	Critical	Compatible	Compatible
	Mental health	Compatible	Compatible	Compatible	Compatible	Severe	Critical	Compatible	Compatible

Unlike the crisp methodology, the fuzzy logic technique proposes that all actions have some level of influence on the components. Additionally, many of these actions have been classified linguistically as critical or severe, offering a more accurate representation of empirical findings. These linguistic labels are more intuitive and easier to interpret, allowing decision-makers to grasp the subtleties of complex environmental interactions.

Despite the differences in how the methodologies classify or label impacts, both exhibit similar patterns in terms of identifying the most critical phases of project development. For example, both approaches consistently indicate that the construction phase of floating devices poses the most significant negative impact, as seen in Tables 8 and 9.

The fuzzy methodology previously mentioned for conducting environmental impact assessments (EIAs) will be utilized to develop an EIA for the installation of a vertical axis turbine in the Cozumel Channel, located on Cozumel Island in Mexico. In contrast to many other regions worldwide, Mexico is characterized by relatively low ocean current speeds, averaging around 1 m/s. The Cozumel Channel is considered a suitable site for the deployment of such turbines, as the average current speeds throughout the year range from 0.88 to 1.04 m/s [24,25].

Table 8. Importance of impacts on the ocean environment by type of device, floating and submerged devices, and stage of development using crisp methodology.

	Devices	Floating				Submerged			
	Stage	**Construction**	**Operation**	**Maintenance**	**Dismantling**	**Construction**	**Operation**	**Maintenance**	**Dismantling**
Hydrologic	Current direction	4	20	10	5	8	40	4	6
	Wave energy	34	66	13	23	4	12	0	0
	Water turbulence	18	34	13	11	13	24	7	10
Geomorphologic	Local sediment transport	0	0	0	0	20	24	0	17
	Local sediment properties	0	0	0	0	0	26	0	0
	Far sediment transport	30	47	18	21	0	23	0	0
	Far sediment properties	30	47	16	21	0	23	0	0
Biological	Collision risk	33	52	18	17	17	40	6	6
	Changes in behaviour	29	52	16	22	24	37	9	23
	Noise and vibration	46	54	24	20	19	31	5	13
	Electromagnetism	28	40	15	15	22	38	13	21
	Population density	47	58	25	17	22	40	18	23
	Ecological connectivity	52	65	25	28	24	50	11	18
	Creation of new habitats	0	37	2	0	0	42	0	0
Chemical	Water quality	9	19	0	6	10	24	3	10
	Nutrients distribution	8	13	0	0	10	24	3	10
Sociocultural	Scenic value	8	12	0	5	0	0	0	0
	Impact on fishing	47	64	4	21	47	64	4	21
	Tourism	0	0	0	1	0	0	0	0
	Mental health	8	12	0	5	0	0	0	0

Table 9. Importance of impacts on the ocean environment by type of device, fixed to the ocean floor and onshore devices, and stage of development using crisp methodology.

	Devices	Fixed to Ocean Floor				Onshore			
	Stage	**Construction**	**Operation**	**Maintenance**	**Dismantling**	**Construction**	**Operation**	**Maintenance**	**Dismantling**
Hydrologic	Current direction	0	9	0	0	0	0	0	0
	Wave energy	0	0	0	0	27	53	9	25
	Water turbulence	25	54	10	22	0	0	0	0

Table 9. *Cont.*

	Devices	Fixed to Ocean Floor				Onshore			
	Stage	Construction	Operation	Maintenance	Dismantling	Construction	Operation	Maintenance	Dismantling
Geomorphologic	Local sediment transport	29	58	0	24	29	56	0	24
	Local sediment properties	29	58	0	24	29	58	0	24
	Far sediment transport	0	22	0	0	0	0	0	0
	Far sediment properties	0	22	0	0	0	0	0	0
Biological	Collision risk	10	27	5	6	0	0	0	0
	Changes in behaviour	27	49	13	23	27	52	13	23
	Noise and vibration	17	34	5	11	23	54	5	11
	Electromagnetism	22	36	13	21	0	0	0	0
	Population density	27	51	19	20	27	51	19	20
	Ecological connectivity	30	62	14	23	30	62	14	23
	Creation of new habitats	0	53	32	46	0	0	0	0
Chemical	Water quality	10	24	3	10	10	26	3	10
	Nutrients distribution	10	24	3	10	10	26	3	10
Sociocultural	Scenic value	0	0	0	0	39	52	0	0
	Impact on fishing	0	17	0	0	9	14	4	9
	Tourism	0	0	0	0	39	52	0	0
	Mental health	0	0	0	0	39	52	0	0

4. Case Study Results

Cozumel Island, whose name comes from the Mayan "Kosom lumil", meaning "Land of the swallows", is a flat island formed from limestone reefs. Located about 18 km off the coast of Playa Del Carmen in the Mexican Caribbean, it is the third largest and second most populous municipality in Mexico [26].

