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Risk-Based Spatial Planning for Seaweed Aquaculture: A Systematic Review of Methods, Indicators, and Decision Support

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A B S T R A C T

Seaweed aquaculture is a key component of the blue economy but faces significant environmental, climatic, and governance risks that challenge conventional site-suitability planning. This systematic review synthesizes risk-based spatial planning approaches for seaweed aquaculture, focusing on methods, risk indicators, and decision-support tools. Following PRISMA guidelines, it finds that most studies rely on GIS and multi-criteria decision analysis, treating risk implicitly through static environmental proxies. Hazard indicators dominate, while exposure, social-institutional vulnerability, adaptive capacity, and uncertainty analysis are rarely addressed. Decision-support outputs are largely map-based, with limited evidence of policy uptake in marine and coastal planning. The review identifies critical gaps and proposes a research agenda emphasizing integrated risk frameworks, social and governance indicators, explicit uncertainty treatment, and co-designed decision-support systems to enhance policy relevance and climate resilience.

INTRODUCTION

Seaweed aquaculture is increasingly recognized as a strategic component of the blue economy and sustainable coastal development frameworks. Its growing prominence in policy and planning reflects expectations that seaweed farming can simultaneously support food security, biodiversity conservation, climate mitigation, and coastal livelihoods (Zhu et al., 2025). Empirical studies highlight that seaweed expansion can align economic development with environmental benefits, including nutrient uptake, ecosystem service provision, and reduced pressure on capture fisheries, thereby contributing to broader sustainability goals (Mantri et al., 2022).

At the same time, rapid expansion of seaweed aquaculture introduces significant environmental, climatic, and governance-related risks. Reported challenges include localized ecological disturbances, nutrient enrichment in semi-enclosed waters, and socio-political conflicts arising from weak or fragmented regulatory frameworks (Chaigneau et al., 2024; Jiang, 2025; Obanor, 2025). These risks are often cumulative and multi-hazard in nature, underscoring the need for spatial planning approaches that move beyond narrow site suitability criteria and explicitly address risk.

Despite increasing recognition of risk, the literature reveals persistent limitations in how risk is conceptualized and operationalized in spatial planning for seaweed aquaculture. Risk is frequently framed through isolated dimensions such as environmental hazards or regulatory constraints rather than through integrated frameworks that capture interactions among hazards, exposure, vulnerability, and adaptive capacity. Although recent studies apply multi-hazard exposure mapping and scenario-based analyses to explore compound risks under climate change, such approaches remain unevenly adopted (Heo et al., 2023; Morris et al., 2025).

Most planning studies continue to rely on conventional site suitability approaches based on static environmental datasets and generalized thresholds. While these methods are transparent and operationally convenient, they tend to oversimplify complex ecological dynamics and underestimate localized or temporal risks (Ghosh et al., 2024; Rimmer et al., 2021). Indicator selection is strongly biased toward biophysical variables, whereas socio-economic vulnerability, institutional capacity, and adaptive responses are weakly integrated or absent. Limited stakeholder engagement further constrains the legitimacy and practical relevance of planning outputs, often resulting in spatial conflicts and missed opportunities for inclusive development (Rimmer et al., 2021; Taji et al., 2022).

Climate change adds an additional layer of complexity to spatial planning for seaweed aquaculture. Rising sea surface temperatures, increased variability, and more frequent extreme events influence growth rates, species distributions, and infrastructure stability, potentially shifting suitable farming zones over time (Mengual et al., 2021). Storms and marine heatwaves can damage cultivation systems and exacerbate risks associated with sea-level rise and altered salinity regimes (Wåhlström et al., 2022).

Marine Spatial Planning (MSP) and Integrated Coastal Zone Management (ICZM) are widely promoted as governance frameworks capable of addressing these challenges. However, evidence indicates uneven integration of aquaculture planning outputs into policy and permitting processes. While climate-smart MSP concepts are gaining traction, adaptation strategies for aquaculture are often weakly connected to existing regulatory instruments, limiting their effectiveness in reducing conflict and enhancing resilience (Cabana et al., 2023; Santos et al., 2024).

In response to these gaps, this systematic literature review (SLR) synthesizes and critically evaluates the state of knowledge on risk-based spatial planning for seaweed aquaculture. The review pursues three objectives: (i) to synthesize methods used to incorporate risk into spatial planning and site selection; (ii) to examine indicators representing hazard, exposure, vulnerability, and adaptive capacity; and (iii) to review decision-support tools informing planning, zoning, and governance. The scope covers spatial planning instruments relevant to seaweed and macroalgae aquaculture, including GIS-based analysis, MCDA, scenario and probabilistic modelling, DSS, and governance-oriented studies.

