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Authors	Avinash Boodoo, Tatsuya Wakeyama, Jeffrey Scott Cross
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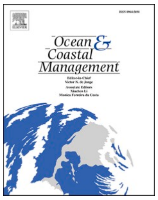

Review

Wave farms for coastal protection: A systematic review of effectiveness, methodologies, and future directions

Avinash Boodoo *, Tatsuya Wakeyama, Jeffrey S. Cross

Department of Transdisciplinary Science and Engineering, School of Environment and Society, Institute of Science Tokyo, Meguro, Tokyo, 152-8550, Japan

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ABSTRACT

The dual use of wave farms for coastal protection and renewable energy has emerged as a potential solution to reduce the high Levelized Cost of Electricity (LCoE) of wave energy. This dual functionality offers effective coastal protection that is adaptable to rising sea levels, while simultaneously generating carbon-free energy. This systematic review explores the effectiveness of wave farms in attenuating wave energy and mitigating coastal erosion, with a focus on the methodologies employed in previous studies, key findings, and challenges. Results indicate that wave farms can reduce wave heights by 10 %–50 % and erosion during short term storm events by 15 %–45 %, depending on factors such as location and wave conditions, Wave Energy Converter (WEC) array layout, device spacing and distance from the shore. Nearshore deployments have achieved the highest levels of wave attenuation, particularly during high-energy storm events. Optimized array configurations such as linear, multi-row or closely spaced layouts further enhance coastal protection by reducing wave energy and promoting sediment deposition. However, the review also highlights critical gaps including the need for field-based validation; comprehensive long-term studies on the impacts of wave farms on coastal morphodynamics, and the development of multi-objective optimization frameworks that consider both energy generation and coastal protection in the design of wave farms.

1. Introduction

Wave energy represents one of the most promising, albeit less developed, renewable energy sources with an estimated global wave resource in the range of 1–10 TW (Astariz and Iglesias, 2015; Guo and Ringwood, 2021) and wave power of approximately 32,000 TWh annually (Arguilé-Pérez et al., 2023; Bertram et al., 2020) which surpassed the total global electricity consumption recorded in 2018 of 22, 315 TWh (Guo and Ringwood, 2021). As such, wave energy emerges as a potential solution to address the growing energy demands while simultaneously contributing to the reduction of carbon emissions through carbon free energy generation (Astariz and Iglesias, 2015; Guo and Ringwood, 2021; Arguilé-Pérez et al., 2023; Bertram et al., 2020; Mustapa et al., 2017; Ozkan et al., 2020; Jin and Greaves, 2021).

Despite the numerous advantages of wave energy including the highest energy density among all the renewables; high availability reaching up to 90 %; high predictability and minimal negative impacts on the environment (Fadaeenejad et al., 2014; Guo and Ringwood, 2021; López et al., 2013), the development and implementation of Wave Energy Converters (WECs) and wave farms face numerous technical and non-technical challenges (Guo and Ringwood, 2021). The most significant among these challenges, however, is the high capital costs and high Levelized Cost of Electricity (LCoE) which make wave energy difficult to compete with traditional renewable energy sources and fossil fuels (Astariz and Iglesias, 2015; S. Foteinis and Tsoutsos, 2017; Guo and Ringwood, 2021; Wimalaratna et al., 2022; Mustapa et al., 2017; Contestabile et al., 2017). Fig. 1 illustrates this substantial disparity in the LCoE between wave energy and traditional fuel sources, with nearshore wave energy costs exceeding 100 €/MWh and offshore wave energy costs surpassing 400 €/MWh. This high LCoE is primarily due to technological challenges such as low efficiency and survivability, limited commercial deployment, high installation and maintenance costs, and the lack of economies of scale compared to technologies such as wind and solar (Guo and Ringwood, 2021).

Although subsidies and technological investments can improve the economic viability of WECs and wave farms (Astariz and Iglesias, 2015; Guo and Ringwood, 2021; S. Foteinis and Tsoutsos, 2017; Jin and Greaves, 2021), it has been proposed that the sustainability,

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* Corresponding author.
E-mail address: boodoo.a.aa@m.titech.ac.jp (A. Boodoo).

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cost-effectiveness and the harnessing of wave energy can be drastically improved by integrating WECs with a secondary function such as offshore aquaculture, desalination, tourism (Spyros Foteinis, 2022; S. Foteinis and Tsoutsos, 2017) and most notably, coastal protection (Abanades et al., 2018; Bergillos et al., 2018; Rodriguez-Delgado, Bergillos, and Iglesias, 2019a).

Previous studies (Abanades et al., 2018; Abanades, Greaves, and Iglesias, 2014a, 2014b, 2015a; Bergillos et al., 2018; Mendoza et al., 2014; Rodriguez-Delgado and Bergillos, 2021; Rodriguez-Delgado, Bergillos, and Iglesias, 2019a, 2019c; Venugopal et al., 2017) have demonstrated the effectiveness of wave farms in reducing nearshore wave energy and mitigating coastal hazards such as coastal erosion and flooding. The use of wave farms for both coastal protection and renewable energy generation presents an innovative strategy to offset the high costs associated with harnessing wave energy by eliminating the need for additional coastal protection structures. This dual functionality can provide effective coastal protection adaptable to rising sea levels while simultaneously generating carbon-free energy. (Abanades et al., 2018; Abanades, Greaves, and Iglesias, 2014a; S. Foteinis and Tsoutsos, 2017; Rodriguez-Delgado, Bergillos, and Iglesias, 2019a; Manasseh et al., 2017).

Although wave farms have been widely studied for their renewable energy production, a critical gap persists regarding their economic assessment. Specifically, while the literature identifies numerous secondary benefits including erosion mitigation, enhancements to marine fisheries and aquaculture and increased coastal tourism, the economic impact of these additional benefits on the Levelized Cost of Electricity (LCoE) remains unexplored. To date, no published study has quantitatively assessed how integrating coastal protection into wave farm design could reduce overall project costs or LCoE. Addressing this knowledge gap through comprehensive techno-economic analyses is crucial for accurately determining the feasibility and broader value of multi-purpose wave farms.

Existing reviews on WECs (Table 1) have extensively analyzed various aspects, including the classification and global potential of wave energy technologies (López et al., 2013), advancements in device design and hybrid applications (Clemente et al., 2021), and the economic feasibility and barriers to commercialization (Astariz and Iglesias, 2015; Wimalaratna et al., 2022). However, these reviews focus predominantly on the energy generation potential and economic aspects, with limited attention given to the coastal protection benefits of wave farms. This review provides a novel contribution by offering a quantitative comparison of the effectiveness of wave farms in terms of wave attenuation and erosion mitigation, synthesizing results from numerical modelling studies. As such, the aim of this review is to use a systematic review approach to synthesize findings from the previous studies to provide an understanding of current methodologies; highlight key findings and results; draw connections between various findings and provide valuable insights and recommendations for future research and practical applications regarding this dual functionality of wave farms.

Table 1 summarizes the focus, contributions, and limitations of these earlier reviews, and highlights how the present study addresses critical gaps, particularly through a quantitative synthesis of wave farms' coastal protection benefits, which has not been done in any prior review.

This review is structured as follows: The systematic review methodology is described in Section 2. Section 3 introduces the concept of wave farms and morphodynamics. This is followed by a description of the numerical modelling approaches used in assessing the coastal protection benefits of wave farms in Section 4. Section 5 provides an analysis of the coastal protection provided by wave farms in terms of