Covering around 470 km^2 and with a coastline of 124 km, Cozumel features a flat landscape composed of limestone from surrounding reefs. The eastern island platform extends between 1500 and 2500 m out to a depth of −50 m, where the platform edge begins. There, five reef terraces are found at depths of −3 m, −10 m, −20 m, −30 m, and −50 m, representing Holocene-era abrasion platforms. On the eastern side, the shelf narrows to between 500 and 1000 m at the −50 m isobath, with three reef terraces located at depths of 50 m, 10 m, and 2 m. The northern platform is almost entirely flat, with depths ranging between 20 and 30 m, and ends at a submerged reef platform called Banco Arrowsmith, about 50 km northeast of Cozumel [27]. See Figure 4.

San Miguel de Cozumel is the island's largest city, and tourism is its primary economic activity. Cozumel is served by an international airport, a cruise ship dock, and a ferry that connects it to Playa del Carmen. The island divides the Yucatan Current, with part of the flow heading east into the Caribbean Sea, while around 20% passes through the Cozumel Channel [28].

The Cozumel Channel, located between Playa del Carmen and Cozumel Island, is 18 km wide, 50 km long, and reaches depths of 400 m. It runs north along the Yucatan Peninsula and eventually becomes part of the Gulf Stream after passing through the Florida Channel. The area is known for its strong and consistent ocean currents.

The average flow velocity through the Cozumel Channel is 1.1 m/s at a depth of 30 m in its central region. This flow is primarily driven by ocean currents, with little influence from tides, waves, or wind [28]. According to [24], the area near Cozumel Island's

International Airport is well-suited for installing a low-speed turbine, with an estimated capacity of 3.2 MW.

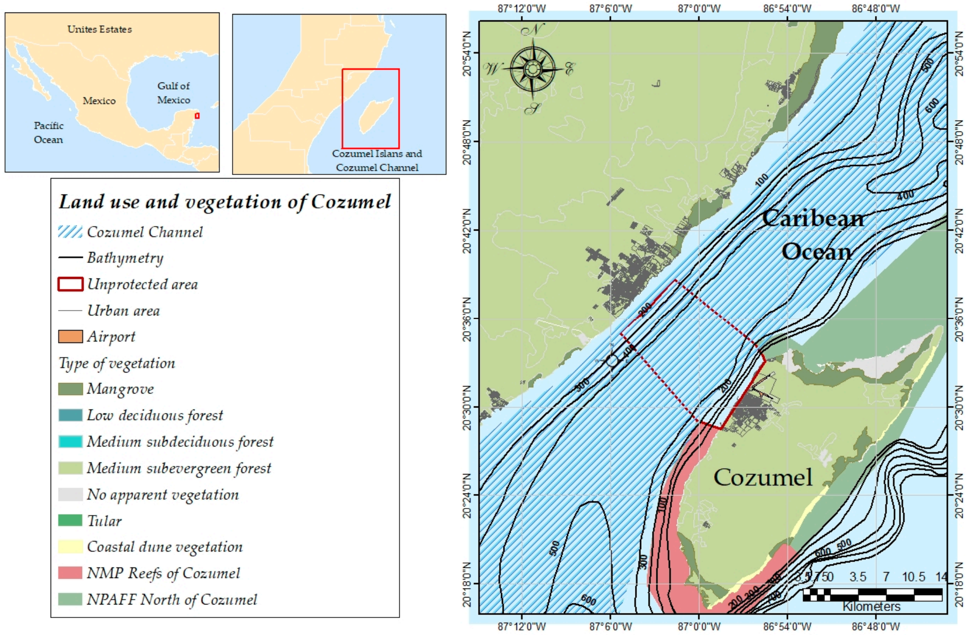

Figure 4. Cozumel Island. The main human settlements in the area are shown, as well as the location of the Cozumel International Airport and the protected areas of the island and its type of vegetation.

4.1. Environmental Systems

Within the study area, there are four protected natural areas, as depicted in Figure 5. The largest of these is the Mexican Caribbean Biosphere Reserve, highlighted in green. The North Cozumel Flora and Fauna Protection Area is marked in pink, while the National Marine Parks of Puerto Morelos are shown in light blue. Additionally, mangroves, designated as priority areas, are represented in dark green [29].

The region is home to a rich biodiversity, encompassing a wide variety of ecosystems such as coral reefs, seagrasses, coastal dunes, mangroves, wetlands, and coastal lagoons. A unique feature of this area is the presence of microatolls, which are reef formations created by coralline algae. These reefs are part of the Mesoamerican Reef System and are additionally safeguarded by the Inter-American Convention for the Protection and Conservation of Sea Turtles, the Ramsar Convention on Wetlands of International Importance, and the Convention on Biological Diversity (CBD) [30].