In this review, risk-based spatial planning refers to the explicit integration of hazards, exposure, vulnerability, and adaptive capacity into spatial allocation and zoning decisions for seaweed aquaculture, while decision support denotes analytical tools that translate data and models into spatial recommendations with transparent treatment of assumptions and uncertainty. Guided by this framing, the review addresses four research questions concerning risk conceptualization, methodological practice, indicator use, and policy integration. The article is structured as follows: Section 2 outlines the review methodology, Section 3 presents the theoretical background, Section 4 synthesizes the findings, Section 5 discusses implications and research gaps, and Section 6 concludes with directions for future research.

LITERATUR REVIEW

METHODOLOGY

This systematic literature review (SLR) was designed and conducted following established best practices for evidence synthesis in marine spatial planning (MSP) and aquaculture research. The methodological approach emphasizes transparency, reproducibility, and comprehensive coverage, in line with internationally recognized systematic review standards.

Search Strategy

The literature search was designed in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, which provide a structured framework for identifying, screening, and synthesizing relevant studies (Page et al., 2021). Multiple bibliographic databases were consulted to ensure broad and multidisciplinary coverage of research on risk-based spatial planning for seaweed aquaculture. The core database was Scopus, which indexes a wide range of peer-reviewed journals in marine science, spatial planning, environmental management, and sustainability (Tokamani, 2025). Google Scholar was used selectively to capture relevant grey literature, particularly policy-oriented reports and planning documents related to MSP and aquaculture governance.

Search strings combined keywords related to risk, spatial planning, and seaweed aquaculture. Core terms included variations of *risk-based* or *risk-informed*, *spatial planning* or *marine spatial planning (MSP)*, *seaweed* or *macroalgae aquaculture*, and methodological descriptors such as *GIS*, *remote sensing*, *multi-criteria decision analysis (MCDA/MCDM)*, *decision support systems (DSS)*, *probabilistic modelling*, and *scenario analysis*. Boolean operators (AND, OR, NOT) were systematically applied to refine search results and improve precision, following established guidance for database querying (Tokamani, 2025). A generalized Boolean structure was: *(aquaculture AND (risk OR uncertainty) AND (marine spatial planning OR zoning))*.

To maintain relevance and analytical focus, predefined limits were applied, including publication year range, language, document type, and subject area. Only English-language, peer-reviewed journal articles and high-quality review papers were included. Subject areas were restricted to environmental sciences, marine and coastal studies, geography, sustainability science, and closely related disciplines. In addition, backward and forward snowballing was applied to key review and seminal articles to identify influential studies not captured through keyword-based searches.

Screening and Eligibility Criteria

Study screening and selection followed a multi-stage process consistent with PRISMA recommendations (Page et al., 2021). After compiling records from all sources, duplicates were removed. Remaining records were screened sequentially at the title, abstract, and full-text levels.

Inclusion and exclusion criteria were defined a priori to ensure relevance and methodological rigor. Studies were included if they: (i) addressed spatial planning, zoning, or site selection for seaweed or macroalgae aquaculture; (ii) incorporated at least one element of risk, uncertainty, or risk-informed decision-making (e.g., hazard, exposure, vulnerability, or scenario analysis); and (iii) provided sufficient methodological detail, indicators, or outputs to enable data extraction and comparative synthesis (Page et al., 2021; Yang et al., 2025). Studies focusing on marine or coastal ecosystems and addressing environmental, social, or economic dimensions of spatial viability were also considered eligible (Ebrahimi et al., 2024).

Studies were excluded if they: (i) focused exclusively on non-spatial aspects such as physiology or laboratory experiments without spatial implications; (ii) addressed aquaculture systems other than seaweed or macroalgae without clear methodological transferability; or (iii) consisted of opinion pieces or conceptual commentaries lacking explicit methods or empirical findings (Ebrahimi et al., 2024; Zhao et al., 2025).

The selection process involved title and abstract screening followed by full-text eligibility assessment. Where feasible, screening decisions were conducted by two independent reviewers, with disagreements resolved through discussion and consensus, consistent with best practices in systematic review quality assurance (Page et al., 2021; J. Zhang et al., 2025). The overall process is summarized in Figure 1, which presents the PRISMA flow diagram of study identification, screening, and inclusion.