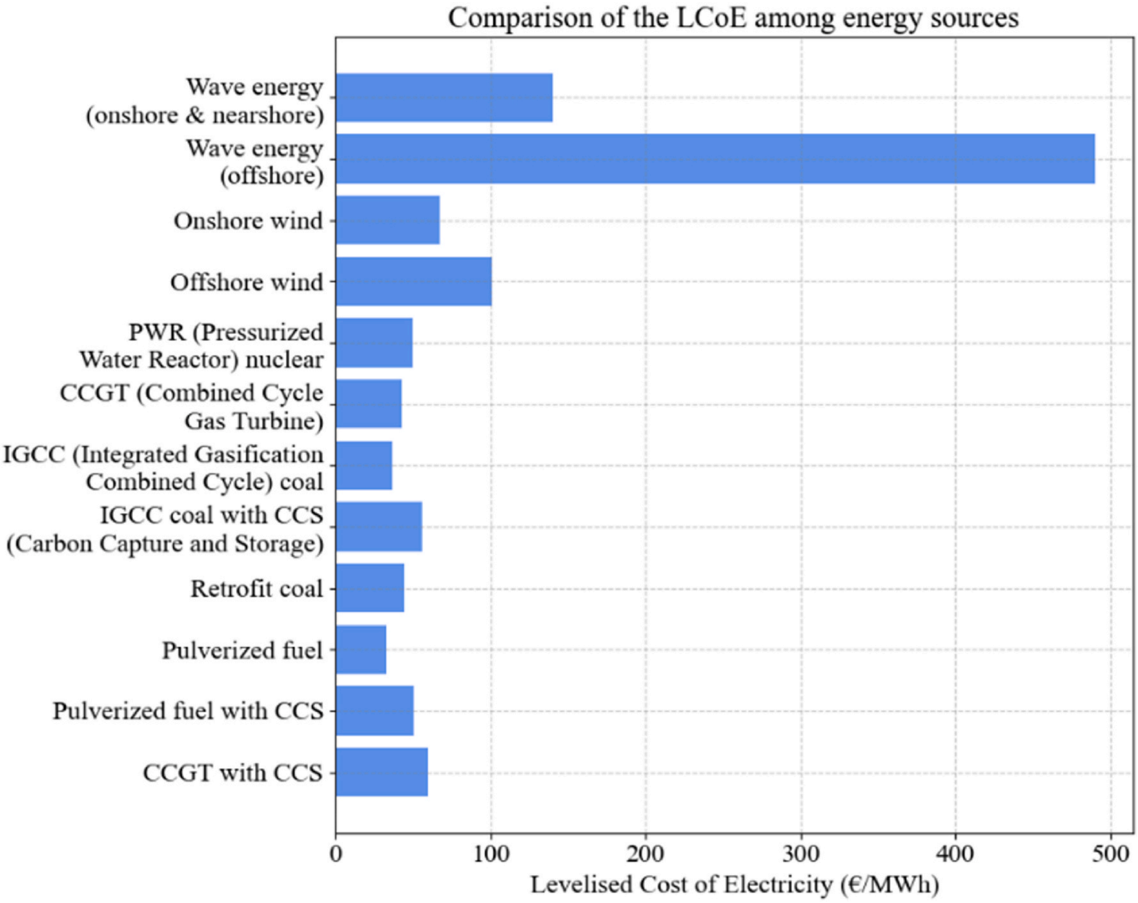

Fig. 1. Comparison of the LCoE among various fuel sources. Data adapted from Astariz and Iglesias, 2015).

Table 1
Review of key literature on wave energy: Focus areas, contributions, and gaps addressed in this study.

Reference	Focus	Key Contributions	Limitations of Prior Studies and Contribution of This Review
López et al. (2013)	Wave energy technology and global resources	Overview of global wave energy potential, WEC classifications, and technical status	Does not address coastal protection. This review is the first to systematically assess how wave farms affect coastal protection.
Fadaeenejad et al. (2014)	Wave energy in small islands	Evaluates wave energy feasibility in island contexts, benefits, and environmental impacts	Does not consider wave farms' role in coastal protection. This review uniquely synthesizes how wave farms reduce erosion and wave energy.
Astariz and Iglesias (2015)	Economic evaluation of wave energy	Compares LCoE of wave energy with other sources	Focuses only on energy economics. This review quantifies coastal protection benefits of wave farms, which had not been done before.
Ozkan et al. (2020)	Impacts of wave farms on coastal morphodynamics	Reviews morphodynamic impacts such as sediment transport	Does not quantify protective benefits. This is the first review to synthesize wave farms' effectiveness for protection.
Clemente et al. (2021)	Hybrid wave systems and infrastructure sharing	Discusses synergies between WECs and other uses	Does not examine coastal protection. This review systematically evaluates how wave farms contribute to shoreline protection.
Guo and Ringwood (2021)	Wave energy development and market perspectives	Discusses technical challenges and commercialization	Lacks focus on coastal protection. This review quantifies protective impacts of wave farms based on model data.
Jin and Greaves (2021)	Wave energy in the UK	Summarizes national progress and decarbonization plans	Regional focus, no discussion of coastal protection. This review is the first to assess protection benefits across multiple case studies.
Wimalaratna et al. (2022)	Wave energy in Australia	Assesses wave resource, key developers, and barriers	Country-specific and energy-focused. This review uniquely synthesizes wave farms' effectiveness for coastal protection.
Foteinis (2022)	WECs in low-energy seas	Reviews secondary benefits and sustainability issues	Mentions protection potential but does not analyze outcomes. This review is the first to aggregate quantitative results on protection effectiveness.

wave attenuation and erosion mitigation based on previous studies. Section 6 highlights notable challenges in current methodologies. Future research directions are presented in section 7. Finally, Section 8 will conclude by summarising key findings and implications for research.

2. Methodology

This systematic review followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency and rigor. The aim was to identify peer-reviewed studies that quantitatively assess the effectiveness of wave farms (arrays of WECs) for coastal protection, specifically through metrics such as wave attenuation, sediment transport, and erosion mitigation. This PRIMA methodology is summarized in Fig. 2.

2.1. Search strategy

A comprehensive literature search was conducted in Web of Science, Science Direct and Google Scholar using the following keyword combinations: “wave energy converters” OR “wave farms” AND

> “coastal protection” OR “erosion” OR “wave attenuation” OR “morphodynamics” The search was conducted in August 2024 and limited to peer-reviewed journal articles published in English between 2014 and 2024.

2.2. Screening and selection process

The selection process followed PRISMA guidelines and consisted of three stages: (i) initial screening of titles and abstracts, (ii) full-text review of potentially relevant articles, (iii) application of inclusion and exclusion criteria.

The screening and selection process is summarized in the updated PRISMA flow diagram (Fig. 2). Additionally, to increase transparency and reproducibility, we provide a list of included studies and reasons for exclusion in Appendix A (Supplementary Material). Studies excluded as "not relevant" primarily failed to evaluate any coastal protection outcomes, instead focusing solely on energy generation, WEC design, or offshore infrastructure.

2.3. Inclusion and exclusion criteria

To ensure relevance to the objectives of this review, studies were included only if they met all of the following criteria:

i. Investigated wave farms (i.e., arrays of WECs, not single devices)
ii. Quantitatively evaluated coastal protection outcomes, such as wave attenuation, sediment transport, or shoreline change

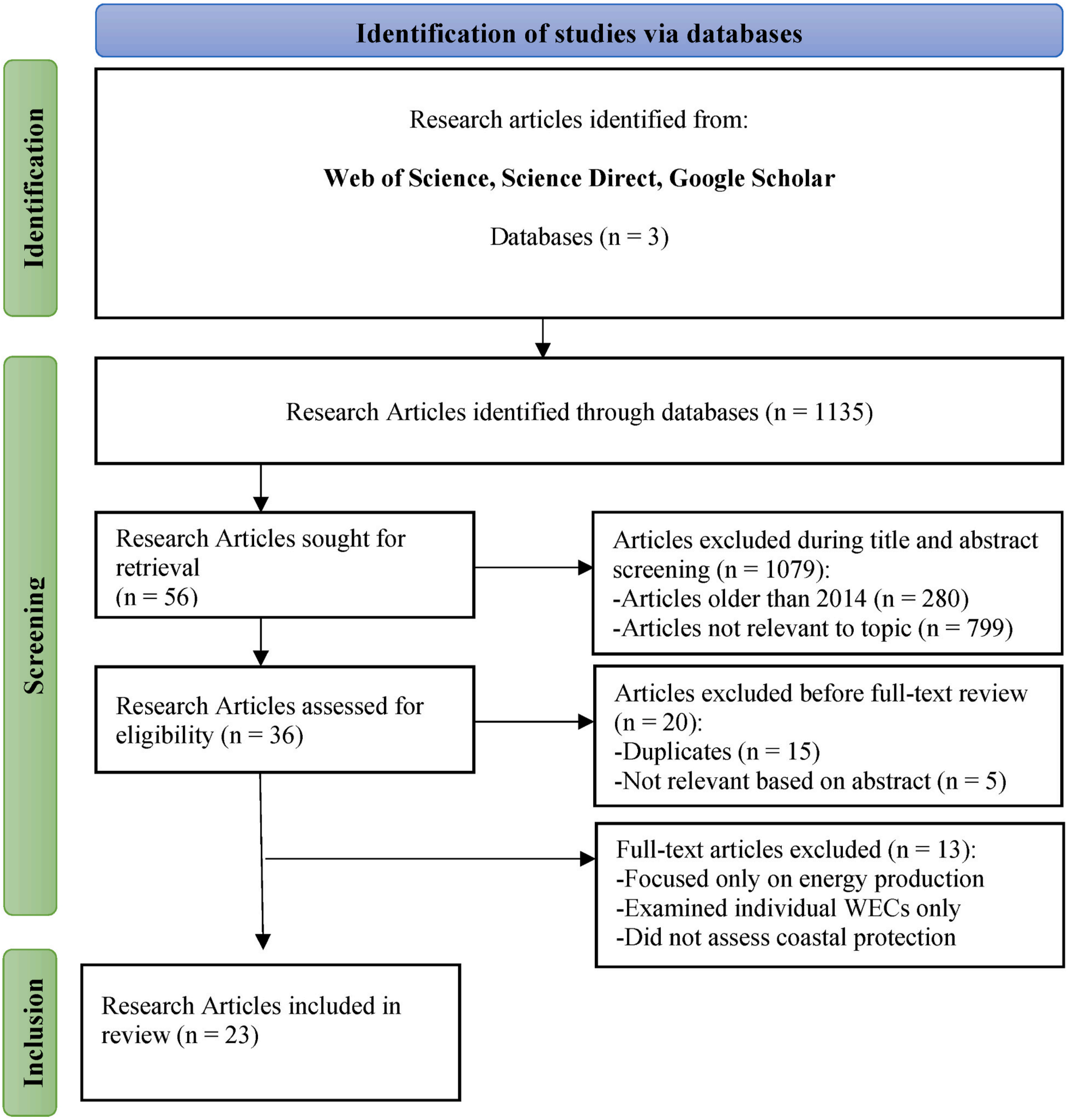

Fig. 2. Flowchart for systematic review methodology and article selection.