The unique characteristics of the study area create a combination of protected natural areas, abundant biodiversity, and considerable anthropogenic pressure due to high levels of tourism. This has resulted in several species being designated for protection under various categories [31–33]. The most notable of these species are listed in Table 10.

4.2. Economic Importance

The Mexican state of Quintana Roo hosts the largest number of international tourists in the country, with most arriving through international airports, notably in Cancun and Cozumel. In 2023, these airports saw approximately 10,041,700 and 234,814 tourists, respectively. Visitors primarily came from Mexico, the USA, Canada, Colombia, the UK, and Argentina [29].

During the same year, Cozumel received the highest number of cruise ships, totaling 1155, marking a 3.7% increase compared to the previous year. Tourist arrivals reached 4,076,976, a 38.8% rise from the prior year. Other regional destinations, such as Akumal, Playacar, Cancun, and Playa del Carmen, recorded hotel occupancy rates between 83% and 85% [34].

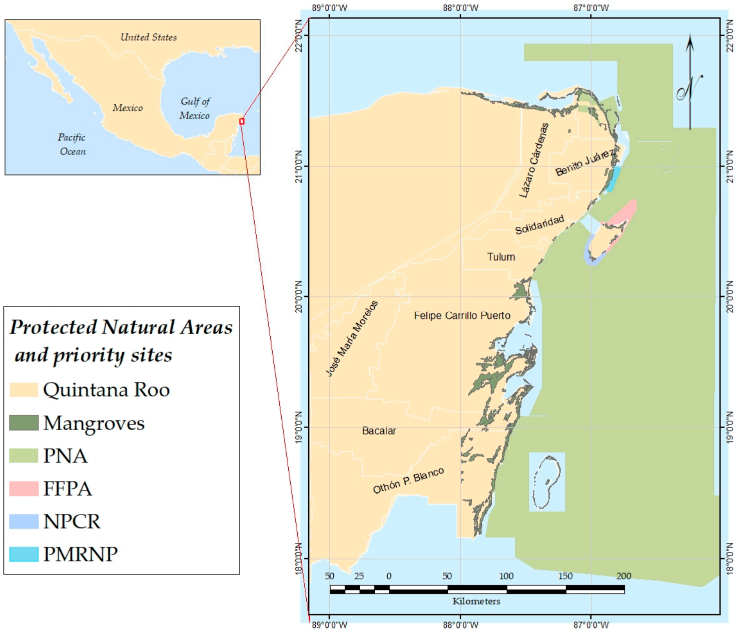

Figure 5. Protected natural areas and priority sites within the study area. PNA, protected natural area; FFPA, Flora and Fauna Protected Area North Cozumel; NPCR, Cozumel Reefs National Park; PMRNP, Puerto Morelos Reef National Park.

Table 10. Marine species with some category of protection.

Group	Family	Genus	Species	Common Name	Cat.NOM-059-SEMARNAT-2001	Cat.IUCN Red List
Corals	Acroporidae	Acropora	cervicornis	Deer horn	special protection	
	Acroporidae	Acropora	palmata	Elk horn	special protection	
	Antipathidae	Antipathes	bichitoena	Black coral	special protection	
	Antipathidae	Antipathes	grandis	Black coral	special protection	
	Antipathidae	Antipathes	ulex	Black coral	special protection	
	Plexauridae	Plexaura	homomalla	Sea chandelier	special protection	
	Plexauridae	Plexaurella	dichotoma	Sea chandelier	special protection	
Plants	Combretaceae	Conacarpus	erectus	Button or tight mangrove	special protection	
	Rhizophoraceae	Rhizophora	mangle	red mangrove	Special protection Endemic	
Fish	Balistidae	Balistes	vetula	Triggerfish		VU A2d
	Batrachoididae	Sanopus	splendidus	Frog fish		VU A2D
	Poecilidae	Poecilia	velifera	Big fin mole	Endangered Endemic	
Herpetofauna	Cheloniidae	Caretta	caretta	Loggerhead sea turtle	Endangered	EN A1abd
	Cheloniidae	Chelonia	mydas	White turtle	Endangered	EN A1abd
	Cheloniidae	Eretmochelys	imbricata	Hawksbill sea turtle	special protection	CR A 1BD ver 2.3 (1994)
	Dermechelyidae	Dermochelys	coriacea	Leatherback sea turtle	Endangered	CR A 1BD
Marine mammals	Delphinidae	Globicephala	macrorhynchus	Short-finned Pilot Whale	special protection	LR/cd
	Trichechidae	Trichechus	manatus	Caribbean manatee	Endangered	VU A2d

Cozumel's coastline drew 10,930 visitors per day, 15% of whom were overnight tourists, while 85% were cruise passengers. The island is a key attraction for mass tourism, with a significant portion of visitors arriving by cruise ships. A range of tourist packages is available, designed to offer diverse recreational and leisure options. The island currently has 47 hotels, across all categories, providing a total of 4070 rooms [34,35].

