International Journal of
Geo-Information

MDPI

Systematic Review

GIS-Based Multi-Criteria Evaluation (MCE) Methods for Aquaculture Site Selection: A Systematic Review and Meta-Analysis

Sanae Chentouf [1], Boutaina Sebbah [1,*], El Houssine Bahousse [2], Miriam Wahbi [1] and Mustapha Maâtouk [1]

[1] Geomatic, Remote Sensing and Cartography Research Group (GéoTéCa), FSTT, Abdelmalek Essaadi University, Tetuan 93000, Morocco; sanae.chentouf1@etu.uae.ac.ma (S.C.); mwahbi@uae.ac.ma (M.W.); mmaatouk@uae.ac.ma (M.M.)
[2] Regional Inspectorate of Urbanism, Architecture and Territory Development RTTA, Tangier 90060, Morocco; iruaat.tth.bh@gmail.com
* Correspondence: bsebbah@uae.ac.ma

Abstract: With the growing demand for aquatic products, aquaculture has become a prominent means of meeting this demand. However, the selection of suitable sites for aquaculture remains a key factor in the success of any aquaculture operation. While various methods exist for site selection, geographic information system (GIS)-based multi-criteria evaluation (MCE) methods have emerged as the most widely utilized approach to identifying potential aquaculture sites. Following the guidelines of the preferred reporting items for systematic reviews and meta-analyses (PRISMA), this paper presents a systematic review and meta-analysis of GIS-based MCE methods used in aquaculture sites selection. The objective of this study is to offer a comprehensive overview of existing research in this field and develop a general model for selecting sites for fish and shellfish aquaculture. The main findings indicate a growing number of studies utilizing GIS-based MCE in aquaculture site selection in recent years, with Asia being the leading continent in terms of publications in this domain. Among the journals publishing in this field, the *Aquaculture* journal stands out as the top publisher. Using consistent criteria across the reviewed studies, two models have been generated, each consisting of four sub-models: water quality, soil quality, infrastructure, and socioeconomic factors; and topography, environment, and physical parameters. These models can aid future researchers and assist decision-makers in identifying optimal locations for aquaculture development.

Keywords: aquaculture; GIS-based MCE; PRISMA

Citation: Chentouf, S.; Sebbah, B.; Bahousse, E.H.; Wahbi, M.; Maâtouk, M. GIS-Based Multi-Criteria Evaluation (MCE) Methods for Aquaculture Site Selection: A Systematic Review and Meta-Analysis. *ISPRS Int. J. Geo-Inf.* **2023**, *12*, 439. https://doi.org/10.3390/ijgi12100439

Academic Editors: Wolfgang Kainz and John P. Wilson

Received: 10 August 2023
Revised: 1 October 2023
Accepted: 20 October 2023
Published: 23 October 2023

1. Introduction

Aquatic foods consumption has experienced a significant increase since 1961, with an average annual growth of 3.0% [1]. Thus, the consumption per capita has more than doubled, rising from an average of 9.9 kg in 1960 to 20.5 kg in 2019 [1]. This surge can be attributed essentially to human population growth and changes in dietary habits [2]. Aquaculture has emerged as an important source of animal protein and an essential component of global food production, providing significant employment and income for many communities worldwide [3]. According to the latest report of FAO on world fisheries and aquaculture state [1], aquaculture production has consistently increased over time and has reached a total production of 122.6 million tons valued at USD 281.5 billion, including 87.5 million tons of aquatic animals and 35.1 million tons of algae. A total of 68.1 million tons of aquaculture products were produced in marine and coastal aquaculture, while 54.4 million tons were produced in inland waters. Global aquaculture production has experienced a continuous growth in 2020, with a noted dominance of the Asian continent as the world's largest aquaculture producer, accounting for 91.6% of world's total production [1].

The continued growth of aquaculture production is essential in order to satisfy the growing seafood demand while minimizing the environmental impacts of overfishing and unsustainable practices.

However, selecting suitable sites for aquaculture operations is a complex task that requires careful consideration of multiple factors, including water quality, environmental conditions, and accessibility [4]. Various methods have been developed to aid in the selection of suitable aquaculture sites, including empirical and model-based approaches [5] and, more recently, geographic information system (GIS)-based multi-criteria evaluation (MCE) methods [6–8].

Empirical approaches rely on field observations, water sampling, and environmental data to evaluate the potential of a site for aquaculture production. Model-based approaches use statistical and mathematical models to evaluate the suitability of potential sites. However, both of these approaches are often limited in their ability to consider multiple factors and to assess the spatial variability of environmental conditions accurately. GIS-based MCE methods have emerged as a promising tool for identifying and prioritizing potential aquaculture sites [9]. The use of GIS-based MCE methods provides a comprehensive evaluation of the site selection process; these methods use geospatial technologies to integrate multiple datasets and criteria to generate a suitability map that highlights areas suitable for aquaculture [7,10]. The chosen criteria may include water quality, bathymetry, distance to ports, and infrastructure [7,11,12].

GIS-based MCE methods involve three main steps: (i) identification of criteria and data collection; (ii) weighting and scoring of criteria; and (iii) spatial analysis and suitability mapping. The identification of criteria and data collection involves the identification of factors that impact aquaculture suitability and the collection of relevant data, including environmental data, water quality data, economic and infrastructure data, etc. [10,11,13]. The process of weighting and scoring criteria entails assigning a weight to each criterion in accordance with its relative significance, followed by scoring each criterion based on its suitability [7,14]. Finally, spatial analysis and suitability mapping involve the integration of weighted and scored criteria to generate a suitability map that highlights areas suitable for aquaculture [7,15].

The primary objective of this paper is to conduct a systematic review and meta-analysis of GIS-based MCE methods utilized in aquaculture site selection. The review covers the period from 2000 to 2022. In Addition, the paper aims to provide a generic model for aquaculture site selection based on the criteria identified in the reviewed papers.

2. Data Source and Methods

The present systematic review has been carried out in accordance with the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines [16].

The PRISMA method consists of a 27-item checklist that covers the essential components of a systematic review and meta-analysis, including the identification and selection of relevant studies, screening, eligibility assessment, data extraction, quality assessment, and synthesis of the studies included in the review. The checklist also includes a four-phase flow diagram that outlines the study selection process and helps to provide transparency and accountability.

Although the PRISMA method was developed specifically for use in the healthcare field, it has been widely adapted and used in many other fields such as social sciences, environmental sciences, and engineering to ensure that systematic reviews and meta-analyses in these fields are conducted and reported using a rigorous and transparent methodology. Figure 1 outlines the four-phases (i.e., identification, screening, eligibility, inclusion) followed in this paper.