iii. Employed numerical modelling, physical modelling, or field studies
iv. Published in peer-reviewed journals and written in English

The following exclusion criteria were applied:

i. Studies focusing solely on energy generation performance or WEC efficiency
ii. Analyses of individual WECs without array-scale deployment
iii. Papers with no assessment of coastal protection outcomes
iv. Conceptual papers, opinion pieces, or reviews
v. Conference proceedings and non-peer-reviewed publications

This process yielded a total of 23 studies for full review and synthesis. While a large number of articles were initially retrieved, most were excluded during the full-text screening stage due to their focus on individual WEC performance, energy production, or device design without any evaluation of coastal protection outcomes such as wave attenuation, shoreline response, or erosion mitigation. Since the objective of this review is to synthesize findings specific to the dual role of wave farms in both renewable energy generation and coastal protection, only studies that investigated array-scale WEC deployments and quantitatively assessed their impact on coastal processes were included.

Potential limitations of this review process include the likelihood of publication bias, given that studies reporting favourable coastal protection outcomes may be more commonly published. Additionally, the exclusion of non-English articles may have led to language bias. The focus on peer-reviewed literature may also have resulted in the omission of relevant grey literature or technical studies.

Data extraction was performed using a literature matrix to capture key information from each study, including study title, authors, and publication year; objectives and scope of the study; methodological approaches and models used; key findings related to coastal protection; and identified challenges and recommendations for future research. The extracted data were synthesized to provide a comprehensive overview of the existing literature and analyzed to identify common trends, gaps in the research as well as areas for future research.

3. Wave farms and morphodynamics

Although commercial-scale wave farms have yet to be fully realized, several pilot- and demonstration-scale projects have been deployed in recent decades, offering valuable insights into technical feasibility and coastal integration. For example, the WaveRoller device was deployed by AW-Energy off the coast of Portugal with an installed capacity of 350 kW (Onea and Rusu, 2016; Rusu and Onea, 2016). The conceptual design of these farms is based on deploying an array of nearshore WECs along coastal regions in formations that are strategically designed to optimize energy capture. These formations must take into account a variety of factors, such as incident wave characteristics including wave height; wave period and wave direction; coastal morphology and sediment transport processes, and the interactions between individual WECs within the array (Abanades, Greaves, and Iglesias, 2014a, 2014b; Ozkan et al., 2020).

Fig. 3 illustrates the interaction between wave farms and nearshore morphodynamic and sediment transport processes. Wave farms, when deployed nearshore, function similarly to nearshore detached breakwaters by dissipating incoming wave energy before it reaches the shoreline. This reduction in wave energy in the lee of the wave farm alters the local wave climate, leading to decreased wave-induced sediment resuspension and transport. As a result, there is enhanced sediment deposition in the sheltered zone behind the wave farm, promoting beach accretion and stabilization of the shoreline. The modification of longshore and cross-shore sediment transport pathways can help mitigate coastal erosion and flooding, thereby enhancing coastal resilience. In this way, wave farms offer the dual benefit of generating renewable energy while simultaneously acting as dynamic coastal protection structures.

Recent studies (Abanades et al., 2018; Abanades, Greaves, and Iglesias, 2014a, 2014b, 2015a; Bergillos et al., 2018; Rodriguez-Delgado, Bergillos, and Iglesias, 2019a, 2019c) have demonstrated the efficacy of wave farms in reducing nearshore wave energy, mitigating coastal erosion and flooding, as well as aligning with adaptations to Sea Level Rise (SLR). As a result, there is a growing body of literature focused on optimizing the layout of wave farms to maximise coastal protection. These studies typically employ a numerically modelling approach through the coupling of spectral wave models such as SWAN (Simulating WAves Nearshore) and morphodynamic models such as XBeach.

4. Numerical modelling approaches

4.1. Spectral wave modelling

The impact of WECs within wave farms on wave characteristics can be explored through numerical modelling approaches. Specifically, spectral wave models like SWAN has the capability to model the propagation of random, short-crested wind-generated waves along coastal areas, taking into account the transformation of waves due to shoaling, refraction, diffraction, and breaking (Booij et al., 1999). The majority of the studies described in this systematic review (Abanades et al., 2018; Abanades, Greaves, and Iglesias, 2014a, 2014b, 2015a, 2015b; Bergillos et al., 2018; Rodriguez-Delgado, Bergillos, and Iglesias, 2019a) have used SWAN as part of their methodology. SWAN can simulate various phenomena such as wave generation by wind; whitecapping; quadruplet and triad wave-wave interactions and dissipation due to bottom friction. Most notably for the wave farms, SWAN can also simulate wave transmission through and reflection against obstacles. The model solves the discrete spectral action balance equation (Equation (2)) using structured or unstructured grids.

$$\frac{\partial N}{\partial t}+\nabla_{\overrightarrow{x}}\cdot\left[\left(\overrightarrow{c_g}+\overrightarrow{u}\nabla\right)N\right]+\frac{\partial c_\sigma N}{\partial \sigma}+\frac{\partial c_\theta N}{\partial \theta}=\frac{S_{tot}}{\sigma} \tag{2}$$

The first term represents the temporal change in action density N

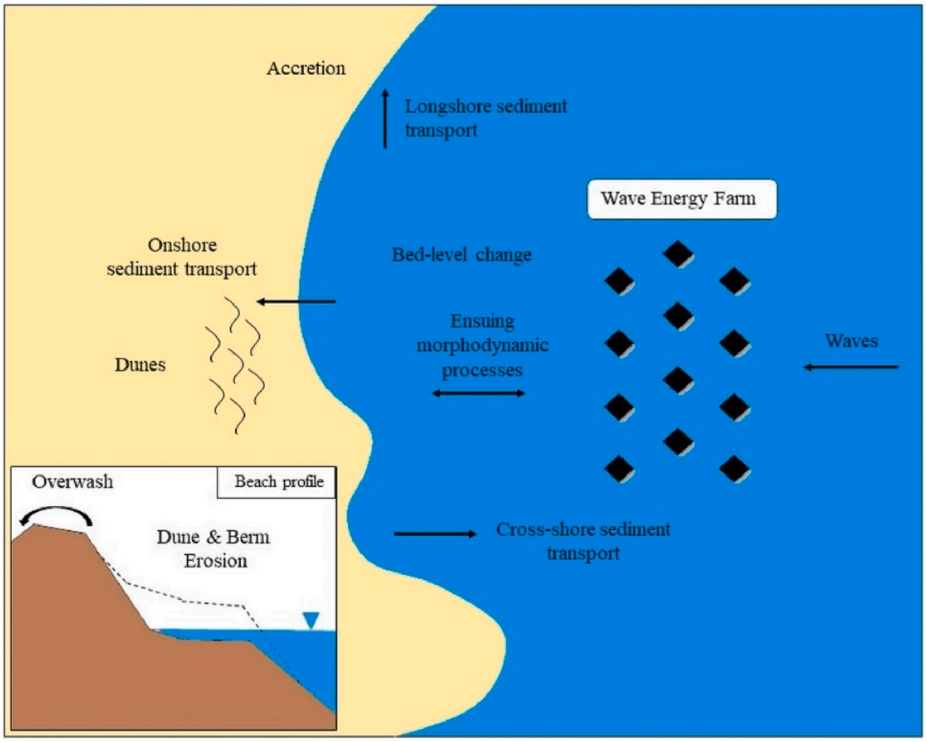

Fig. 3. The effect of wave farms on morphodynamic processes. Adapted from Ozkan et al. (2020).

with time, t, while the second term captures its spatial propagation due to wave group velocity $\overrightarrow{c_g}$ and currents $\overrightarrow{u}$. The third and fourth terms account for spectral shifting in frequency σ and direction θ, caused by depth variations and refraction. On the right-hand side, the source term S_{tot}, normalized by frequency, includes all energy inputs and losses—such as wind forcing, wave breaking, bottom friction, and nonlinear interactions. Further details on these formulations are available in the official SWAN documentation.