Cozumel's economy is dominated by three sectors. Commerce and tourism account for 74% of economic activity, while agriculture, livestock, hunting, and fishing contribute 23.4%. The remaining 2.6% comes from manufacturing, construction, and electricity [36].

4.3. Energy Scenario in the Mexican Caribbean

In Quintana Roo, there is a legislative proposal at the state level aimed at promoting the use of renewable energy sources, with the goal of fostering a balance between local communities, tourism, and the environment, while creating energy-efficient and sustainable spaces. At the federal level, the legal framework also allows for the generation and commercialization of electricity by private companies [37,38].

The peninsular region, which includes Campeche, Quintana Roo, and Yucatán, currently faces a generation deficit and is expected to see the highest growth rate at 3.6% annually, increasing from 11,228 GWh to 18,946 GWh [39]. In this area, electricity is mainly generated using low-efficiency gas technology, natural gas, fuel oil, and diesel. Power is provided by the Federal Electricity Commission (CFE) and private entities under the Independent Energy Producer (PIE) model in four generation plants, two located in Mérida and two in Valladolid. There is also one renewable self-supply generation plant, although it plays a minor role in the overall energy supply [40].

Quintana Roo, in particular, has notable deficiencies in its electrical system. The state's installed capacity ranges between 373 and 391 MW, primarily from low-efficiency gas power plants at the SE Nizuc, Cancún, and Chankanaab substations. This represents just 0.51% of the national electrical system, placing the state 28th among Mexico's federal entities. Furthermore, 87% of the installed capacity relies on conventional technologies that use 80% fossil fuels. In terms of electricity generation, Quintana Roo produces 149 GWh, which accounts for only 0.04% of the national total, making it the state with the lowest production and the largest energy deficit. As a result, electricity rates in the region are among the highest in the country, compounded by significant challenges in transmission lines and energy distribution networks [39,40].

4.4. Project Description

The use of marine current energy depends on several factors, such as current speed, installation depth, marine life, operational lifespan, and maintenance. One of the key advantages of marine current energy compared to other renewable sources like wind power is the presence of semi-permanent or permanent currents throughout the year. Additionally, the higher viscosity of water compared to air enables the devices to be smaller, as increased lift and drag forces in water reduce the necessary size [41,42].

In the Cozumel Channel, Mexico, average annual current speeds range from 0.8 to 1.1 m/s, making it a prime location for harnessing ocean current energy [24,25]. As part of the CEMIE-Océano project, a prototype of a low-speed hydrokinetic turbine with a 1 m diameter vertical axis helical turbine was designed and built by the Engineering Institute of UNAM [8,43,44] (Figure 6). This type of turbine system is seen as an ideal choice for energy conversion in hydrokinetic setups. Specifically, a vertical axis hydrokinetic turbine (VAHT) is suitable for low current speed environments. These turbines have a starting speed of less than 1 m/s, which matches the current speeds observed in the Cozumel Channel [45]. Additionally, VAHTs are omnidirectional, meaning they do not need to be aligned with the main water current [46].

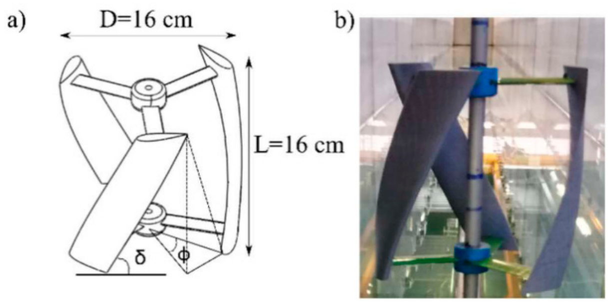

Figure 6. Vertical axis helical turbine: (**a**) turbine diagram; (**b**) scale model of the turbine.

The turbine operates efficiently at low speeds and has reduced torque ripple. It also offers easy maintenance, does not require a yaw mechanism, takes up little space, is easy to manage, has a low production cost, and produces minimal mechanical vibration [43,47]. From a biological perspective, [47] suggests that the turbine's design—specifically its dimensions, blade angle, and spacing—allows fish to pass through safely.

4.5. Turbine Requirement

It is advised that vertical axis helical turbine anchors be installed at depths not exceeding 100 m [44]. This recommendation aligns with Alcerreca's (2020) findings, which suggest that the ideal locations for deploying floating devices are between 30 and 100 m in depth [24].

Furthermore, areas with restrictions, such as those involving maritime traffic, protected natural zones, strategic infrastructure (e.g., electrical or telecommunications cables), and locations near airports, military zones, or research centers, should be excluded from consideration for turbine installation.