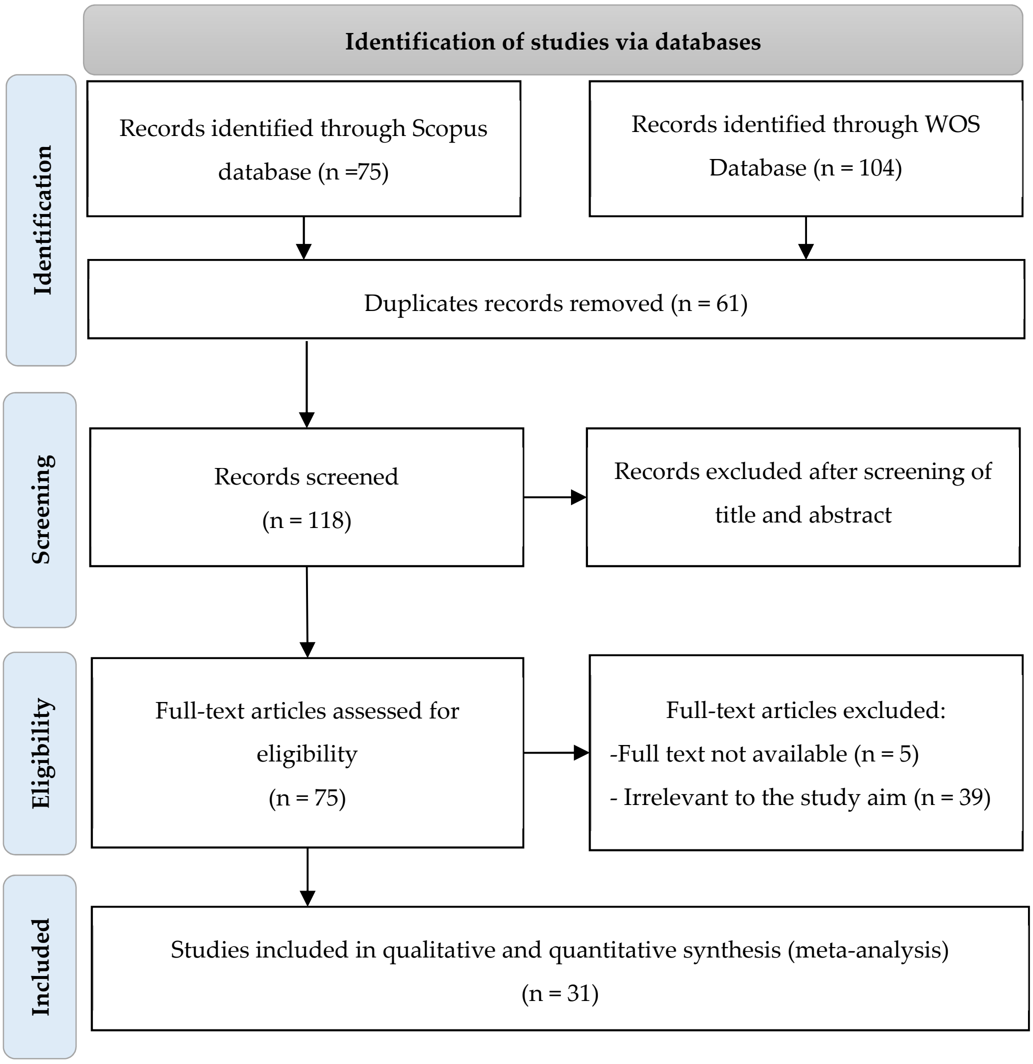

Figure 1. Flowchart of the literature search process according to PRISMA (preferred reporting items for systematic reviews and meta-analyses) guidelines.

2.1. Resources

To conduct this systematic review, two primary databases were utilized—Scopus and Web of Science (WoS)—which are two of the most widely used databases in systematic reviews. Scopus provides access to over 79 million records, including articles, conference proceedings, book chapters, and patents from more than 5000 publishers worldwide. It covers medical, technical, scientific, and social science literature, and its coverage extends back to 1823. On the other hand, WoS provides access to over 155 million records from over 34,000 journals worldwide, and it covers about 250 subject areas.

2.2. Systematic Searching Approach

The searching strategy adopted in this paper consisted of four steps, namely, identification, screening, eligibility, and inclusion. The electronic literature search for this review was undertaken in February 2023.

2.2.1. Identification

In the initial stage, records were determined by identifying keywords related to aquaculture, site selection, and geographic information system. A combination of keywords, with the aid of Boolean operators, has been created to identify articles to be included (Table 1).

Table 1. The search string employed in the selection process from Scopus and WoS databases.

Database	Keywords
Scopus	TITLE-ABS-KEY ((“aquaculture” OR “fish farming”) AND “site selection” AND (“GIS” OR “geographic information system”))
Web of Science	TS = (“aquaculture” OR “fish farming”) AND “site selection” AND (“GIS” OR “geographic information system”)

Various criteria for inclusion and exclusion were determined in the identification phase from databases. The processes utilized criteria that included the publication year, document type, publication stage, source type, and language used (Table 2). First, with respect to the timeline, a period of 22 years from 2000 to 2022 has been selected, which is deemed sufficient for analyzing the development of studies using GIS–MCE-based methods for the selection of aquaculture potential sites. Only journal articles written in the English language at the final stage of publication have been included in this systematic review. The selection of articles in English was primarily favored as it facilitated the authors' comprehension of the article's contents, while book chapters, conference papers, and review articles were excluded from the selection criteria. As a result, 75 records were identified from Scopus database and 104 records from Web of Science, while 61 records have been excluded as they were duplicated in the two databases.

Table 2. Inclusion and exclusion criteria.

Criteria	Inclusion	Exclusion
Publication year	Between 2000 and 2022	Earlier than 2000, later than 2022
Document type	Article	Book chapter, Review, Conference paper
Source type	Journal	Book, Conference Proceeding, Trade Journal, Book Series
Publication stage	Final publication stage	Articles in press
Language	English	Other languages

2.2.2. Screening

After the identification of recorders and the exclusion of duplicated ones, a total of 118 records were selected for screening. This phase consisted of the selection of studies relevant to the review's aim by reading the title and abstract of each paper. This analysis has led to the exclusion of 43 records from the 118. These studies have been identified by the authors as not relevant to the study or as being out of the context.

2.2.3. Eligibility

The next phase of systematic review process followed in this paper was the assessment for eligibility. The full text of the remaining articles has been analyzed and checked for suitability. The main objective of this phase is to make sure that all selected articles meet the standards identified by the authors.

A total of 75 full texts have been assessed for eligibility; the assessment has conducted to the exclusion of 5 records for which the full text could not be retrieved from the database, while 39 records have been identified by the authors as irrelevant to the study aim.

As a result, only 31 papers were included in the qualitative synthesis and meta-analysis.

3. Results and Discussion

3.1. Bibliometric Analysis

Bibliometric analysis is a powerful tool for tracking trends in research output over time, providing valuable information on the number of publications, top publishing journals, and most cited articles, etc. This section presents a bibliometric analysis of the 31 selected papers.

3.1.1. Publication Year

This axis tracks the number of publications per year that have used GIS-based-MCE methods to identify suitable sites for aquaculture (Figure 2). It is observed that the number of published papers is not stable and fluctuates over the selected time period (from 2000 to 2022). Furthermore, there were no articles published before 2005 meeting the criteria defined by authors previously. However, three articles were published in 2005, which may indicate renewed interest in the use of GIS–MCE methods in the aquaculture field.

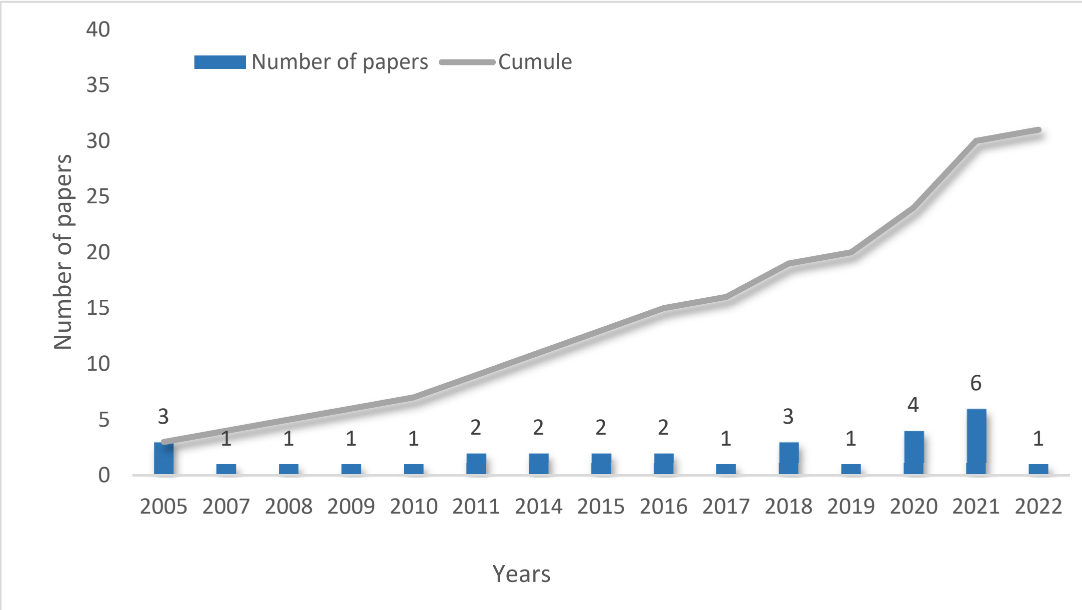

Figure 2. Annual publication rates of reviewed articles.

After 2005, there were only sporadic publications until 2011, when the number of publications began to increase again. The years 2014, 2015, and 2016 saw a similar number of publications to 2011, suggesting that interest in the topic remained steady.