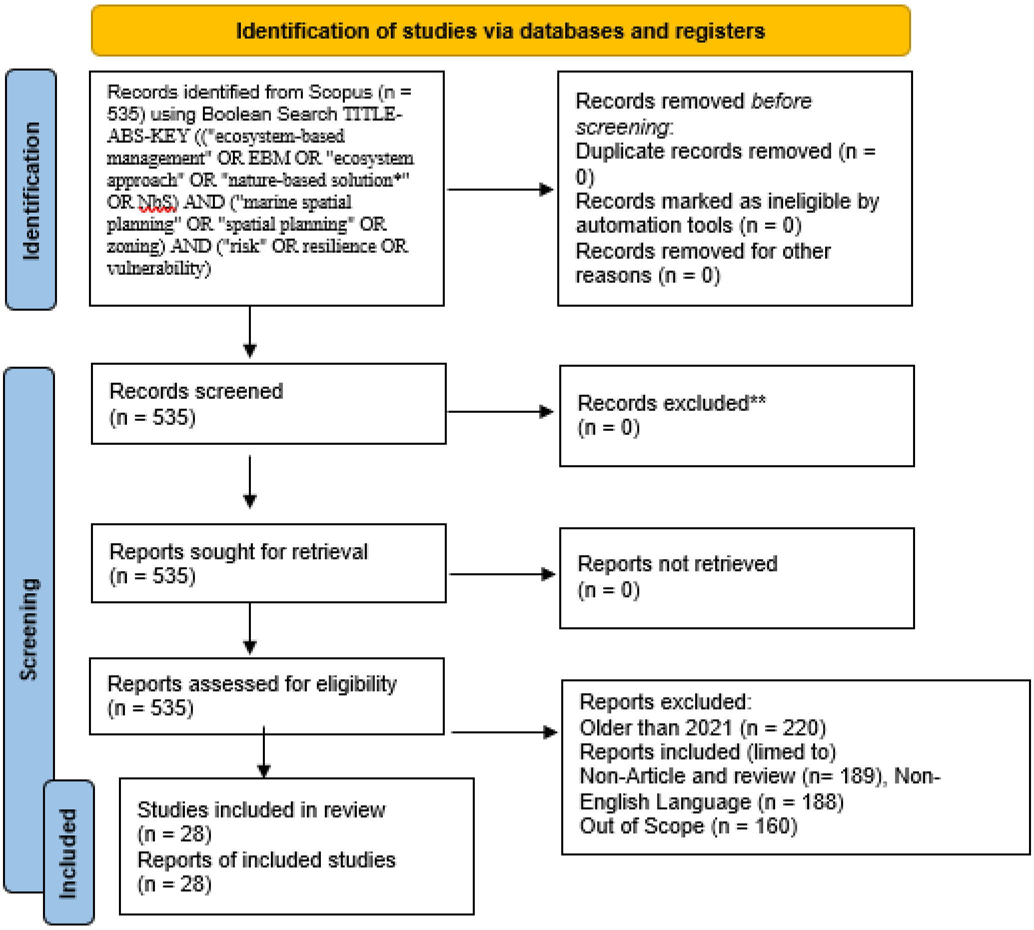

Figure 1. The PRISMA flow diagram detailing the screening and selection process of the literature.

Data Extraction, Quality Appraisal, And Synthesis

A structured data extraction form was developed to ensure consistent capture of information across included studies. Extracted data comprised bibliographic details, geographic context, spatial and temporal scale, and stated planning objectives, with particular attention to how risk was defined and operationalized and which conceptual frameworks were applied.

Methodological characteristics were systematically recorded, including analytical approach (e.g., GIS-based analysis, MCDA/MCDM, probabilistic or scenario-based modelling), input datasets, indicator selection, weighting or parameterization techniques, and any reported validation or ground-truthing procedures. Indicators were classified according to hazard, exposure, vulnerability, and adaptive-capacity dimensions, alongside their data sources and spatial resolution. Information on decision-support outputs such as risk maps, zoning recommendations, site rankings, or DSS tools and any reported stakeholder engagement or policy application was also documented.

Quality appraisal focused on criteria commonly applied in SLRs of spatial planning and risk assessment, including transparency of assumptions, reproducibility, data adequacy, treatment of uncertainty, and the presence of validation or sensitivity analysis (Dasari et al., 2025; Sun et al., 2025). Where possible, appraisal was conducted independently by multiple reviewers, with discrepancies resolved through discussion to enhance robustness (J. Zhang et al., 2025).