The use of SWAN for numerical modelling of wave farms involves the creation of a structured or unstructured grid, depending on the coastline; interpolation of bathymetry; input of parameters related to related to wave breaking, bottom friction, and wind input growth coefficients and applying initial and boundary conditions. The latter usually consists of wind data (wind speed and wind direction), wave data (significant wave heights, period and direction) as well as currents and water level data.

With respect to wave farms, WECs are represented in the model as partial obstacles that modify wave fields through transmission and reflection. In SWAN, parameters can be defined for each WEC in the array that describe the percentage of wave energy that is transmitted and reflected by these devices. This approach requires knowledge of the transmission (K_t) and reflection (K_r) coefficients for the WECs, which can be derived from physical or numerical experiments and the studies presented in this review have used various K_t and K_r to represent different WECs. The model is usually calibrated and validated using field collected measurements such as significant wave heights, water levels and currents.

4.2. *Morphodynamic modelling*

In some previous studies, SWAN has been coupled with the morphodynamic model XBeach to investigate the effect of the wave farms on short term trends of erosion and accretion during storm conditions. An example of this coupled model, including the model grids and interpolated bathymetry can be seen in Fig. 4.

XBeach is a coastal morphodynamic model developed to simulate the short-term response of sandy coasts to storms. It combines wave transformation, hydrodynamics, sediment transport, and bed level change using a process-based approach. Wave transformation is modelled using the wave action balance equation, coupled with roller energy equations to capture wave breaking effects. The hydrodynamics are governed by the nonlinear shallow water equations (NSWE), and sediment transport is described by a depth-averaged advection-diffusion equation (Equation (3)), which models the movement and distribution of sediment in response to currents and waves.

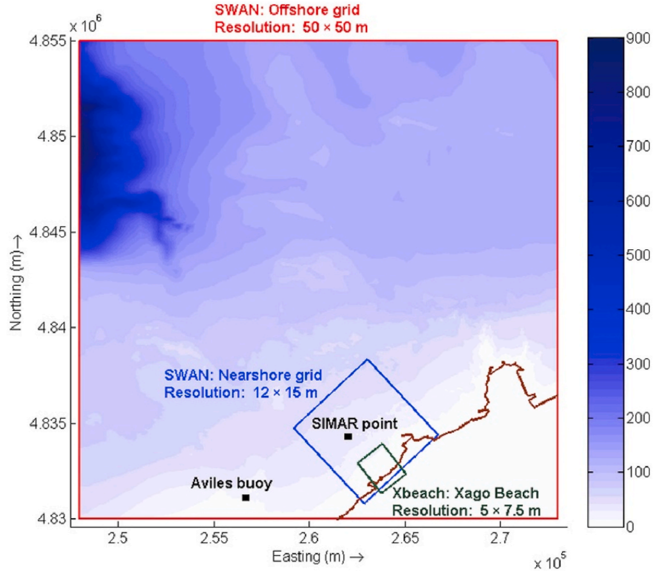

Fig. 4. Coupled SWAN and XBeach model with model grids, interpolated bathymetry and location of wave buoys for model validation. Adapted from Abanades et al. (2018).

$$\frac{\partial(hC)}{\partial t}+\frac{\partial(hCu^E)}{\partial x}+\frac{\partial(hCv^E)}{\partial y}=\frac{\partial}{\partial x}\left[D_{h,x}\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[D_{h,y}\frac{\partial h}{\partial y}\right]-\frac{hC_{eq}-hC}{T_s} \tag{3}$$

The advection-diffusion equation expresses how sediment concentration, denoted by C, within a water column of depth h, changes over time t, and space. The advection component of the equation accounts for the transport of sediment due to currents, where u^E and v^E represent the depth-averaged current velocities in the x and y directions, respectively. The diffusion component, on the other hand, describes the spreading and mixing of sediment due to turbulent processes, modelled using dispersion coefficients $D_{h,x}$ and $D_{h,y}$ for the x and y directions. The last term of the equation incorporates the settling of sediment towards the seabed at a rate governed by the settling velocity and the difference between the equilibrium concentration C_{eq} and the actual concentration C, with T_s representing the time scale over which sediment returns to equilibrium. Two sediment transport formulations are available in XBeach which include bedload and suspended sediment: the Soulsby-Van Rijn (Soulsby, 1997) and the Van Thiel-Van Rijn transport equations (van Rijn, 2007). Depending on the gradients in sediment transport, the changes in bed level, and morphology can be calculated using the Exner equation (Equation (4)).

$$\frac{\partial z_b}{\partial t}+\frac{f_{mor}}{(1-p)}\left(\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}\right)=0 \tag{4}$$

Equation (4) represents the rate of change in the bed level z_b over time t, which is balanced by the divergence of the sediment transport rates in the x-direction (q_x) and y-direction (q_y). The term f_{mor} is a morphological factor that can accelerate or decelerate the morphological changes for computational efficiency. The porosity, p accounts for the volume of the voids within the sediment bed relative to the total volume. The left side of the equation quantifies the change in bed elevation due to sediment transport, ensuring the conservation of sediment mass. The equation is set to zero indicating that any increase in sediment in one area must be balanced by a decrease elsewhere within the system. Further details on the additional formulation used in XBeach can be found in the official XBeach documentation.

The model inputs include bathymetry; wave boundary conditions; tidal data; sediment properties such as grain size, which are essential for assessing sediment transport mechanisms as well as the results generated by the wave propagation model, which can then be used as input for the model (Ozkan et al., 2020). Model parameters including roughness coefficients and calibration factors are selected to fine-tune the simulation to observed conditions. The model can operate in a one-dimensional (1D) mode simulating alterations in bed elevation in the cross-shore dimension or two-dimensional (2D) mode to simulate the longshore morphological changes. While XBeach has proven effective for short-term simulations, such as those spanning a single storm event, it has yet to demonstrate the capacity to generate results over the extended temporal and spatial scales required to fully characterize the long-term influences of WEC farms on coastal erosion.

5. Effectiveness of wave farms at coastal protection

5.1. *Wave attenuation and wave energy reduction*

While the primary objective of wave farms is renewable energy generation, numerous studies have also highlighted their effectiveness in enhancing coastal protection. Table 2 presents a comprehensive summary of these studies, detailing the methodologies used and the key findings related to wave attenuation and erosion mitigation. It is important to note that the reported values for wave attenuation and

Table 2

Summary of studies on the use of wave farms for coastal protection in terms of wave attenuation and erosion mitigation. N/A = Not applicable; the study did not assess or report on this criterion.