The number of published papers applying GIS–MCE methods increased in 2018 to reach three published papers, including studies interested in the selection of potential aquaculture sites in different ecosystems such as lakes [17] and lagoons [12]. This trend continued in 2020, with four articles published, and a maximum of six articles published in 2021. Throughout this year, all published articles focused on fish aquaculture, whether in in the form of land-based aquaculture [7,18] or mariculture [6,19]. Overall, the bibliometric analysis reveals a fluctuation in research output over time, with several years seeing no publications and others experiencing a surge in interest. The increase in publications in recent years could indicate a growing interest in using GIS-based MCE methods in the selection of aquaculture sites.

3.1.2. Journals Published and Citations

The present paper reviews a total of 31 papers that investigate the application of GIS-based MCE method for selecting aquaculture sites. The analyzed papers were published in 19 different journals (as presented in Table 3). Out of these, 14 journals have published only a single paper using this method. Only journals that have published two or more peer-reviewed papers on the use of GIS techniques for identifying suitable aquaculture areas are represented in Figure 3.

Table 3. Number of published papers per journal.

Source Title	Number of Published Papers
Aquaculture	6
Aquaculture Research	4
Aquaculture International	3
Aquacultural Engineering	2
Sustainability	2
Ocean and Coastal Management	1
Coastal Management	1
Agriculture and Food Security	1
Computers and Electronics in Agriculture	1
Egyptian Journal of Aquatic Biology and Fisheries	1
Environmental earth sciences	1
Environmental Management	1
ICES Journal of marine science	1
Indian Journal of Fisheries	1
Journal of Cleaner Production	1
Journal of Environmental Management	1
Land	1
Landscape and Urban Planning	1
Science of the Total Environment	1

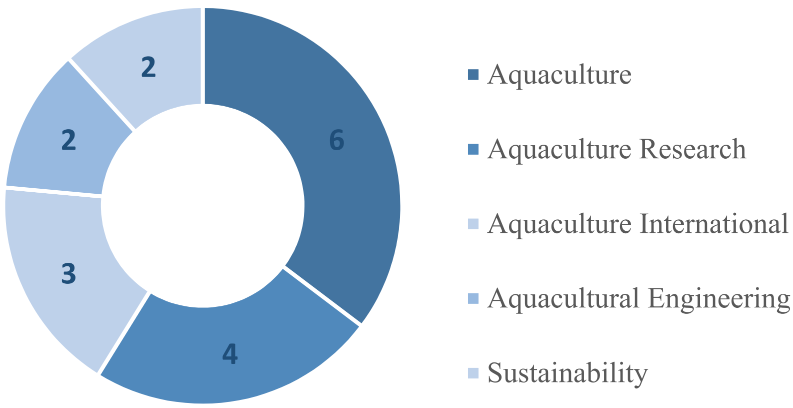

Figure 3. Top five productive journals ranked by number of contributions.

Moreover, the top three journals for publishing peer-reviewed papers on aquaculture site selection using this methodology were found to be *Aquaculture*, with a count of six papers. Following behind, four were published in *Aquaculture Research*, and three in *Aquaculture International*. The frequency of publications in these journals indicates the growing interest and importance of this approach in aquaculture site selection.

Table 4 presents the top 10 most cited research papers that have implemented the GIS-based MCE approach for selecting suitable aquaculture sites. According to Scopus and WoS databases, the study conducted by Radiarta et al. [11] in 2008 and published in the *Aquaculture* journal is the most cited article among the included papers, having been cited 122 times. This study utilized GIS-based MCE to identify appropriate sites for the aquaculture of Japanese scallop in Funka Bay. The second paper, published by Silva et al. [20] in the *Aquaculture* journal in 2011, employed GIS-based methods to select sites for Pacific oyster farming in the Valdivia Estuary, located in south-central Chile. The third study listed in Table 4 was published in the *Landscape and Urban Planning* journal in 2009 by Hossain et al. [21] This study utilized GIS-based MCE to identify potential sites for carp aquaculture in urban water bodies of Chittagong, Bangladesh.

Table 4. Most cited articles among the included papers.

Title	Authors	Year	Source Title	Cited by
GIS-based multi-criteria evaluation models for identifying suitable sites for Japanese scallop (*Mizuhopecten yessoensis*) aquaculture in Funka Bay, southwestern Hokkaido, Japan	Radiarta et al. [11]	2008	*Aquaculture*	122
Site selection for shellfish aquaculture by means of GIS and farm-scale models, with an emphasis on data-poor environments	Silva et al. [20]	2011	*Aquaculture*	110
Integration of GIS and multicriteria decision analysis for urban aquaculture development in Bangladesh	Hossain et al. [21]	2009	*Landscape and Urban Planning*	89
GIS-based multi-criteria evaluation to land suitability modelling for giant prawn (*Macrobrachium rosenbergii*) farming in Companigonj Upazila of Noakhali, Bangladesh	Hossain and Das [10]	2010	*Computers and Electronics in Agriculture*	86
Geographical information systems-based models for offshore floating marine fish cage aquaculture site selection in Tenerife, Canary Islands	Pérez et al. [22]	2005	*Aquaculture Research*	83
Multi-criteria evaluation approach to GIS-based land-suitability classification for tilapia farming in Bangladesh	Hossain et al. [23]	2007	*Aquaculture International*	66
A spatial multi-criteria evaluation for site selection of offshore marine fish farm in the Ligurian Sea, Italy	Dapueto et al. [13]	2015	*Ocean and Coastal Management*	59
A single-use site selection technique, using GIS, for aquaculture planning: Choosing locations for mangrove oyster raft culture in Margarita Island, Venezuela	Buitrago et al. [24]	2005	*Environmental Management*	50
Brackish water aquaculture site selection in Palghar Taluk, Thane district of Maharashtra, India, using the techniques of remote sensing and geographical information system	Karthik et al. [25]	2005	*Aquacultural Engineering*	48
Land suitability evaluation for brackish water aquaculture development in coastal area of Hormozgan, Iran	Hadipour et al. [26]	2014	*Aquaculture International*	42

3.1.3. Geographic Distribution: By Continent and by Country

The geographic distribution of the included papers by country and by continent are shown in Figures 4 and 5, respectively. Research on the selection of aquaculture sites using GIS-based MCE was carried out in 20 different countries around the world, and in different ecosystems. As illustrated in Figure 4, most studies were conducted in India and Iran, with five published papers for each; followed by Bangladesh, with three articles, representing a notable number of studies; then Italy, with two records. The remaining countries have only published one article.

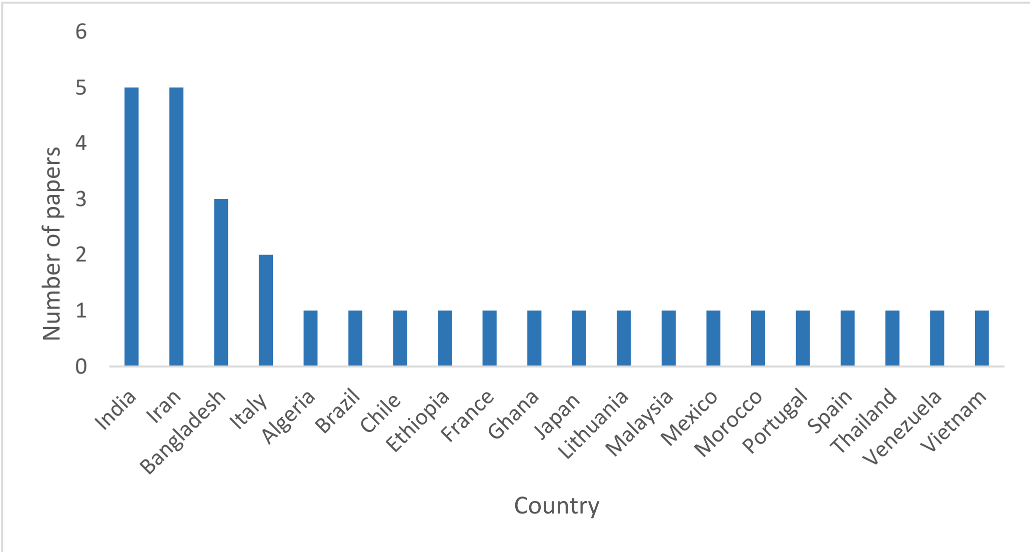

Figure 4. Number of publications per country. A list of contributing countries and contributed number of records.