4.6. Application of the Fuzzy Methodology to the Environmental Impact Assessment

We apply the mathematical model and fuzzy logic methodology presented in earlier sections. Specifically, fuzzy sets and membership functions are utilized to assess the impacts on environmental factors such as hydrological, geomorphological, and biological components. For each project phase (construction, operation, maintenance, and dismantling), linguistic labels such as "Critical", "Severe", and "Moderate" are assigned to quantify the severity of impacts.

The fuzzy rules and membership functions from the methodology are directly applied to the case study, using these to calculate and classify the importance of each impact in a fuzzy set format. The calculations ensure consistency with the theoretical framework, bridging the gap between the mathematical model and its practical application in the case study. This allows for a nuanced evaluation of each phase and environmental factor, with the methodology offering more precise and realistic results than traditional approaches, especially by accounting for the uncertainties and interactions between the environment and the turbines.

As evidenced in Table 11, the majority of impacts identified as critical and severe occur during the operational phase, followed by those observed during the construction and dismantling stages. Conversely, the maintenance stage is associated with the lowest level of impact. This is due to the fact that the interactions between the device and the environment are continuous throughout the operational stage, whereas the remaining stages have a relatively brief duration.

Table 11. Importance of impacts received by the environmental factor in the development stage of vertical axis helical turbine.

Device		Vertical Axis Helical Turbine			
	Stage	Construction	Operation	Maintenance	Dismantling
Hydrological	Current direction	Moderate	Critical	Compatible	Moderate
	Wave energy	Moderate	Severe	Compatible	Moderate
	Water turbulence	Moderate	Severe	Compatible	Moderate
Geomorphological	Local sediment transport	Severe	Critical	Compatible	Severe
	Local sediment properties	Severe	Critical	Compatible	Severe
	Far sediment transport	Moderate	Severe	Compatible	Moderate
	Far sediment properties	Moderate	Severe	Compatible	Moderate
Biological	Collision risk	Severe	Moderate	Compatible	Severe
	Changes in behavior	Severe	Critical	Moderate	Severe
	Noise and vibration	Severe	Critical	Severe	Severe
	Electromagnetism	Moderate	Severe	Compatible	Moderate
	Population density	Severe	Severe	Severe	Severe
	Ecological connectivity	Severe	Severe	Compatible	Severe
	Creation of new habitats	Compatible	Moderate	Compatible	Compatible
Chemical	Water quality	Moderate	Severe	Severe	Moderate
	Nutrients distribution	Moderate	Severe	Severe	Moderate
Sociocultural	Scenic value	Compatible	Compatible	Compatible	Compatible
	Impact on fishing	Severe	Severe	Compatible	Severe
	Tourism	Compatible	Compatible	Compatible	Compatible
	Mental health	Compatible	Compatible	Compatible	Compatible

In the construction and maintenance stage, impacts classified as severe occur in the geomorphological components, particularly in the transport subcomponents and properties of the local sediment. This is due to the typical movements of infrastructure construction, whereby sediments from the sea floor are removed for the fixation and anchoring of pilots and turbine shoes.

With regard to the biological components, the risk of collision, alterations in behavior and ecological connectivity, and the generation of noise and vibration have been classified as severe. This is attributable to the constant movement of boats and construction maneuvers, which frighten the local fauna, prompting them to relocate or collide with boats or become entangled in cables.

The chemical components, primarily those pertaining to water quality, may be susceptible to alteration due to the potential for leaching of chemicals from boats and construction materials.

As previously stated, the operational phase is associated with the most significant and severe impacts across the majority of components, with the exception of the sociocultural ones. In the hydrological components, the number of devices deployed in the area can affect the direction of the current, as well as the level of water turbulence. The effects on wave energy also depend on the depth at which the devices are anchored.

The movement of the devices will cause localized shear stresses and turbulence that may be damaging to aquatic organisms. On larger scales, the extraction of energy from the currents may reduce the ability of streams to transport sediment and debris and cause the deposition of suspended sediments, thereby altering bottom habitats.

The geomorphological components, local characteristics, and sediment transport may be affected by the scour around the turbine's support structures. Additionally, shifts in sedimentation patterns at more distant locations could result from changes in wave direction, depending on the number of devices and their installation depth.

The introduction of these physical structures will influence biological components by creating new habitats where none existed before, potentially leading to collisions with marine organisms. The presence of the devices may also disrupt ecological connectivity, with the extent of disruption depending on the number of turbines.

There is a risk that fish, aquatic organisms, diving birds, and marine mammals could be struck by the moving parts of the turbines. Larger mobile animals might become entangled in submerged cables. The environmental impact of single devices could differ significantly from the full deployment of multiple turbines, affecting hydrological regimes and sediment dynamics.

The movement of turbines, as well as the noise and vibrations they produce, may cause stress in local organisms, altering their behavior, especially in detecting prey, predators, and mates. This could lead to species permanently relocating from the area, affecting population density. Anchoring the device to the seabed and routing power cables to shore may disturb bottom habitats.