No.	Study	Location	WEC	Methodology	Key Findings	
					Wave Attenuation	Erosion Mitigation
1.	Abanades, Greaves, and Iglesias (2014a)	Perranporth Beach (UK) - WaveCat	WaveCat	Coupled SWAN + XBeach model	Wave height reduction of 30 % in the lee of the farm. 10 % reduction in 20m depth	Beach erosion reduced by up to 50 %,
2.	Bento et al. (2014)	São Pedro de Moel, Portugal	N/A	SWAN with varied energy transmission (0 %–100 %) over a one-year period (2009).	Wave height reduction varied by season, with winter wave height reductions ranging from 5.8 % to 11.7 % and between 6.25 % and 12.2 % for the summertime.	N/A
3.	Iglesias and Carballo (2014)	Galicia, NW Spain	WaveCat	Used SWAN to analyze the effect of farm-to-coast distances (2 km, 4 km, and 6 km)	Wave Height Reduction: -Wave Dragon: ~25–27 % -Blow-Jet:~23–25 % -Dexa: ~30 % -Seabreath: ~37 % Closer wave farms (2 km) resulted in greater reductions in nearshore wave energy	N/A
4.	Mendoza et al. (2014)	Las Glorias Beach, Mexico	Wave Dragon Blow-Jet Dexa Seabreath	2D elliptic mild-slope model for wave propagation + long-shore sediment transport (LST) equation	Wave height reductions ranging from 10 % to 30 % depending on the location and based on maximum absorption	N/A
5	Zanopol, Onea, and Rusu (2014)	Romanian coastline, Black Sea	N/A	Used SWAN to model wave conditions under various scenarios of wave transmission	The wave farm significantly reduced wave height in the lee of the farm, with reductions up to 50 %	N/A
6.	Abanades, Greaves, and Iglesias (2015a)	Perranporth Beach, UK	WaveCat	SWAN + XBeach for three scenarios with wave farms located at 2 km, 4 km, and 6 km offshore	The wave farm at 2 km distance resulted in averaging average 25 % reduction at a 10 m water depth, with peak reductions of 40 % in certain areas. Greater distances (4 km and 6 km) led to smaller reductions in wave height and beach erosion	N/A
7.	Abanades, Greaves, and Iglesias (2015b)	Perranporth Beach, UK	WaveCat	Used SWAN to simulate wave propagation and established beach modal states based on empirical classifications, incorporating tidal regime and sediment characteristics.	The wave farm at 2 km caused a 25 % reduction in wave power along a 3 km stretch of coastline, significantly altering the beach from wave-dominated to tide-dominated states. Seasonal variations influenced the modal state, with winter conditions shifting the beach profile towards a barred dissipative state, while summer conditions resulted in an ultra-dissipative state due to the milder wave climate.	15 % erosion reduction for the closest wave farm and approx. 10 % for further wave farm
8.	Onea and Rusu (2016)	Porto, Portugal	N/A	SWAN for simulating wave propagation over a 20-year period to analyze impact of absorption scenarios on significant wave height	The wave farm reduced wave height by up to 41 % in high absorption scenarios, especially in winter conditions when wave energy is higher.	N/A
9	Rusu and Onea (2016)	Portuguese coast	WaveCat DEXA Seabreath	Used SWAN model for wave propagation and analyzed three different farm-to-coast distances: 1 km, 4 km, and 7 km and under three wave absorption scenarios	WaveCat/DEXA: ~20–25 % wave attenuation Seabreath: ~35–40 % The wave farm at 1 km provided the most significant reduction in nearshore wave height The 4 km and 7 km distances resulted in less reduction in nearshore energy but extending over a larger area.	N/A
10.	Abanades et al. (2018)	Xago Beach, Spain	WaveCat	Used SWAN for wave propagation modelling and XBeach for coastal processes modelling.	The wave farm reduced significant wave height by up to 50 % directly behind it, decreasing nearshore to about 15 %	N/A
11.	Bergillos et al. (2018)	Guadalfeo delta in southern Spain	WaveCat	Delft3D-Wave for spectral wave modelling + XBeach-G model for morphodynamic modelling	The wave farm induced an 18.3 % reduction in wave height at 10 m depth and a 10.6 % reduction in wave run-up in the Playa Granada	Erosion was reduced by 44.5 % in Playa Granada and by 23.3 % across the entire deltaic coastline in the most favourable scenarios.

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Table 2 (*continued*)

No.	Study	Location	WEC	Methodology	Key Findings	
					Wave Attenuation	Erosion Mitigation
					area, which is highly vulnerable to erosion.	
12	Rodriguez-Delgado et al. (2018a)	Playa Granada in southern Spain	WaveCat	Delft3D-WAVE + one-line model for shoreline evolution. Analyzed four scenarios with different wave farm layouts (1–4 rows) under varying sea states (low energy and storm) and directions (easterly and westerly waves).	The wave farms reduced wave height by up to 20 % in the lee of the farm, with significant shoreline accretion in all scenarios. Layouts with fewer rows but covering a greater coastline length provided better coastal protection.	Under the best scenarios, there were average increases in dry beach area ranging from 16.05 m^2 to 35.29 m^2
13.	Rodriguez-Delgado et al. (2018b)	Playa Granada, southern Spain	WaveCat	Delft3D-WAVE + a one-line model to assess shoreline evolution. Analyzed eight different alongshore positions of the wave farm, considering both storm and low-energy conditions, and applied various wave directions.	Certain positions led to a 16.4 % reduction in significant wave height	44.6 % reduction in longshore sediment transport (LST) under easterly storm conditions. The best scenario increased the dry beach area by approximately 25.58 m^2
14.	Stokes and Conley (2018)	South West Ireland	N/A	SWAN + XBeach. Analyzed three scenarios based on wave transmission, K_t: 0, 0.58 and 0.9	The scenario for full energy absorption showed a 44 % reduction in wave energy, 16 % for $K_t = 0.58$ and 4 % for $K_t = 0.9$	N/A
15.	Atan et al. (2019)	West coast of Ireland	N/A	Used SWAN and simulated three wave farm configurations	Wave height and wave power reductions remained below 1 % at distances of 1–3 km from the shoreline (in water depths ranging from 20 to 60 m).	N/A
16.	Bergillos et al. (2019)	Playa Granada, Spain	WaveCat	SWAN + XBeach-G for storm impact and flood modelling. Simulated three sea-level rise (SLR) scenarios: the present (SLR0), an optimistic projection (SLR1), and a pessimistic projection (SLR2).	The wave farm reduced breaking wave heights by 10–25 % depending on storm direction, with higher reductions under easterly storms. Total run-up was reduced by 5.9-1.5 % (westerly) and 6.8–5.1 % (easterly) across SLR scenarios, showing the farm's effectiveness in lowering flood risks.	
17.	Rodriguez-Delgado, Bergillos, and Iglesias (2019a)	Playa Granada, Spain	WaveCat	SWAN + one-line shoreline evolution model to examine shoreline changes under different sea level rise (SLR) scenarios.	The wave farm reduced significant wave height by up to 20 % behind the farm.	Increase subaerial beach area by 8–28 m^2 across SLR scenarios.
18.	Rodriguez-Delgado, Bergillos, and Iglesias (2019b)	Playa Granada, Spain	WaveCat	SWAN + one-line model for shoreline evolution. Simulated four configurations with different inter-WEC spacings (D, 2D, 3D, 4D) and analyzed the impact on wave height reduction and longshore sediment transport (LST)	N/A	Optimal spacing (2D and 3D) yielded the highest coastal protection benefits, with dry beach area increases of 25.9 m^2 and 24.5 m^2, respectively. Smaller spacing (D) led to concentrated accretion but also caused erosion in other areas, while the widest spacing (4D) reduced effectiveness.
19.	Rodriguez-Delgado, Bergillos, and Iglesias (2019c)	Playa Granada, Spain	WaveCat	Developed an artificial neural network (ANN) model to predict the coastal protection efficiency of wave farms Analyzed various wave farm configurations, including inter-device spacing, number of rows, and wave conditions to identify the optimal structure.	N/A	Optimal wave farm configurations showed a positive impact on coastal protection, with the best layout consisting of two rows with 180 m spacing (2D), which increased the dry beach area by approximately 5400 m^2 per year.
20.	David et al. (2022)	Theoretical model with idealized conditions	N/A	Compared the performance of two different modelling approaches: a wave-averaged model (Delft3D-SNL-SWAN) and a wave-resolving model (SWASH) to predict coastal impacts due to wave farms.	The wave-resolving model (SWASH) generally predicted larger impacts on nearshore hydrodynamics than the wave-averaged model, particularly closer to the wave farms.	N/A
21.	Lo Re et al. (2022)	Mediterranean Sea	N/A	SNL-SWAN to evaluate wave energy extraction and shoreline impact over 39 years with reanalysis data from ERA5. Modelled various WEC types (e.g., Pelamis, Wave Dragon, Oyster 2)	The WEC arrays reduced significant wave height by up to 0.18 m and energy flux by 2 kW/m.	N/A
22.	Ozkan et al. (2022)	Dauphin Island, Alabama	N/A	Used the XBeach to simulate two major hurricanes (Hurricane Ivan and Hurricane Katrina) and	The model results indicated potential for WECs to reduce	Coastal morphology was positively impacted, with higher post-storm bed levels and a 15 %

(*continued on next page*)

Table 2 (*continued*)

No.	Study	Location	WEC	Methodology	Key Findings	
					Wave Attenuation	Erosion Mitigation
				compare scenarios with and without WEC deployment. Represented WECs by reducing wave heights by 30 % in the model to simulate wave energy extraction effects.	wave heights nearshore by an average of 0.3 m.	reduction in net sand volume loss in the presence of WECs during Hurricane Ivan.
23.	Berrio et al. (2023)	La Guajira coast, Colombian Caribbean	WaveCat	Delft3D + XBeach to evaluate three wave farm configurations (linear, semicircular perpendicular, semicircular oblique) at distances of 1.3 km, 2 km, and 4 km from the shore.	The linear WEC array at 1.3 km from the shore provided the greatest coastal protection, reducing wave energy by approximately 30–50 %. The semicircular configurations showed lower effectiveness in wave attenuation and sediment retention compared to the linear arrangement.	Mitigated coastal erosion by up to 0.25 m in storm conditions.

erosion mitigation vary significantly across studies due to differences in wave conditions, WEC types and configurations (gap spacing and distance from the coast), bathymetric profiles, and numerical modelling approaches. Accordingly, these values represent context-dependent outcomes and should not be generalized without considering the specific conditions and assumptions of each study. Wave farms have demonstrated considerable potential for coastal protection by attenuating wave energy, reducing wave heights, and decreasing energy flux. The effectiveness of wave attenuation is influenced by location and wave conditions; wave farm array configurations and spacing and the farm-to-coast distance. Reported wave attenuation values typically range from 10 % to 50 %, with higher reductions observed in densely packed, nearshore arrays and under high-energy conditions.