Given the heterogeneity of methods, indicators, and outputs, synthesis combined narrative synthesis with structured comparative analysis. Narrative synthesis integrated qualitative insights and contextual findings, while typologies of methods and decision-support approaches enabled systematic comparison across studies (Wiedermann et al., 2025). Thematic mapping was used to identify patterns, biases, and gaps in risk indicators and reporting practices. Where comparable outcomes were available, insights from meta-analytic or semi-quantitative synthesis were noted, following recent approaches in spatial planning and environmental risk assessment (Nuño et al., 2024; Tahir et al., 2025; Xiang et al., 2024). Through this multi-layered synthesis, the review provides a rigorous assessment of current practice while identifying methodological limitations and priorities for future research

RESEARCH RESULTS

This review synthesizes evidence on how risk is conceptualized, operationalized, and translated into decision support in spatial planning for seaweed aquaculture. Across the reviewed literature, risk-based planning is increasingly recognized but remains uneven in integration, validation, and governance alignment, limiting its fitness for purpose under climate change and intensifying spatial competition.

Risk Conceptualization in Spatial Planning

Risk conceptualization is fragmented and often implicit. As summarized in Table 1 and Figure 3, most studies embed risk within ecological sensitivity, cumulative pressure, or exposure mapping rather than applying an integrated hazard–exposure–vulnerability–adaptive capacity framework. MSP-oriented approaches commonly infer risk from spatial overlap between ecological importance and human-use intensity, producing static constraint maps (Borja et al., 2022; Liu et al., 2022). Event-driven applications adopt hazard–exposure logic for climate-related stressors such as pelagic *Sargassum* inundation, while vulnerability remains weakly operationalized (Degla et al., 2024). Governance and interaction framings appear mainly in multi-use and co-location studies, where risk is treated as uncertainty and trade-offs rather than a quantified metric (O'Shea et al., 2024; Gonzalez & Murayama, 2024). Socio-economic and biosecurity risks remain marginal but emerging (Gibson et al., 2025; Spillias et al., 2022). Overall, risk is more often inferred than tested, constraining comparability and policy translation.

Figure 3. Typologies of risk conceptualization in the reviewed literature

No.	Study / tool (year)	Primary users (as stated / implied)	Stakeholder engagement (as stated)	Policy linkage (MSP/ICZM/permitting/management)	Implementation / uptake evidence	Evaluation metrics & outcomes (as stated)	Ref. (Author, year)
1	A site selection decision framework for effective kelp restoration (2025)	Coastal managers / restoration planners (implied)	NR	Management/restoration planning; site prioritization for kelp recovery	NR	Spatially explicit site ranking/classification using kelp metrics + tree model (restoration decision support)	Giraldo-Ospina et al., 2025
2	Managing offshore multi-use settings: conceptual mapping to reduce uncertainty of co-locating seaweed aquaculture and wind farms (2024)	Offshore planners, developers, regulators (implied)	NR (conceptual mapping approach suggests structured/participatory input, but not explicit in snippet)	Offshore spatial planning for multi-use (aquaculture–wind co-location)	NR	A mapping approach intended to reduce/structure uncertainty and support sustainability-guided decisions	O'Shea et al., 2024
3	Towards a data-driven marine spatial plan for the maritime area of Bangladesh (2023)	National MSP planners / government agencies (implied)	NR	Direct MSP enabling output (data foundation for MSP development)	Provides a data-driven baseline to support MSP development (uptake not quantified)	Production of an integrated spatial evidence base (specific performance metrics NR)	Sarker & Failler, (2023)
4	Checklist and reporting framework for GIS-based Multi-Criteria Evaluation (MCE) models for aquaculture site selection (2025)	Researchers + practitioners applying GIS–MCE siting (stated)	NR	Improves transparency/reproducibility for siting studies used in planning/permitting contexts	Intended to improve documentation and communication (no uptake statistics in snippet)	A structured reporting/checklist to standardize criteria, weighting, validation, and uncertainty reporting	Silverthorn et al., 2025
5	Identification and delineation of mariculture area based on Maxent and Marxan: Jiangsu, China (2025)	Regional planners / mariculture zoning authorities (implied)	NR	Spatial delineation for mariculture planning (zoning/area selection)	Produces delineated mariculture areas (policy uptake NR)	Integrated outputs: suitability (Maxent) + optimization/selection (Marxan); evaluation details NR	Chen et al., 2025