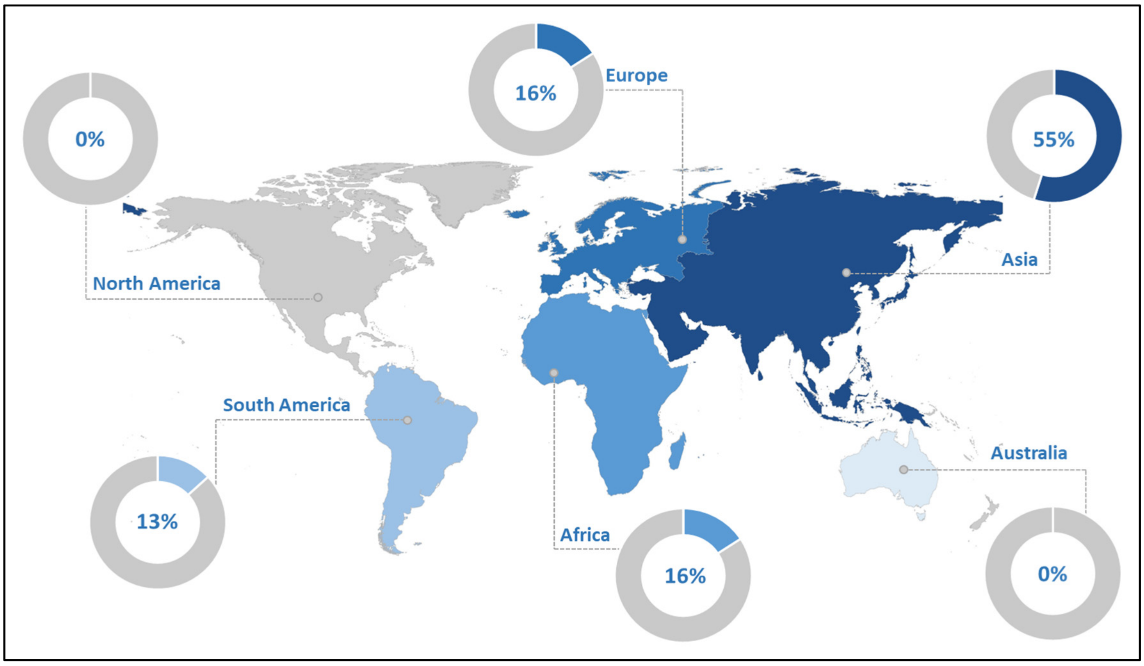

Figure 5. Worldwide distribution of reviewed studies.

At a continental scale, the Asian continent accounts for the maximum number of studies, representing 55% of the research papers included in this review (Figure 5). Africa and Europe both represent 16% of published papers, while only four studies were conducted in south America (13%). It is worth noting that no study included in the present review was conducted in North America or Australia.

3.1.4. Keyword Analysis

Using VOSviewer (version 1.6.18, Centre for Science and Technology Studies, Leiden University, The Netherlands), 385 author keywords were found from the 31 articles included in this study. A Minimum number of occurrences equal to three has been defined by the authors; however, only 39 keywords have met this threshold (Table 5). For each of the 39 keywords, the total strength of co-occurrence links with other keywords is calculated, and keywords with the highest total link strength are selected. Selected keywords were grouped into three clusters or groups based on their similarity, as is presented in Figures 6 and 7.

Table 5. Occurrence of author keywords.

Keyword	Occurrence	Total Link Strength	Keyword	Occurrence	Total Link Strength
Site selection	25	162	Animals	3	25
GIS	24	149	Aquaculture production	3	15
Aquaculture	17	100	Aquaculture site selection	3	10
Multi-criteria evaluation	9	68	Bivalvia	3	22
Analytical hierarchy process	7	45	Carrying capacity	3	15
Geographic information systems	7	58	Coastal zone	3	12
Decision making	6	46	Culture	3	16
Bangladesh	5	40	Growth rate	3	21
Eurasia	5	44	Iran	3	15
Remote sensing	5	33	Land suitability	3	25
Sustainability	5	43	Models	3	16
Asia	4	38	South Asia	3	32
Cage culture	4	30	Spatial analysis	3	23
Fish culture	4	35	Stakeholder	3	25
Geographic information system	4	35	Strategic approach	3	24
Multicriteria analysis	4	28	Sustainable development	3	25
Ostreidae	4	25	Tenerife	3	15
Resource development	4	33	Tilapia	3	28
Water quality	4	34	World	3	24
AHP	3	18			

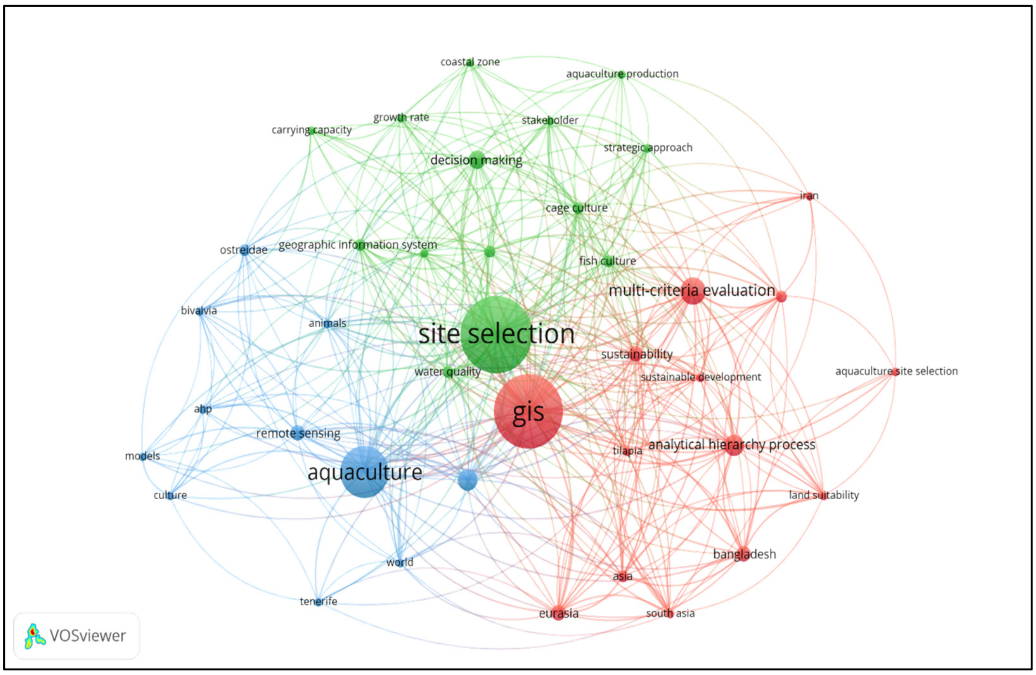

Figure 6. Co-occurrence of author keywords network map.

Table 5 highlight the co-occurrence of the 39 selected author keywords and their respective total link strength (TLS). Through VOSviewer analysis, it was found that the most significant clusters are represented by the colors green, red, and blue, as illustrated in Figure 6. Notably, the green cluster consists of papers that emphasize the importance of site selection in decision-making and planning. The two most frequently used author keywords in this cluster are “Site selection” which appears 25 times, with a TLS of 162, and “decision making”, which has occurred 6 times with a TLS of 46. These papers are grouped together to demonstrate how the process of selecting a suitable site is a crucial factor in making informed decisions and formulating effective plans.