To better visualize and compare the wave attenuation performance of different wave farms across geographical contexts and WEC types, a synthesis figure was developed (Fig. 5). This figure illustrates the reported wave height reduction percentages grouped by country and differentiated by WEC type.

Fig. 5 A highlights that WaveCat, the most commonly modelled device, consistently achieves attenuation levels of 25–50 %, particularly in UK and Spanish case studies. The Seabreath also demonstrates high attenuation performance (up to 37 %) in Colombia. Studies that did not specify WEC types showed more variable results, generally depending on farm configuration and distance from shore. These findings emphasize how both WEC selection and site-specific conditions play key roles in determining coastal protection outcomes.

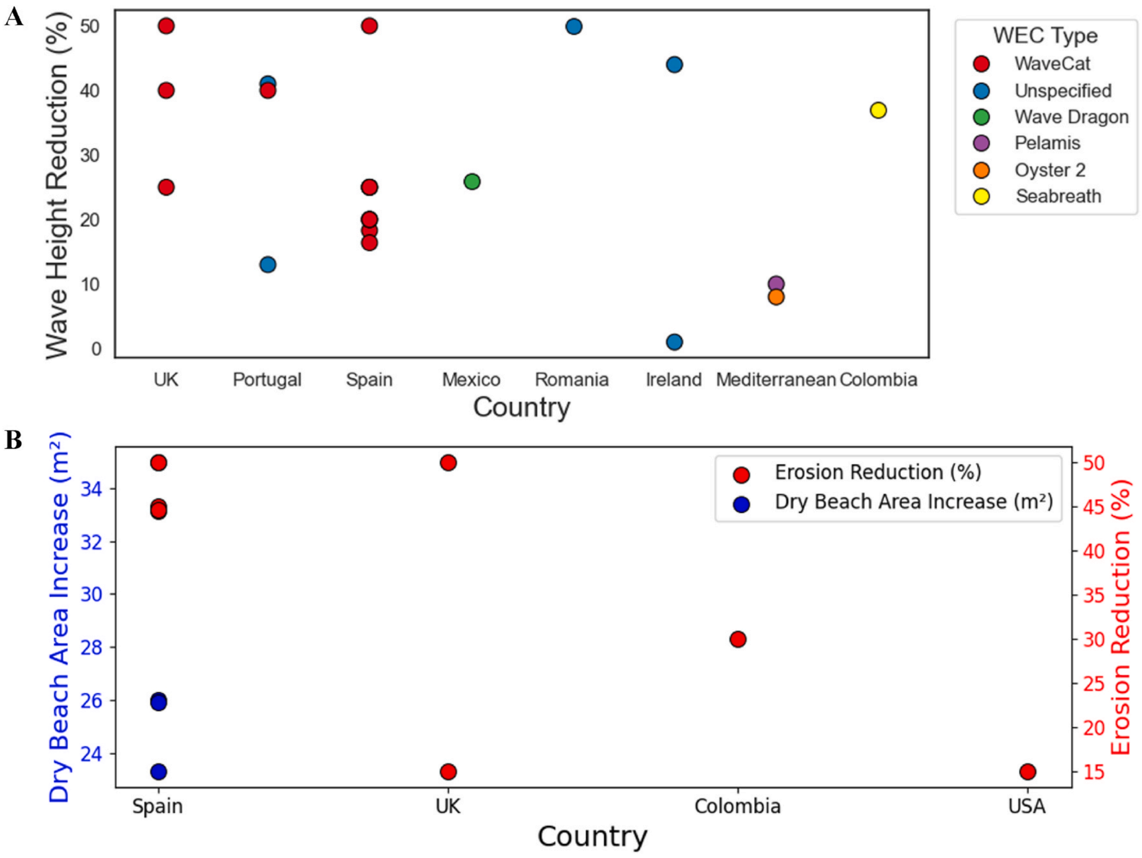

Fig. 5. (A) Wave Height Reduction by Country and WEC Type, (B) Erosion Mitigation: % Reduction + Dry Beach Area increase in various countries.

5.1.1. Impact of WECs, array configuration and spacing on wave attenuation

Array configuration and inter-device spacing are crucial factors in optimizing wave attenuation. Close, multi-row arrays often yield greater attenuation than widely spaced or single-row configurations. Berrio et al. (2023) conducted a comprehensive numerical assessment of WEC arrays along the La Guajira coast, evaluating three configurations: linear, semicircular perpendicular, and semicircular oblique. The linear configuration positioned 1.3 km offshore demonstrated the highest wave attenuation, reducing significant wave height by 30–50 %, especially during storm conditions. Semicircular perpendicular configurations achieved wave height reductions of 20–35 %, while semicircular oblique configurations showed the least attenuation, ranging from 15 to 30 %. Rodriguez-Delgado et al. (2018a) similarly found wave height reductions ranging from 15 % to 20 % depending on the wave farm layout and sea conditions. The configurations with fewer rows but longer stretches of coverage provided better wave attenuation and wider coastal protection compared to multi-row layouts over a smaller area.

Rodriguez-Delgado et al. (2018b) examined the impact of inter-device spacing, showing that closely spaced arrays (2D spacing) led to reductions of up to 25 % in wave height. Wider spacing resulted in lower wave attenuation, emphasizing the importance of optimized WEC placement. Abanades et al. (2018) similarly found that the wave farms with a linear array reduced significant wave height by up to 50 % directly behind it, decreasing nearshore to about 15 %.

The wave energy reduction is also affected by the specific device and their characteristics. Mendoza et al. (2014) showed that the Wave Dragon WEC array reduced wave heights by 10–15 % at Santander Bay, with localized reductions of up to 25 % in certain areas. In contrast, the Dexa and Seabreath WEC farms at Las Glorias Beach achieved wave height reductions between 10 % and 20 %, depending on the wave conditions and array setup. The study highlighted the importance in understanding the site-specific conditions and the applicability of various devices and their characteristics on wave energy reduction.

Similarly, studies like Zanopol, Onea, and Rusu (2014), Onea and Rusu (2016) and Stokes and Conley (2018) have evaluated the effect of the wave transmission coefficients (K_t) on wave attenuation. Zanopol, Onea, and Rusu (2014) varied the wave transmission of the hypothetical wave farm in SWAN simulations and found a 10–30 % decrease in significant wave heights from a 0 % wave transmission scenario compared to a 100 % wave transmission scenario (no wave farm). A similar result was obtained by Onea and Rusu (2016) in a different location where the wave farm reduced wave heights by up to 41 % in high absorption scenarios, especially in winter conditions when wave energy is higher. This result was also obtained by Stokes and Conley (2018) with a 44 % reduction in wave energy for a scenario for full energy absorption energy, a 16 % for $K_t = 0.58$ and 4 % for $K_t = 0.9$. These studies highlight the importance of the device design and type and their respective wave transmission. Lo Re et al. (2022) examined various WEC designs in the Mediterranean, finding that the Wave Dragon, an overtopping device, achieved the highest efficiency. This configuration reduced wave heights by an average of 0.18 m, highlighting the effectiveness of high-efficiency devices in enhancing wave attenuation despite its offshore location.

5.1.2. Influence of farm-to-coast distance

The effectiveness of wave attenuation is significantly influenced by the distance between the wave farm and the coastline. Nearshore arrays generally provide stronger wave attenuation, although they may affect a smaller coastal area compared to offshore configurations. Abanades, Greaves, and Iglesias (2015a) assessed the impact of a wave farm located at different distances from the shoreline (2 km, 4 km, and 6 km). The wave farm at 2 km distance resulted in the most significant wave height reduction nearshore, averaging around 25 % at a 10 m water depth, with peak reductions of 40 % in certain areas. Rusu and Onea (2016) also assessed different distances (1 km, 4 km, and 7 km offshore), finding that nearshore arrays (1 km) reduced wave heights by up to 1 m in high-energy conditions. Farther offshore, the attenuation effect was lower, around 10–20 %, but spread over a broader area. Berrio et al. (2023) also examined the role of distance from the shore (1.3 km, 2 km, and 4 km) and found that the linear WEC array at 1.3 km from the shore provided the greatest coastal protection, reducing wave energy by approximately 30–50 %. These studies, however, are in contrast to Atan et al. (2019) that found that wave height and wave power reductions remained below 1 % at distances of 1–3 km from the shoreline (in water depths ranging from 20 to 60 m). Rodriguez-Delgado et al. (2018b) analyzed eight different alongshore positions of the wave farm and found that there was a variation in the alongshore wave attenuation with certain positions having a 16.4 % reduction in significant wave height.