The moving parts of the device may also create new structural habitats in open waters, potentially obstructing the movements and migrations of aquatic species. The deployment and operation of the devices could stir up sediments and buried contaminants, increasing turbidity, while erosion and scour could occur around anchors, cables, and other structures.

Turbine movement, along with the use of chemicals to prevent biofouling, could affect nutrient distribution and water quality. Noise generated during maintenance is likely to have the greatest impact on surrounding organisms, altering their behavior and raising the risk of collisions, though this effect should diminish once maintenance concludes. Chemical runoff from maintenance activities may also negatively impact water quality.

5. Corrective Measures

At present, the majority of current marine energy harvesting projects are still in the pilot phase, which makes it challenging to accurately assess certain aspects of the marine environment. The primary objective of any corrective measures is to minimize, mitigate, or even eliminate any negative effects that may result from the project.

5.1. Geomorphological Components

At the present time, in the area under study, sediment suspension occurs naturally as a result of the action of waves and marine currents aligned with the coastline. The implementation of the project, particularly during the construction and dismantling stages, results in the generation of sediment suspension. One potential method for minimizing the impact of these dynamics is the installation of a geotextile mesh, which would retain and confine them within the designated exploitation area, allowing them to fall back to the seabed without affecting adjacent areas.

5.2. Biological Components

One of the principal concerns is the risk of collision between marine organisms and the devices. However, in the case of the vertical axis helical turbine, due to its dimensions, its angle, and the distance between its blades, it allows fish to pass through, which can prevent, to some extent, damage to marine fauna.

As observed by Popper et al. (2023) [48], noise and vibration levels were found to be elevated following the installation of the device, particularly during periods of power production. However, the frequencies of the highest amplitude noise exhibited variability. At a range of 40 m, the local fish choruses may have been masked. However, for comparison, the authors highlighted that a passing vessel recorded at the site was louder than the devices at all frequencies above 100 Hz [49].

The study area is subject to a constant flow of ferries, which has resulted in the local fauna becoming somewhat accustomed to the presence of noise. It is essential to conduct an analysis to ascertain the noise levels generated by the turbine, in order to determine whether they are masked by existing noise sources in the area.

Cables emitting electromagnetic fields (EMFs) have been a common feature of the oceans for many decades. This includes cables used to transmit power from mainland grids to offshore islands, telecommunications cables, and cables from offshore platforms used for oil and gas production.

It is only certain fish species that possess the sensory apparatus to detect EMFs. Those that live in close proximity to seabed cables, such as demersal fish and those that hunt at depth, may be exposed to EMFs [50]. It is possible that pelagic fish may have minimal exposure to electromagnetic fields (EMFs), as they swim past cables running from surface marine renewable energy (MRE) devices to the seabed, or cables draped in the water column between devices [50]. Furthermore, additional research has demonstrated that a considerable number of fishes are sensitive to EMFs, based upon their orientation in the water column and prey location. Consequently, it is unlikely that a small number of MRE devices will have a significant impact on fish populations [49].

With regard to the creation of new habitats, it has been suggested that the presence of ocean energy conversion devices and associated lines, floats, and other gear placed on the surface, subsurface, or seabed may act as artificial reefs and FADs, attracting species of fish that seek shelter [51]. The presence of benthic organisms that colonize MRE system parts is likely to act as an attractant to fish, providing a food source. This could be considered beneficial, as it may improve habitats and fish populations.

5.3. Chemical Components

It is acknowledged that the study area has other anthropogenic factors that may potentially impact water quality and nutrient distribution. However, it is recommended that special attention be paid to the management of waste that could potentially leach into the ocean. In the event of a spill accident, appropriate measures for its management should be put in place.

5.4. Sociocultural Components

A number of human activities are already being conducted in the area in question. Additionally, due to the nature of the device, its impact is not readily apparent. It is probable that the stages during which it could have a detrimental effect on the scenic value are during the construction, maintenance, and dismantling phases. However, enthusiasm can be fostered through awareness campaigns that emphasize the significance of implementing renewable oceanic energies.

6. Discussion

The results of this study underscore the multifaceted environmental impacts associated with the deployment of marine energy conversion devices, particularly during the construction, operation, and maintenance phases. By employing the fuzzy logic methodology outlined in Section 2, we were able to systematically evaluate and classify impacts across geomorphological, biological, chemical, and sociocultural components. This methodology provided a quantitative framework that allowed for a flexible and adaptable approach, accounting for the unique characteristics of each ecosystem and device type.

Geomorphological Impacts

The findings reveal that severe impacts on geomorphological components primarily arise during construction and maintenance activities. The disturbance of seabed sediments due to infrastructure installation—such as anchoring and piloting—alters sediment transport and local sedimentary properties. Furthermore, during the operational phase, the interaction between turbine structures and hydrodynamic forces exacerbates sediment scouring and deposition. These processes, if unmitigated, could lead to broader alterations in sedimentation patterns, potentially impacting distant habitats. Implementing corrective measures, such as geotextile mesh installations, could confine sediment displacement to specific areas, reducing collateral effects.