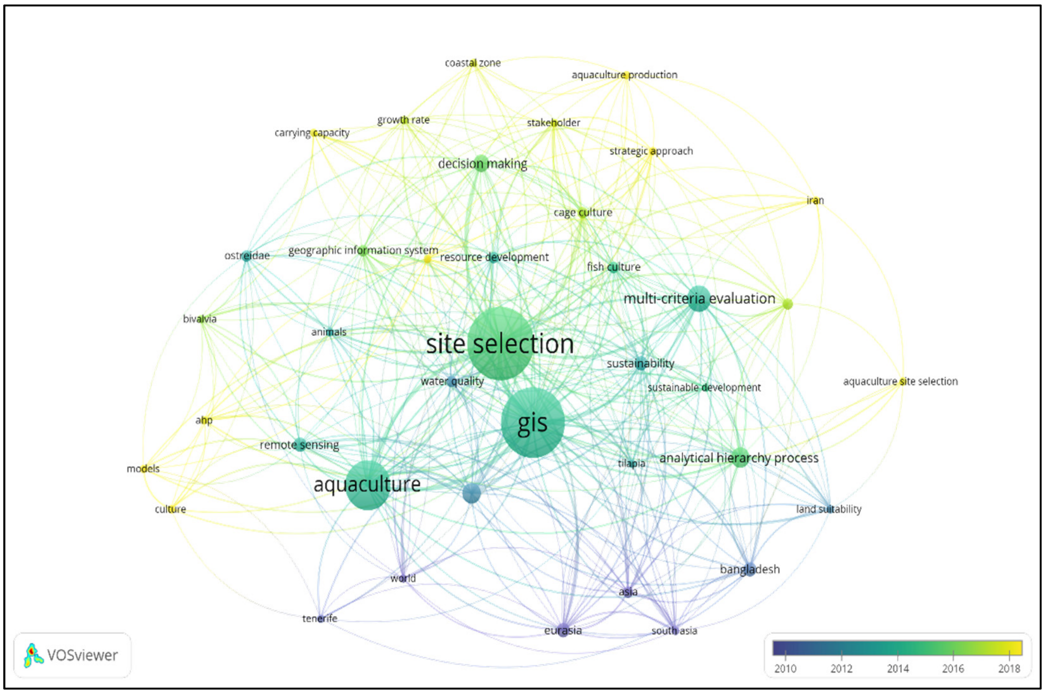

Figure 7. Chronological Co-occurrence of author keywords network map.

In the red cluster, the keyword with the highest occurrence is "GIS", appearing 24 times (149 TLS), followed by "multi-criteria evaluation", which has occurred 9 times (68 TLS), while "Analytical hierarchy process" is the third most commonly used keyword in this cluster, occurring 7 times (45 TLS). This cluster focuses on the application of GIS methods in the selection of aquaculture sites, which are usually combined with multi-criteria evaluation. The articles in this cluster primarily used the analytical hierarchy process to weigh the criteria used. Finally, the blue cluster primarily consists of papers related to the use of remote sensing and GIS methods in the field of aquaculture. The most prominent term in this cluster is "aquaculture", which appears 17 times and has a TLS of 100. The next most frequently occurring term is "Geographic information systems", which appears seven times and has a TLS of 58. Lastly, "remote sensing" has an occurrence of five and a TLS equal to 33.

Concerning the link strength (LS) between keywords from different clusters, the highest link strength, which is equal to 19, is observed between the keywords "site selection" and "GIS". Following this, there is a link strength of 15 between "aquaculture" and "GIS", a link strength of 14 between "aquaculture" and "site selection", and a link strength of 9 between "site selection" and "multi-criteria evaluation" keywords.

Furthermore, VOSviewer can display the most recent research trends in chronological order. Figure 7 illustrates that the correlation between site selection and GIS has been a prominent topic in aquaculture research in recent years, indicating the potential for using GIS techniques in this field.

3.2. Research Evaluation/Models and Criteria Used in the Selection

The subsequent sections outline the main criteria utilized by each study to identify appropriate sites either for fish or shellfish aquaculture. In addition, it introduces a model that can be adopted by researchers to identify potential aquaculture sites based on the commonly used criteria in the studies reviewed in this paper.

3.2.1. Classification According to Species Cultured

In aquaculture, many aquatic organisms can be farmed, such as fish, shellfish, and seaweed. The criteria chosen for the selection of potential sites varies depending on the cultured spices. According to studies reviewed in this paper, it was found that 65% of papers have focused on selecting potential sites for fish farming, indicating that it is the most popular form of aquaculture. These studies have identified potential sites for a variety fish species, including Sparus aurata [22,27,28], a warm-water fish native to the Mediterranean Sea that is highly valued in the aquaculture industry due to its fast growth rate, high market demand, and adaptability to different environments. Other fish species for which potential farming sites have been identified include Rainbow trout (Oncorhynchus mykiss) [19], pangasius [15], carp [21], sturgeon [29], seabass (*Dicentrarchus labrax*) [22,27] and Tilapia, the latter of which has been the subject of three different studies [23,30,31]. Tilapia is a freshwater fish species that is widely farmed due to its fast growth rate and high adaptability. However, 11 out 22 that focused on identifying potential sites for fish aquaculture did not specify any fish species for cultivation in the identified sites.

On the other hand, 35% of the reviewed studies have identified suitable sites for shellfish aquaculture. The studies have focused on different types of shellfish, including the farming of Japanese scallop (*Mizuhopecten yessoensis*) [11] and giant prawn (*Macrobrachium rosenbergii*) [10]. However most of the studies have identified suitable sites for different types of oysters and mussels, such as C. rhizophorae oyster [24], Pacific oyster (*Crassostrea gigas*) [20], green mussels [32], and zebra mussels [12].

It is important to note that oysters and mussels are highly valued commercial species. They are widely consumed and have a high demand in many markets around the world. As a result, there is a significant economic incentive for developing and improving oyster and mussel aquaculture. In addition, oysters and mussels are relatively easy to culture and can be grown in a variety of environments, such as intertidal zones, estuaries, and open water. In contrast, only two of the reviewed articles have focused on identifying sites for shrimp farming in brackish water [25,26]. However, shrimp aquaculture in brackish water has been gaining popularity due to shrimp's ability to tolerate a wide range of salinities. This makes them a good candidate for aquaculture in areas where other forms of aquaculture are not feasible.

3.2.2. Classification According to Aquaculture Ecosystems

A diverse range of aquatic ecosystems are available for the development of aquaculture worldwide. Based on the reviewed papers in this study, mariculture is the most commonly practiced type of aquaculture. A total of 11 out of 31 studies have selected suitable sites for marine aquaculture using GIS-based MCE methods [6,22,33]. There are several reasons for this, including the vast surface area covered by oceans, which provides a significant amount of space for mariculture operations. Additionally, the ocean provides a stable and nutrient-rich environment for many aquatic organisms, making it suitable for large-scale production of seafood products.

Land-based aquaculture, which involves farming freshwater fish and other aquatic organisms in ponds and tanks, is also one of the most commonly practiced types of aquacultures. Of the reviewed studies, eight have identified potential sites for land-based aquaculture [7,18,29,34]. The significance of this type of aquaculture lies in the fact that it can be established in areas where marine ecosystems are not available, such as in arid regions or areas far from the coast. This provides a significant advantage in terms of the accessibility and flexibility for aquaculture operations.

Moreover, the selection of aquaculture sites in various other ecosystems has been the subject of several reviewed papers. These include estuarine ecosystem aquaculture (3 studies) [20,35,36], as well as aquaculture in lakes [17], brackish water [26], lagoons [12], urban water bodies [21], and rivers [15].

3.3. Selection of Multi Criteria Used in Aquaculture Site Selection

The use of the GIS-based MCE method in aquaculture site selection enables decision-makers to take into account different factors influencing this activity. This approach helps to ensure that aquaculture facilities are developed in a sustainable and responsible manner, taking into account the needs of both the environment and local communities.

Selecting a suitable site for aquaculture involves evaluating several factors that determine the most favorable location for the operation. These factors vary depending on the species cultivated and the ecosystems, such as water quality, topography, access to resources, infrastructure, etc.

Based on the 31 reviewed articles, the authors have extracted the criteria used by each study for the selection of suitable aquaculture sites. The studies have been subdivided into two categories: those that focus on fish aquaculture; and those that focus on shellfish aquaculture. The most commonly used criteria, identified in more than three studies, have been selected to create a general model that can be used by researchers in future studies.

The models created are divided into three levels:

- Top level: presenting the goal of the study, which is the selection of suitable site for fish or shellfish aquaculture;
- Intermediate level: presenting the sub-models, which are divided into four main sub-models, namely, water quality, soil quality, infrastructure, and socioeconomic factors; and topography, environment, and physical parameters;
- Bottom level: presenting the criteria adopted in each sub-model.

It is important to note that the proposed models do not provide the weighting of selected criteria. The determination of these weights relies, in the first instance, on the specific characteristics of the study areas and the spices being cultivated.