6	Selection of mariculture sites based on ecological zoning — Nantong, China (2024)	Local coastal planners / regulators (implied)	NR	Explicit linkage to Ecosystem Approach to Aquaculture (EAA) siting and ecological zoning	Provides siting recommendations aligned to zoning (uptake NR)	Spatial siting based on ecological zoning integration (validation/uncertainty NR)	Chen et al., 2024
7	Ecosystem health assessment: PSR analysis combining AHP and entropy weighting for Sansha Bay, China (2024)	Bay managers / aquaculture regulators (implied)	NR	Bay-scale management and zoning prioritization through ecosystem-health / ecological-security diagnostics	Produces management-relevant indices/maps (uptake NR)	Composite PSR indices with hybrid weighting (AHP + entropy); zone classification outputs (details NR)	Li et al., 2024
8	Applying the disaster risk assessment framework to Sargassum inundation in Barbados (2024)	Disaster risk managers; coastal planners (implied)	NR	DRR-aligned coastal risk planning; transferable logic for aquaculture risk zoning	Demonstrates framework application and identifies data needs (uptake NR)	Hazard and exposure mapping within DRR framing; vulnerability data gaps noted (per snippet)	Degla et al., 2024
9	Marine spatial planning and best siting practices to achieve an ecosystem approach to aquaculture in the United States (2025)	MSP practitioners, agencies, permitters (implied)	NR	Direct guidance for embedding EAA into MSP/siting practice	Guidance paper (implementation evidence NR)	Synthesized best siting practices and MSP considerations (evaluation metrics NR)	Morris et al., 2025
10	Scenario analysis can guide aquaculture planning to meet sustainable future production goals (2021)	Strategic planners / policy analysts (implied)	NR	Strategic planning; exploring trade-offs under alternative futures	NR	Scenario-based planning logic to compare futures and guide decisions (quantitative uncertainty NR)	Couture et al., (2021)
11	An Environmental Niche Exploration Tool for Kelp Forest Management (2025)	Kelp managers / conservation practitioners (implied)	NR	Management support tool; can inform MPA/site prioritization (policy linkage NR)	Tool delivered; adoption evidence NR	Provides an exploration tool for kelp environmental niche conditions (performance metrics NR)	Eger et al., 2025
12	Using predictive models to identify kelp refuges in marine protected areas for management prioritization (2025)	MPA managers / restoration	NR	MPA management prioritization (site-based actions and restoration planning)	Demonstrates application with long-term dataset (policy uptake NR)	Predictive identification of refuge areas to target management/restoration (validation details NR)	Young et al., 2025

		planners (stated in title)					
13	Ocean sprawl: The global footprint of shellfish and algae aquaculture… implications for production, environmental impact, and biosecurity (2024)	Global/regional planners; regulators; industry (implied)	NR	Evidence base for spatial planning and regulation (footprint, impacts, biosecurity)	Delivers global footprint synthesis; direct uptake NR	Comparative synthesis of spatial extent/footprint and associated implications (metrics NR in snippet)	Harvey et al., 2024

Decision Support and Policy Integration

Decision-support outputs maps, rankings, indices, and frameworks—are more developed than their documented uptake in MSP, ICZM, or permitting processes (Table 4; Figure 6). Most tools prioritize analytical outputs over evaluated outcomes, with limited evidence of implementation, stakeholder engagement, or post-implementation learning. Scale mismatches between analytical outputs and policy instruments further constrain adoption. Consequently, decision support remains largely output-oriented rather than outcome-oriented.

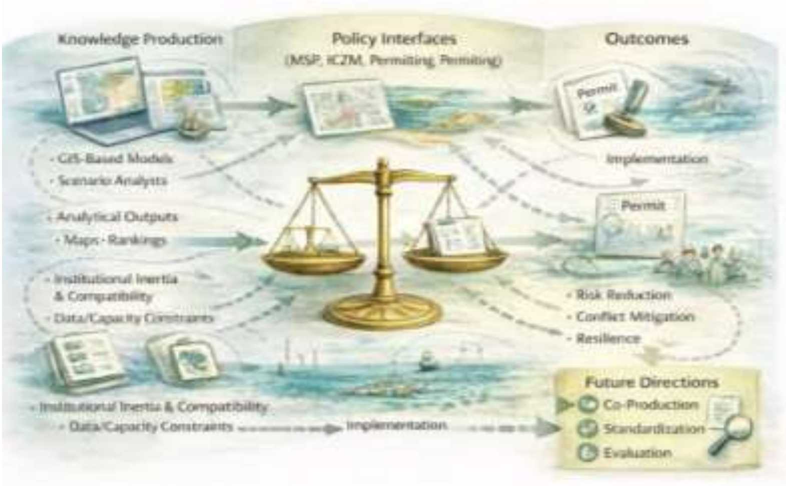

Figure 6. From Decision-Support Outputs To Policy And Practice.