Biological Impacts

Biological components are particularly vulnerable, with severe risks identified during both the construction and operational phases. Behavioral disruptions, ecological connectivity loss, and collisions with moving turbines pose significant threats to marine organisms, including fish, diving birds, and marine mammals. The operational noise and vibration levels may interfere with predator–prey dynamics and mating behaviors, while turbine components may create new habitats, inadvertently attracting species and altering ecological balances. Notably, the unique design of the vertical axis helical turbine mitigates some risks by allowing smaller marine organisms to pass through its blades, though further monitoring is essential.

The study also highlights the dual role of artificial habitats created by turbine infrastructure. While these structures may act as Fish Aggregating Devices (FADs), providing shelter and food sources for certain species, they could simultaneously obstruct migratory routes or increase localized predation pressures.

Chemical Impacts

The potential for chemical contamination during the construction and maintenance stages was also identified as a critical issue. Leaching from construction materials and antifouling agents may negatively impact water quality and nutrient distribution. While the current study area is already subject to anthropogenic influences, robust waste management practices and rapid spill response mechanisms are essential to minimize additional risks.

Sociocultural Impacts

Interestingly, the sociocultural components exhibited the least severe impacts. The primary concerns revolve around potential disruptions to the scenic value of the area during construction and maintenance activities. Public acceptance and enthusiasm for such projects could be bolstered through targeted awareness campaigns emphasizing the ecological and economic benefits of marine renewable energy.

Broader Implications

The results emphasize the importance of a holistic approach in assessing marine energy projects. The interplay between localized and broader-scale impacts, such as sediment transport and hydrodynamic alterations, necessitates adaptive management strategies. Moreover, the findings suggest that, while individual devices may have limited impacts, cumulative effects from large-scale deployments could significantly alter marine ecosystems. This highlights the need for scalable impact assessments as projects transition from pilot phases to full-scale implementation.

The use of fuzzy logic in this study has been instrumental in reducing the uncertainty and subjectivity inherent in traditional EIA methodologies. By representing scenarios that align more closely with real-world conditions, fuzzy logic facilitates more informed decision-making and contributes to the long-term sustainability of marine energy projects. This flexible framework is not only applicable to current technologies but can also be adapted to future advancements in marine energy systems.

As marine energy projects continue to evolve, the findings of this study provide a foundation for improving the consistency and effectiveness of environmental impact assessments. The innovative approach proposed here is a critical step toward bridging the gap in EIA criteria and establishing a more standardized, adaptable methodology for evaluating ocean energy projects globally.

When comparing the results of this framework with traditional approaches, it is crucial to highlight the advantages of fuzzy logic in reducing uncertainty. Research by [18,52] emphasizes how fuzzy systems contribute to better handling of ambiguity and the creation of more reliable and accurate models, especially when dealing with complex and uncertain environmental conditions.

7. Conclusions

The objective of this study was to establish a flexible and quantitative framework for conducting EIAs across different types of ocean energy devices and ecosystems. By applying fuzzy logic, we have addressed the uncertainty and subjectivity typically inherent in these evaluations, leading to more reliable assessments of environmental impacts. The results confirm that marine energy conversion devices, especially during their construction and operational phases, can have significant impacts on geomorphological and biological components. However, the study also suggests practical corrective measures that could mitigate these effects, contributing to the sustainable development of ocean energy projects.

Furthermore, by proposing a standardized yet adaptable EIA methodology, this study advances the long-term sustainability of ocean energy technologies, not only in Mexico but also in global marine environments. The framework developed here can be adapted to various project types and ecosystems, facilitating the incorporation of site-specific characteristics into impact assessments. This work represents a critical step toward establishing a more consistent and effective approach to evaluating the environmental impacts of ocean energy, supporting the successful integration of renewable ocean technologies worldwide.

The novelty of this study lies not in the use of fuzzy logic per se, but in its novel application to the environmental impact assessment (EIA) of marine energy devices, particularly the vertical axis helical turbine, in the Cozumel Channel. While fuzzy logic has been widely applied in various engineering practices, its use in the context of marine energy systems, especially for EIA, remains an area with limited exploration. This study offers a quantitative framework for EIA that is both flexible and adaptable, allowing it to be applied to diverse ocean energy projects. By integrating traditional EIA methodologies with fuzzy logic, this approach can accommodate the specific characteristics of each project and ecosystem, facilitating its use in a variety of marine energy contexts.

A significant challenge in marine energy projects is the lack of consensus on EIA criteria, with different projects developing their own principles and methodologies. This often leads to a fragmented approach to assessing environmental impacts. In response to this, this study introduces a more consistent and standardized methodology, addressing the gap in the current literature and making a significant step toward more uniform environmental assessments in marine energy projects.