3.3.1. Model for Fish Aquaculture Site Selection

As previously mentioned, 20 out of the 31 reviewed papers have concentrated on selecting potential sites for fish aquaculture. The criteria utilized in each study vary based on the properties of the cultured species or the ecosystem in which the farms will be established. For each sub-model, a distinct set of criteria has been chosen, and these criteria were chosen based on their appearance in more than three studies (Figure 8).

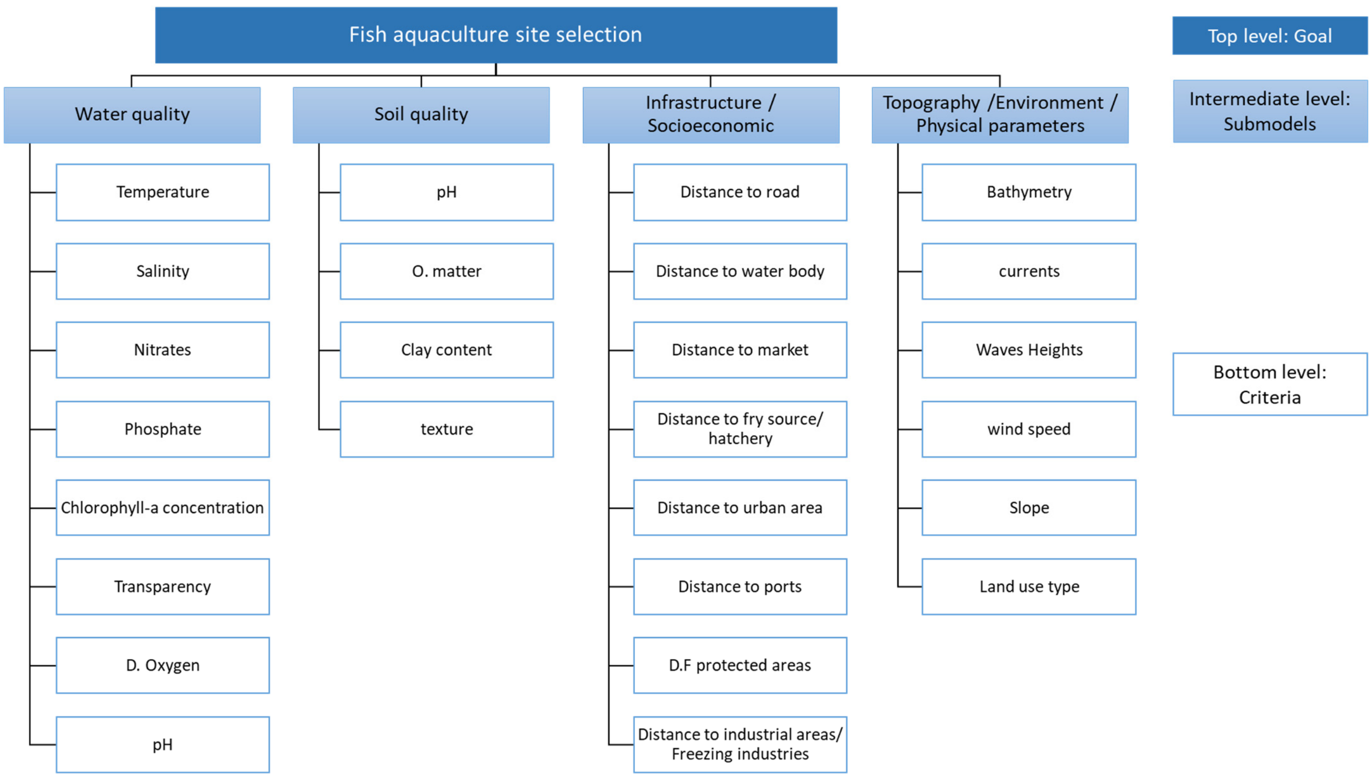

Figure 8. A general model for selecting a suitable site for fish aquaculture.

For the water quality sub-model, temperature is the main parameter to be identified; it has been utilized in 15 studies [13,19,31]. Temperature in suitable sites should be within the range appropriate for fish species intended to be raised. pH and dissolved oxygen are also among the principal parameters characterizing water quality [18]. pH level should be between 6.5 and 9.0 for most fish species, and dissolved oxygen levels should be maintained above 5 mg/L to ensure fish health.

However, some of the reviewed papers have integrated other water parameters for the selection of an appropriate aquaculture site. These parameters were excluded from our model as they have been identified as being used only by one or two authors. For example, Pérez et al. [22], Ross et al. [30], and Haghshenas et al., 2021, [19] have integrated suspended solids as a parameter for the selection of water quality, while Nayak et al. have added hardness, CO_2, and total alkalinity in their studies published in 2014 and 2018. Dapueto et al. [13] have considered many other criteria for water quality, such macroalgae, angiosperms Posidonia, benthic macro invertebrates, and nutrients, while selecting a suitable site for an offshore marine fish farm in the Ligurian Sea, Italy.

For soil quality, pH, organic matter, and texture are the most used criteria considered in aquaculture site selection [7,18,29]. Soil with high clay content is ideal as it can retain water for extended periods. Only Esmaeilpour-Poodeh et al. [29], in their study published in 2019, have added sand percentage, fertility, and soil depth in their selection of a site for sturgeon farming in the Caspian Sea southern coasts.

Regarding the infrastructure and socioeconomic parameters, distance to roads, markets, and urban areas are among the principal parameters taken into account while selecting appropriate sites [18,36,37]. Proximity to markets minimizes transportation costs and reduces the time taken to transport the fish to market. The site should also be easily accessible for the transportation of supplies, equipment, and fish. Adequate roads or other examples of transportation infrastructure should be available to transport the necessary materials and equipment to the site. However, many other parameters have been included in some papers, such as fingerling spots, pelagic fisheries, and rocky platforms, considered by Pérez et al. [22], or the consumption behavior and production experience, considered by Assefa and Abebe [17] in their model for selecting an aquaculture site in the Lake Tana basin, Northwest Ethiopia.

Several parameters have been included in the last sub-model (i.e., topography, environment, and physical parameters), such land use type and slope [17,23]. The land use type has an important impact on water quality as certain activities such as agriculture can induce water pollution. In addition, other parameters that can impact water quality or fish growth and survival; bathymetry, currents, and waves height have also been considered as essential parameters in the selection of potential aquaculture sites [8,19,28]. Other parameters, such as seabed composition, wave exposure [38], and tidal amplitude [6,27], which have been used only by one or two authors, have been excluded from the proposed model.

3.3.2. Model for Shellfish Aquaculture Site Selection

Similar to the fish aquaculture model, four sub-models were identified for shellfish aquaculture (Figure 9). In the water quality sub-model, water temperature has been recognized as the most essential parameter for the selection of a suitable site; it has been utilized in over 70% of reviewed studies [11,26,32,33]. Despite the importance of this parameter in indicating water quality, it has not been taken into account by three studies [12,32,34]. Salinity, chlorophyll-a, and dissolved oxygen have also been identified as crucial parameters that have been utilized in the majority of reviewed models. Karthik et al. [25] have included alkalinity, ammonium, nitrites, nitrates, and phosphate as the main criteria for water quality in their model for the selection of an aquaculture site in Brackish water.