5.1.3. Impact of wave direction and seasonal conditions

Wave direction and seasonal wave conditions significantly influence wave attenuation, with higher reductions typically observed during storm events. Bergillos et al. (2019) at Playa Granada reported reductions in breaking wave heights by 10–25 % under easterly storm conditions, indicating the importance of wave direction. The array was less effective against westerly waves due to its orientation. Bento et al. (2014) noted seasonal variations in wave attenuation at São Pedro de Moel, Portugal, with winter wave height reductions ranging from 7 to 23 cm and summer reductions from 5 to 14 cm. This seasonal difference highlights the increased wave energy during winter, which enhances the attenuation effectiveness of WEC arrays. The studies illustrate the importance of considering seasonal and directional wave climates when designing wave farms. However, the results may be limited to regions with pronounced seasonal variability and may not apply to more stable wave climates. Ozkan et al. (2022) simulated hurricane conditions at Dauphin Island, Alabama, and showed that WECs reduced nearshore wave heights by an average of 0.3 m. The devices effectively decreased coastal erosion and dune loss during peak storm waves, highlighting the potential of WECs in extreme weather events.

5.2. Sediment transport and accretion

5.2.1. Quantitative synthesis of erosion mitigation

Beyond wave attenuation, several studies assessed coastal protection through erosion metrics, such as shoreline accretion and dry beach area gain. Fig. 5B presents erosion reduction percentages and dry beach area increases for countries where such data were reported. Spain features prominently with multiple studies showing erosion reduction between 44 and 50 % and dry beach area gains ranging from 23 to 35 m^2. Colombia showed up to 30 % erosion mitigation using linear WEC arrays, while the UK reported a 50 % reduction in erosion and a 15 % reduction in net sand loss post-storm events.

This figure highlights the spatial variability in erosion mitigation and underscores the effectiveness of WaveCat configurations in Spain. However, limited data from field validation and differences in output metrics across studies suggest the need for standardized methodologies in future research. The erosion mitigation effectiveness of wave farms, based on the previous studies, typically ranges between 15 % and 45 %, with specific reductions influenced by location, wave conditions, sediment type as well as the wave farm array configurations and farm-to-coast distance.

5.2.2. Impact of array configuration and spacing on erosion mitigation and sedimentation

The layout and spacing of WEC arrays significantly affect their capacity to mitigate erosion and promote sedimentation. Close, multi-row configurations generally demonstrate better performance in fostering sediment deposition and reducing shoreline erosion. Abanades, Greaves, and Iglesias (2014a) used a linear row of WECs which reduced beach erosion by up to 50 %. While most studies focus on sandy shorelines, limited research has explored the influence of shoreline composition such as gravel or mixed-sediment beaches on the effectiveness of wave farms.

Rodriguez-Delgado et al. (2018a) examined the impact of wave farm configurations on a gravel-dominated deltaic beach in southern Spain. Their findings revealed that wave farms could reduce wave energy and promote shoreline accretion even in coarse-grained environments, particularly when deployed in wider configurations with fewer rows. This suggests that wave farms may be adaptable across varying sediment types, although the sediment response may differ depending on local hydrodynamics and sediment transport processes. Rodriguez-Delgado et al. (2018a) not only found significant wave attenuation with the extensive linear arrays but also found average increases in dry beach area ranging from 16.05 m^2 to 35.29 m^2 under these scenarios. The best alongshore positioning for the wave farm in Rodriguez-Delgado et al. (2018b) increased the dry beach area by approximately 25.58 m^2.

Rodriguez-Delgado, Bergillos, and Iglesias (2019b) found that optimal inter-device spacing (twice the diameter of the device) increased sediment retention and reduced erosion in a gravel-dominated coastal environment, with dry beach area increases of up to 25.9 m^2. The reduced wave energy due to the presence of the wave farms allowed for calmer conditions that facilitated sediment deposition. Rodriguez-Delgado, Bergillos, and Iglesias (2019c) employed an artificial neural network (ANN) model to predict sediment accretion with optimized WEC configurations, noting increases in the dry beach area by 5400 m^2/year in optimal configurations. It must be noted, however, that the above-mentioned studies were based on short term storm events ranging from 2 days to 5 days.

5.2.3. Proximity of WEC arrays to shoreline and erosion mitigation

The distance between WEC arrays and the shoreline affects sediment transport and erosion patterns. Nearshore arrays are generally more effective at erosion mitigation due to direct wave attenuation. Abanades, Greaves, and Iglesias (2015a) found that arrays positioned 2 km offshore led to a 15 % reduction in beach erosion over the 3-day storm period. Berrio et al. (2023) observed that linear configurations positioned 1.3 km offshore contributed to a 15–30 % increase in accretion, particularly during storm events.

5.2.4. Impact of wave direction and storm events on sediment transport

Wave farms are especially effective in altering sediment transport during high-energy wave conditions, such as storms and seasonal variations and wave direction also influence sediment dynamics. The study by Ozkan et al. (2022) showed a 15 % reduction in net sand volume loss in the presence of WECs during Hurricane Ivan, showcasing the benefits of WECs under extreme conditions. Bergillos et al. (2018) found erosion reductions of 44.5 % in highly vulnerable areas, particularly under high-energy conditions, showcasing the potential for WEC arrays to provide substantial coastal protection in deltaic environments. Bergillos et al. (2019) at Playa Granada found that WEC farms provided both flood and erosion protection. The wave farm reduced flooded areas by 5.7 % and reduced erosion under sea-level rise scenarios.

6. Gaps in current methodologies and future research directions

6.1. Evaluation of numerical modelling approaches

These wave farm studies typically rely on three broad classes of numerical models (Table 3): spectral wave models (e.g. SWAN), process-based morphodynamic models for short-term events (e.g. XBeach), and fully coupled hydrodynamic–wave–sediment models for long-term evolution (e.g. Delft3D). As shown in Table 3, each framework solves a different set of governing equations, treats wave processes and sediment transport differently, and involve various trade-offs. Depending on the study objectives, some modelling efforts adopt simplified or idealized bathymetry and wave conditions to perform parametric or sensitivity analyses (David et al., 2022), while others use site-specific setups with time-varying, coupled wave and hydrodynamic forcing to capture realistic coastal processes (Abanades et al., 2018; Bergillos et al., 2018; Berrio et al., 2023; Boodoo and Villarroel-Lamb, 2025).

Table 3
Comparison of key numerical modelling approaches used in wave farm and coastal morphodynamic studies.

Feature	SWAN	XBeach	Delft3D
Governing equation	Spectral action balance equation	Shallow water equations + roller/ infragravity terms	Depth-averaged Navier–Stokes equations
Wave resolution	Multi-frequency, multi-directional	Parametrized short-wave + roller + infragravity	Coupled wave–flow (external SWAN or internal module)
Time stepping	Implicit finite difference	Explicit finite volume	Semi-implicit finite difference
Sediment transport	Not included (requires coupling)	Mixed bedload/ suspended load; roller-induced shear	Mixed load; dynamic grain sorting; k–ε turbulence
Morphological update	–	Exner equation at each time step	Exner equation with optional morphological scale factor (morfac)
Computational cost	Low to moderate	Moderate	High

SWAN addresses wave propagation by solving the spectral action balance equation over discrete frequency and direction bins using an implicit finite-difference scheme. Its core strength lies in high spectral resolution, which combined with the porous-barrier approach using user-defined K_t and K_r coefficients, allows efficient simulation of WEC arrays without meshing their geometries. In addition to standard source terms such as wind input, whitecapping, nonlinear wave–wave interactions, depth-induced breaking, and bottom friction, SWAN’s newer ST6 physics package improves the representation of triad interactions and updates wind-input and whitecapping formulations, leading to better spectral energy distribution in shallow-water and storm conditions. Although SWAN does not include sediment transport or bed evolution, it can be coupled with morphodynamic models such as XBeach or Delft3D’s Morphology module to simulate sediment dynamics and bed level changes.

XBeach extends the shallow-water framework by incorporating roller and infragravity wave modes that translate breaker energy into enhanced bed shear stress. Sediment transport is handled using a mixed formulation: a Van Rijn-type bedload expression calibrated for combined current–wave shear, along with an advection–diffusion solver for suspended load.

The XBeach-G variant is specifically designed for gravel beaches and includes gravel transport formulations and infiltration/exfiltration processes relevant for permeable shorelines. Bed level evolution follows the Exner equation at each time step. XBeach is well suited for storm-scale (hours to days) simulations of surf-zone morphodynamics, especially where infragravity waves and wave breaking dominate. However, while it can be run in 2DH mode, many applications remain focused on cross-shore dynamics, and the computational cost increases significantly with higher spatial resolution or larger domains.