No.	Study / tool (year)	Primary users (as stated / implied)	Stakeholder engagement (as stated)	Policy linkage (MSP/ICZM/permitting/management)	Implementation / uptake evidence	Evaluation metrics & outcomes (as stated)	Ref. (Author, year)
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Cross-Cutting Implications

Across themes, three implications emerge: (i) risk-based planning remains hazard-centric and fragmented, (ii) uncertainty and validation gaps limit confidence in spatial recommendations, and (iii) governance integration is the primary bottleneck for adoption. Advancing risk-based spatial planning for seaweed aquaculture requires better alignment between risk framing, indicator balance, uncertainty-aware methods, and policy-oriented decision support.

DISCUSSION

Many studies still conflate site suitability with risk, so "risk" outputs are often derived from static environmental thresholds or composite indices rather than explicit likelihood–impact logic (Tables 1–2). As a result, zoning may fail to anticipate extreme events and economic losses, consistent with broader MSP and ecosystem-based planning concerns (Farmer et al., 2022).

Although the hazard–exposure–vulnerability–adaptive capacity framework is frequently referenced, it is rarely implemented in full (Table 3; Figure 5): hazard indicators dominate while exposure and especially social–institutional vulnerability and adaptive capacity remain marginal, limiting legitimacy, targeting, and understanding of differential impacts and recovery potential. Methodologically, GIS overlay and MCDA dominate because they are accessible and transparent (Table 2; Figure 4), but their outputs are sensitive to subjective weighting and scale mismatches, and only a minority of studies adopt probabilistic or scenario-based approaches that represent uncertainty more explicitly (Maru et al., 2025; Sameer et al., 2021).

A further constraint is weak validation: few studies evaluate planning outcomes using empirical evidence such as production failures, infrastructure damage, or spatial conflicts (Tables 2 and 4), leaving claims about superiority over suitability-only approaches largely suggestive despite positive applied indications (Li et al., 2024). Ultimately, uptake depends on alignment with MSP, ICZM, and permitting processes; tools not co-designed with regulators and stakeholders often remain academic products (Galdames et al., 2025), so progress requires standardized reporting, integration of social data, explicit uncertainty analysis, and co-productive DSS design to deliver scientifically robust and policy-relevant planning under climate change and intensifying spatial competition.

CONCLUSION AND RECOMMENDATION

This systematic literature review shows that, despite growing recognition of risk in seaweed aquaculture planning, current spatial planning practices remain only partially risk-informed. Many studies implicitly equate environmental suitability with low risk, relying on static biophysical indicators and composite indices that inadequately represent the probability, magnitude, and distribution of adverse outcomes. As a result, zoning and site-selection decisions may fail to anticipate extreme events, socio-economic losses, or governance-related conflicts.

Across the reviewed literature, the hazard–exposure–vulnerability–adaptive capacity framework is rarely applied in an integrated manner. Hazard characterization dominates, while exposure dynamics, social and institutional vulnerability, and adaptive capacity are weakly operationalized or omitted. Methodologically, GIS overlay and MCDA approaches prevail due to their usability and transparency, yet they remain sensitive to subjective weighting, scale mismatches, and limited treatment of uncertainty. Probabilistic and scenario-based methods, together with outcome-based validation using empirical evidence, remain the exception rather than the norm.

ADVANCED RESEARCH

Decision-support tools for seaweed aquaculture planning often prioritize analytical outputs over implementation outcomes, limiting policy relevance and real-world impact. Weak alignment with MSP, ICZM, and permitting processes, combined with limited stakeholder engagement, further constrains adoption. Advancing risk-based spatial planning therefore requires standardized reporting, explicit uncertainty treatment and validation, stronger integration of socio-economic and governance data, and co-designed decision-support systems with policymakers and coastal communities.

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