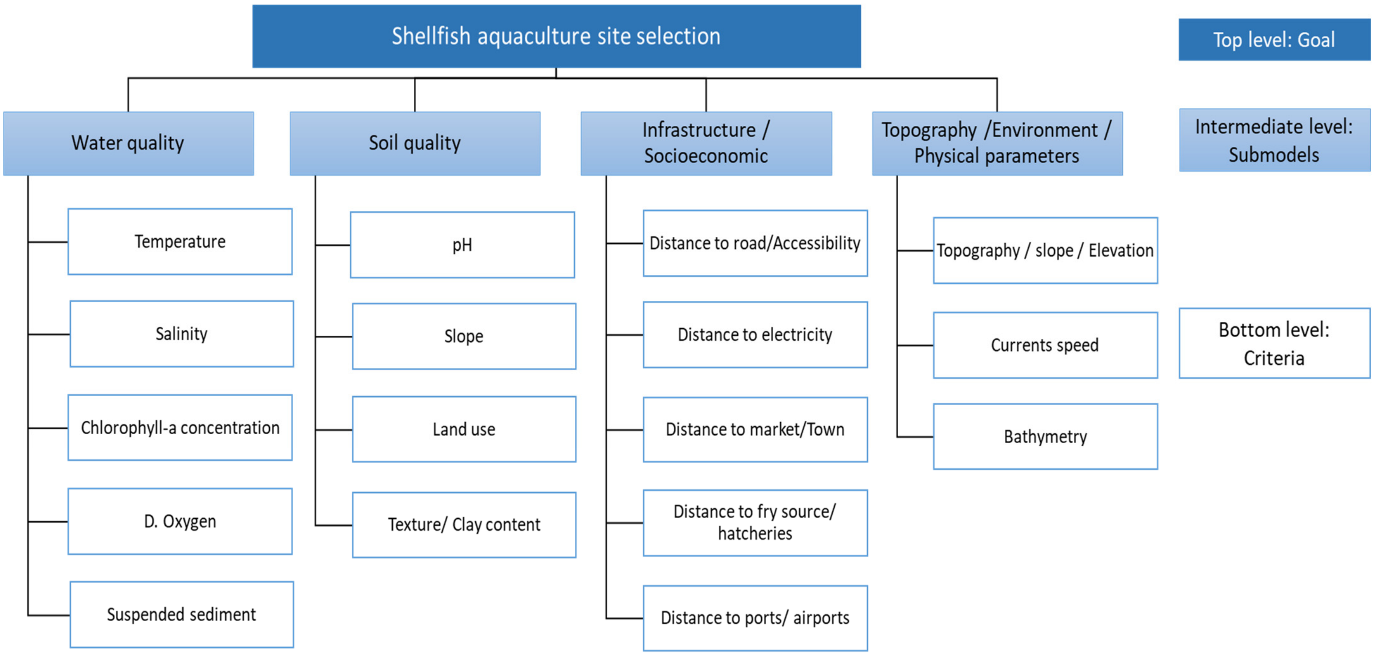

Figure 9. A general model for selecting suitable sites for shellfish aquaculture.

Regarding soil quality, pH, soil texture, land use, and slope are among the crucial criteria employed to select s suitable site for aquaculture, as identified by several studies [10,26,34]. In studies conducted by Karthik et al. [25] and Keshtkar et al. [34], criteria such as nitrogen, phosphorus, soil elevation, and erosion were included.

In the infrastructure and socioeconomic sub-model, and similar to the fish aquaculture model, distance to road, to electricity, and to the market remain the most important criteria to take into account while selecting the appropriate locations for aquaculture [10,25,26,32], while topography, bathymetry, and current speed were recognized as the most important parameters in the last sub-model [20,32,33]. Some other parameters were excluded from the proposed model as they were only used by one author (e.g., distance from water source, tidal amplitude, and sewage pollution).

4. Conclusions

The selection of an appropriate site plays a pivotal role in every aquaculture operation. This systematic review presents a comprehensive examination of studies that employed geographic information system (GIS)-based multi-criteria evaluation (MCE) techniques for the selection of suitable aquaculture sites.

The utilization of this method has witnessed a notable rise in research publications in recent years. Each study incorporated distinct criteria in their site selection process, tailored to the specific characteristics of the study area and the species targeted for cultivation.

Notably, the majority of the research included in this review originated from Asia (approximately 55%), with a predominant focus on fish aquaculture (65% of the reviewed papers), while shellfish aquaculture accounted for 35% of the reviewed papers. However, the potential for expanding this research to include other aquaculture species and geographical regions remains an area for future exploration.

Based on the analysis of similar criteria used by these studies, two general models were developed, one for fish aquaculture and another for shellfish aquaculture. Each model comprised four sub-models encompassing water quality, soil quality, infrastructure, and socioeconomic factors, as well as topography, environment, and physical parameters. These sub-models incorporated commonly employed criteria documented in the literature. The outcomes of this research contribute to existing knowledge in the aquaculture field and offer practical tools with which to enhance the efficiency of site selection for aquaculture. This study aims principally to facilitate the future selection of potential aquaculture sites through GIS methods. The models presented in this study have the potential for enhancement or adaptation through incorporating additional criteria that researchers deem crucial based on species-specific requirements and the unique characteristics of the study areas.

Author Contributions: Conceptualization, Sanae Chentouf, Boutaina Sebbah, and Mustapha Maâtouk; methodology, Sanae Chentouf, Boutaina Sebbah, and Miriam Wahbi; investigation, Sanae Chentouf, Boutaina Sebbah, and Miriam Wahbi, El Houssine Bahousse; resources, Sanae Chentouf and Boutaina Sebbah; writing—original draft preparation, Sanae Chentouf; writing—review and editing, Boutaina Sebbah, El Houssine Bahousse, and Mustapha Maâtouk. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors would like to express their gratitude to the anonymous reviewers and members of the editorial team for their valuable time, effort, and constructive comments.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Food and Agriculture Organization of United Nations. *The State of World Fisheries and Aquaculture: Towards Blue Transformation*; Food and Agriculture Organization of United Nations: Rome, Italy, 2022.
2. Porporato, E.M.D.; Pastres, R.; Brigolin, D. Site Suitability for Finfish Marine Aquaculture in the Central Mediterranean Sea. *Front. Mar. Sci.* **2020**, *6*, 772. [CrossRef]
3. Yin, S.; Takeshige, A.; Miyake, Y.; Kimura, S. Selection of suitable coastal aquaculture sites using Multi-Criteria Decision Analysis in Menai Strait, UK. *Ocean Coast. Manag.* **2018**, *165*, 268–279. [CrossRef]
4. McLeod, I.; Pantus, F.; Preston, N. The use of a geographical information system for land-based aquaculture planning. *Aquac. Res.* **2002**, *33*, 241–250. [CrossRef]
5. Bricker, S.B.; Getchis, T.L.; Chadwick, C.B.; Rose, C.M.; Rose, J.M. Integration of ecosystem-based models into an existing interactive web-based tool for improved aquaculture decision-making. *Aquaculture* **2016**, *453*, 135–146. [CrossRef]
6. Bandira, P.N.A.; Mahamud, M.A.; Samat, N.; Tan, M.L.; Chan, N.W. Gis-based multi-criteria evaluation for potential inland aquaculture site selection in the george town conurbation, Malaysia. *Land* **2021**, *10*, 1174. [CrossRef]
7. Divu, D.N.; Mojjada, S.K.; Pokkathappada, A.A.; Sukhdhane, K.; Menon, M.; Mojjada, R.K.; Tade, M.S.; Bhint, H.M.; Gopalakrishnan, A. Decision-making framework for identifying best suitable mariculture sites along north east coast of Arabian Sea, India: A preliminary GIS-MCE based modelling approach. *J. Clean. Prod.* **2020**, *284*, 124760. [CrossRef]
8. Landuci, F.S.; Rodrigues, D.F.; Fernandes, A.M.; Scott, P.C.; Poersch, L.H.D.S. Geographic Information System as an instrument to determine suitable areas and identify suitable zones to the development of emerging marine finfish farming in Brazil. *Aquac. Res.* **2020**, *51*, 3305–3322. [CrossRef]
9. von Thenen, M.; Maar, M.; Hansen, H.S.; Friedland, R.; Schiele, K.S. Applying a combined geospatial and farm scale model to identify suitable locations for mussel farming. *Mar. Pollut. Bull.* **2020**, *156*, 111254. [CrossRef]
10. Hossain, M.S.; Das, N.G. GIS-based multi-criteria evaluation to land suitability modelling for giant prawn (*Macrobrachium rosenbergii*) farming in Companigonj Upazila of Noakhali, Bangladesh. *Comput. Electron. Agric.* **2010**, *70*, 172–186. [CrossRef]
11. Radiarta, I.N.; Saitoh, S.-I.; Miyazono, A. GIS-based multi-criteria evaluation models for identifying suitable sites for Japanese scallop (*Mizuhopecten yessoensis*) aquaculture in Funka Bay, southwestern Hokkaido, Japan. *Aquaculture* **2008**, *284*, 127–135. [CrossRef]
12. Bagdanavičiūtė, I.; Umgiesser, G.; Vaičiūtė, D.; Bresciani, M.; Kozlov, I.; Zaiko, A. GIS-based multi-criteria site selection for zebra mussel cultivation: Addressing end-of-pipe remediation of a eutrophic coastal lagoon ecosystem. *Sci. Total Environ.* **2018**, *634*, 990–1003. [CrossRef]
13. Dapueto, G.; Massa, F.; Costa, S.; Cimoli, L.; Olivari, E.; Chiantore, M.; Federici, B.; Povero, P. A spatial multi-criteria evaluation for site selection of offshore marine fish farm in the Ligurian Sea, Italy. *Ocean Coast. Manag.* **2015**, *116*, 64–77. [CrossRef]
14. Anand, A.; Krishnan, P.; Suryavanshi, A.S.; Choudhury, S.B.; Kantharajan, G.; Rao, C.S.; Manjulatha, C.; Babu, D.E. Identification of Suitable Aquaculture Sites Using Large-Scale Land Use and Land Cover Maps Factoring the Prevailing Regulatory Frameworks: A Case Study from India. *J. Indian Soc. Remote Sens.* **2021**, *49*, 725–745. [CrossRef]
15. Falconer, L.; Telfer, T.C.; Ross, L.G. Investigation of a novel approach for aquaculture site selection. *J. Environ. Manag.* **2016**, *181*, 791–804. [CrossRef] [PubMed]