Furthermore, this specific case study of the Cozumel Channel, combined with the integration of fuzzy logic and traditional EIA, presents a unique approach that has not been widely explored. This innovation contributes to advancing the sustainability of marine energy systems and improving the understanding of their environmental impacts, particularly in Mexico, but also globally.

In conclusion, this study not only demonstrates the feasibility of applying fuzzy logic to EIA in marine energy systems but also introduces a novel and adaptable framework that can be used across various types of marine energy projects. By doing so, it offers valuable insights into improving the environmental assessment process and contributes to the broader goal of sustainable ocean energy development.

For future work, the exploration of hybrid approaches combining fuzzy logic with other techniques like Artificial Intelligence (AI) and sustainability models could further enhance the robustness and adaptability of impact assessments. Hagras (2022) and Bennagi et al. (2024) suggest that integrating fuzzy logic with AI presents significant opportunities for improving decision-making and ensuring long-term sustainability in environmental assessments. These approaches offer promising directions for more precise and dynamic evaluations of marine energy projects [18,53].

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Appendix A

Literature Review

The development of the methodology began with a comprehensive literature review to identify the current trends and challenges in assessing the environmental impacts (EIs) of marine energy conversion projects. This review covered articles published between 1983 and 2021, focusing on projects that had already been installed and where at least one environmental impact—whether ecological, physicochemical, or social—had been evaluated. To ensure the practical relevance of the data, theoretical studies and numerical modeling were excluded whenever feasible.

Additionally, we consulted with experts in marine energy and coastal ecosystems to validate and supplement the data. This expert input was essential for ensuring that the findings were both accurate and aligned with the latest practices in environmental impact assessment. The literature was retrieved from the Scopus digital database using the search terms "renewable energy", "ocean", "coastal", and "impact" (Figure A1). By combining a thorough literature review with expert consultations, we ensured that the data used were reliable, pertinent, and applicable to the specific context of marine energy conversion devices and their potential impacts on coastal ecosystems (Figure A1).

Energy conversion devices have been deployed across various regions, including Asia (primarily in China, Japan, India, Russia, Turkey, Malaysia, and Iran), Europe (such as the United Kingdom, France, Italy, Spain, Sweden, Portugal, Ireland, the Netherlands, Denmark, Norway, and Germany, among others), and the Americas (including the United States, Canada, Mexico, Peru, Colombia, Brazil, Barbados, and the Bahamas). However, impact assessments have only been analyzed for deployments in the UK, USA, Canada, Sweden, Portugal, Japan, Denmark, and Germany. Notably, the United States was the first country to publish an EIA.

Between 1986 and 2021, a total of 464 articles were identified. Of these, only 28 addressed energy projects that described or included information about EIs. The remaining articles provided information on device functionality and presented numerical modeling of potential effects. Only 6% of the total publications reviewed offered information on the impacts identified in the projects (Figure A1a). Among these, 75% addressed ecological impacts, 11% focused on socioeconomic impacts, and 7% each on hydrodynamic and physicochemical impacts (Figure A1b). Most studies analyzed impacts during the operational phase of the projects, with three evaluating potential impacts beforehand (Figure A1c).

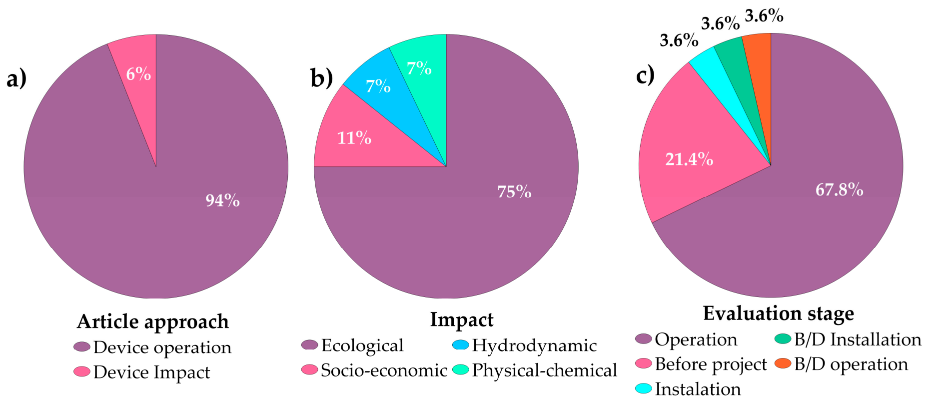

Figure A1. The percentage of publications that implemented some form of EIA is presented in (**a**). In (**b**), the evaluations are categorized based on the type of impact. Lastly, (**c**) indicates the project stage during which these evaluations were conducted.

The majority concur that further research is needed in the field, particularly during the pre-construction, construction, and operation and maintenance stages. Additionally, there is a consensus that standardization is required regarding the objectives, measurement methods, and monitoring frequency.

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