16. Moher, D.; Shamseer, L.; Clarke, M.; Ghersi, D.; Liberati, A.; Petticrew, M.; Shekelle, P.; Stewart, L.A.; PRISMA-P Group. Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. *Syst Rev.* **2015**, *4*, 1. [CrossRef] [PubMed]
17. Assefa, W.W.; Abebe, W.B. GIS modeling of potentially suitable sites for aquaculture development in the Lake Tana basin, Northwest Ethiopia. *Agric. Food Secur.* **2018**, *7*, 72. [CrossRef]
18. Ghobadi, M.; Nasri, M.; Ahmadipari, M. Land suitability assessment (LSA) for aquaculture site selection via an integrated GIS-DANP multi-criteria method; a case study of lorestan province, Iran. *Aquaculture* **2020**, *530*, 735776. [CrossRef]
19. Haghshenas, E.; Gholamalifard, M.; Mahmoudi, N.; Kutser, T. Developing a gis-based decision rule for sustainable marine aquaculture site selection: An application of the ordered weighted average procedure. *Sustainability* **2021**, *13*, 2672. [CrossRef]
20. Silva, C.; Ferreira, J.G.; Bricker, S.B.; DelValls, T.A.; Martín-Díaz, M.L.; Yáñez, E. Site selection for shellfish aquaculture by means of GIS and farm-scale models, with an emphasis on data-poor environments. *Aquaculture* **2011**, *318*, 444–457. [CrossRef]
21. Hossain, M.S.; Chowdhury, S.R.; Das, N.G.; Sharifuzzaman, S.M.; Sultana, A. Integration of GIS and multicriteria decision analysis for urban aquaculture development in Bangladesh. *Landsc. Urban Plan.* **2009**, *90*, 119–133. [CrossRef]
22. Perez, O.M.; Telfer, T.C.; Ross, L.G.; Pérez, O.M.; Telfer, T.C.; Ross, L.G. Geographical information systems-based models for offshore floating marine fish cage aquaculture site selection in Tenerife, Canary Islands. *Landsc. Urban Plan.* **2009**, *90*, 119–133. [CrossRef]
23. Hossain, M.S.; Chowdhury, S.R.; Das, N.G.; Rahaman, M.M. Multi-criteria evaluation approach to GIS-based land-suitability classification for tilapia farming in Bangladesh. *Aquac. Int.* **2007**, *15*, 425–443. [CrossRef]
24. Buitrago, J.; Rada, M.; Hernández, H.; Buitrago, E. A single-use site selection technique, using GIS, for aquaculture planning: Choosing locations for mangrove oyster raft culture in Margarita Island, Venezuela. *Environ. Manag.* **2005**, *35*, 544–556. [CrossRef] [PubMed]
25. Karthik, M.; Suri, J.; Saharan, N.; Biradar, R.S. Brackish water aquaculture site selection in Palghar Taluk, Thane district of Maharashtra, India, using the techniques of remote sensing and geographical information system. *Aquac. Eng.* **2005**, *32*, 285–302. [CrossRef]
26. Hadipour, A.; Vafaie, F.; Hadipour, V. Land suitability evaluation for brackish water aquaculture development in coastal area of Hormozgan, Iran. *Aquac. Int.* **2015**, *23*, 329–343. [CrossRef]
27. Nhhala, I.; Bahida, A.; Nhhala, H.; Chadli, H.; Baldan, D.; Wahbi, M.; Erraioui, H. Site selection for fish farming using integrated GIS-spatial multi-criteria evaluation and carrying capacity approaches: Case study of M'diq bay, Morocco. *Egypt. J. Aquat. Biol. Fish.* **2022**, *26*, 807–841. [CrossRef]
28. Chahinez, L.; Abderrahim, H.; El Islem, B.N. Site selection for finfish cage farming using spatial multi-criteria evaluation and their validation at field in the Bay of Souahlia (Algeria). *Aquac. Int.* **2020**, *28*, 2419–2436. [CrossRef]
29. Esmaeilpour-Poodeh, S.; Ghorbani, R.; Hosseini, S.A.; Salmanmahiny, A.; Rezaei, H.; Kamyab, H. A multi-criteria evaluation method for sturgeon farming site selection in the southern coasts of the Caspian Sea. *Aquaculture* **2019**, *513*, 734416. [CrossRef]
30. Ross, L.G.; Falconer, L.L.; Mendoza, A.C.; Palacios, C.A.M. Spatial modelling for freshwater cage location in the Presa Adolfo Mateos Lopez (El Infiernillo), Michoacan, Mexico. *Aquac. Res.* **2011**, *42*, 797–807. [CrossRef]
31. Asmah, R.; Falconer, L.; Telfer, T.C.; Karikari, A.Y.; Al Wahaibi, M.; Xia, I.F.; Handisyde, N.; Quansah, K.E.; Amoah, D.K.; Alshihhi, J.; et al. Waterbody scale assessment using spatial models to identify suitable locations for cage aquaculture in large lake systems: A case study in Volta Lake, Ghana. *Aquac. Res.* **2021**, *52*, 3854–3870. [CrossRef]
32. Kumgumpol, H.; Liu, Y.; Pokavanich, T.; Alabia, I.D.; Yin, Z.; Saitoh, S.-I.; Tian, Y. Environmental habitat mapping of green mussel: A gis-based approach for sustainable aquaculture in the inner gulf of Thailand. *Sustainability* **2020**, *12*, 10643. [CrossRef]
33. Brigolin, D.; Porporato, E.M.D.; Prioli, G.; Pastres, R. Making space for shellfish farming along the adriatic coast. *ICES J. Mar. Sci.* **2017**, *74*, 1540–1551. [CrossRef]
34. Keshtkar, A.R.; Oros, Z.; Mohammadkhan, S.; Eagdari, S.; Paktinat, H. Multi-criteria analysis in Artemia farming site selection for sustainable desert ecosystems planning and management (case study: Siahkouh Playa, Iran). *Environ. Earth Sci.* **2016**, *75*, 1195. [CrossRef]
35. Barillé, L.; Le Bris, A.; Goulletquer, P.; Thomas, Y.; Glize, P.; Kane, F.; Falconer, L.; Guillotreau, P.; Trouillet, B.; Palmer, S.; et al. Biological, socio-economic, and administrative opportunities and challenges to moving aquaculture offshore for small French oyster-farming companies. *Aquaculture* **2020**, *521*, 735045. [CrossRef]
36. Jayanthi, M.; Thirumurthy, S.; Samynathan, M.; Kumararaja, P.; Muralidhar, M.; Vijayan, K.K. Multi-criteria based geospatial assessment to utilize brackishwater resources to enhance fish production. *Aquaculture* **2021**, *537*, 736528. [CrossRef]
37. Nayak, A.K.; Pant, D.; Kumar, P.; Mahanta, P.C.; Pandey, N.N. GIS-based aquaculture site suitability study using multi-criteria evaluation approach. *Indian J. Fish.* **2014**, *61*, 108–112.
38. Micael, J.; Costa, A.C.; Aguiar, P.; Medeiros, A.; Calado, H. Geographic Information System in a Multi-Criteria Tool for Mariculture Site Selection. *Coast. Manag.* **2015**, *43*, 52–66. [CrossRef]