Delft3D-FLOW provides the most comprehensive process-based modelling framework, solving depth-averaged Navier–Stokes equations and coupling with a wave module (SWAN). Its sediment transport module supports dynamic grain-size sorting across multiple fractions, user selection among several bedload transport formulas (e.g., Van Rijn, 2007, Soulsby–Van Rijn), and suspended load transport using a k–ε turbulence closure for vertical mixing. Bed evolution is computed using the Exner equation, and a morphological scale factor (morfac) can be applied to accelerate long-term bed level changes. This enables Delft3D to simulate both cross- and longshore sediment transport over decadal timescales, but it requires high computational resources and careful tuning of coupling parameters.

In practice, model selection should align with the study objectives and computational constraints. SWAN is ideal for estimating wave attenuation by WEC arrays and assessing large-scale wave propagation. XBeach (including XBeach-G) is more suitable for storm-scale erosion and surf-zone morphodynamics, particularly where infragravity and breaking waves drive sediment processes. Delft3D, though computationally intensive, is best suited for long-term simulations that require full coupling of hydrodynamics, waves, and sediment transport. A combined approach is often most effective: SWAN can be used for initial screening of WEC layouts, followed by XBeach for surf-zone responses, and Delft3D for detailed, long-term morphological evolution, thereby balancing accuracy and computational efficiency.

In addition to integrated modelling approaches, emerging technologies such as artificial intelligence (AI) and machine learning offer promising avenues for optimizing wave farm design (Rodriguez-Delgado, Bergillos, and Iglesias, 2019c). For example, artificial neural networks (ANNs) and other AI-based algorithms can be used to rapidly assess large datasets, identify optimal configurations, and adjust WEC array layouts in response to seasonal or storm-driven wave conditions. These tools also hold potential for data assimilation from real-time monitoring systems and weather forecast databases, allowing for adaptive, real-time optimization of wave farms. Despite their potential, such techniques remain largely unexplored in current wave farm research and represent an important future research direction for enhancing the long-term effectiveness and operational resilience of multi-purpose wave energy systems.

6.2. Gaps in field validation, WEC representation and research objectives

The reviewed literature demonstrates the effectiveness of wave farms for coastal protection, particularly in wave attenuation and erosion mitigation. However, several challenges and gaps in current methodologies limit our understanding and optimization of these systems. One major issue is the heavy reliance on numerical simulations, using models such as SWAN, XBeach, and Delft3D, to assess wave attenuation and erosion mitigation. While these models offer valuable insights, they often rely on simplified representations of WECs and assume simplified conditions that may not fully capture the complex interactions between WEC devices and coastal processes.

In the models, the WECs are represented by wave transmission and reflection coefficients and simple wave conditions representative of the area (Abanades et al., 2018; Abanades, Greaves, and Iglesias, 2014a; Bergillos et al., 2018; Rodriguez-Delgado, Bergillos, and Iglesias, 2019a) for computational efficiency. Additionally, the wide variety of WEC designs ranging from oscillating water columns and point absorbers to bottom hinged oscillating wave surge and overtopping devices has contributed to a lack of convergence in modelling approaches (Guo and Ringwood, 2021; López et al., 2013). Different devices interact with waves in fundamentally different ways (e.g., scattering, absorption, overtopping, or reflection), and this has led to inconsistent assumptions across studies regarding K_t and K_r, array spacing, and energy capture efficiency. As a result, comparing findings or synthesizing conclusions across different modelling efforts remains challenging, particularly when device-specific performance characteristics are not fully described or validated.

Furthermore, the lack of comprehensive field validation is a significant limitation; only a few studies (Abanades et al., 2018; Abanades, Greaves, and Iglesias, 2014a, 2014b; Berrio et al., 2023) include real-world data for validation, especially short term morphodynamic modelling using XBeach. Other studies rely on theoretical models or simply validating the wave conditions without any validation of the morphodynamic model. This reduces confidence in the findings and limits the applicability of the results to diverse coastal environments.

In addition to the challenges of field validation and simplified WEC representation, it is important to acknowledge the diverse research aims found across the literature. Most studies fall into one of three broad categories: (i) those focused on the design of wave farms for maximizing energy extraction (Arguilé-Pérez et al., 2023; Carballo et al., 2019; Venugopal et al., 2017; Zheng and Chong, 2015), (ii) those evaluating coastal protection performance such as wave attenuation and erosion mitigation (Abanades et al., 2018; Abanades, Greaves, and Iglesias, 2014a, 2015b; Bergillos et al. 2018, 2019; Bergillos et al., 2019a,b; Berrio et al., 2023), and (iii) those investigating the influence of WEC layout, spacing, or configuration on overall system behaviour (Abanades, Greaves, and Iglesias, 2015a; Rodriguez-Delgado, Bergillos, and Iglesias, 2019b; Rodriguez-Delgado et al., 2018a; Mendoza et al., 2014). These aims shape decisions about model selection, array geometry, boundary forcing, and the way WECs are parameterized (e.g., as transmission–reflection barriers or porous structures). Despite increased attention to dual-use functionality, true multi-objective optimization that balances both energy output and coastal protection goals has not yet been achieved in the literature. This remains a significant gap and highlights the need for more integrated modelling approaches that can capture the trade-offs involved in multi-functional wave farm design.

6.3. Future research directions

6.3.1. Long term morphodynamic impact of wave farms

A critical gap in literature is the limited focus on long-term morphodynamic impacts. The reviewed studies concentrate on short-term effects or specific storm scenarios. While the short-term benefits of storm-induced erosion mitigation are well-documented, there have been no studies on the long-term morphodynamic impacts of wave farms, addressing multi-year changes in beach profiles, sediment budgets, or shoreline stability. Additionally, the methodologies often overlook the influence of climate change and sea-level rise, which could alter wave climates and exacerbate erosion in the long term. Understanding the long-term morphodynamic impacts of wave farms is crucial for their long-term deployment.

6.3.2. Multi-objective optimization of wave farm designs

The lack of multi-objective optimization approaches that consider both coastal protection and energy production is a crucial gap that must be addressed. Many studies optimize WEC layouts solely for energy yield, overlooking potential trade-offs in coastal protection performance. In reality, the optimal configuration for energy generation may not coincide with that which best mitigates erosion or flooding.

Future research should integrate both objectives into design and site selection processes. Adaptive WEC layouts that respond to seasonal wave conditions or extreme events may offer a more resilient and efficient approach. The incorporation of artificial intelligence and machine learning—such as Artificial Neural Networks (ANNs)—could support real-time optimization based on forecasted wave conditions, improving the responsiveness and effectiveness of wave farms.

6.3.3. Integration of coastal protection benefits into economic assessments of wave farms

The incorporation of coastal protection benefits into the economic assessment of wave farms represents a promising approach to reducing the Levelized Cost of Energy (LCoE). One of the main barriers to widespread adoption of wave energy is the high capital cost and elevated LCoE, which make it challenging to compete with traditional renewable energy sources and fossil fuels. By quantifying the coastal protection benefits provided by WEC arrays, such as accretion and erosion mitigation, these advantages can be integrated into the economic evaluation of wave farms. Future research should focus on developing techno-economic models that account for the dual benefits of wave farms, thereby reducing the perceived cost and increasing the overall value proposition of these systems. This approach could help justify the higher initial investment in wave energy by highlighting the additional benefits of erosion mitigation and enhanced shoreline resilience.

6.3.4. *Environmental, social and legal challenges*

While the primary aim of this systematic review is to assess technical methodologies and effectiveness, we recognize the importance of incorporating environmental, socio-economic, and legal frameworks in future interdisciplinary studies. Environmental and socio-economic impacts are often underrepresented in the current methodologies. While most studies emphasize the impacts of wave farms on wave attenuation and erosion mitigation, the broader impacts on marine ecosystems and coastal communities are rarely considered. There is a pressing need to investigate the ecological consequences of altering sediment transport and hydrodynamic conditions, as well as the legal and policy frameworks required for integrated ocean management. These environmental, social, and legal dimensions alongside technical and economic perspectives should be considered in future interdisciplinary research to provide a more comprehensive evaluation of wave farm effectiveness.

Engaging stakeholders, including local communities, regulatory agencies, and maritime industries, in the planning and optimization process is essential for integrating socio-economic considerations into the development of wave farms. Understanding the trade-offs between different coastal uses, such as tourism, fisheries, and energy production, can help balance competing interests and promote more effective decision-making. Additionally, future research should investigate policy frameworks that support the dual-purpose role of WEC arrays, facilitating their deployment as part of integrated coastal zone management strategies.

7. Conclusion

This systematic review has demonstrated the significant potential of wave farms in providing coastal protection. The reviewed studies indicate that wave farms can effectively attenuate wave energy, with reductions in wave height ranging from 10 % to 50 %, depending on factors such as array configuration, spacing, wave climate, and distance from the shore. Nearshore, linear, closely spaced arrays showed greater wave attenuation capabilities, highlighting their potential in enhancing coastal protection, especially during storm events.

In terms of sediment transport and erosion mitigation, wave farms have shown promising results, with typical reductions in erosion ranging between 15 % and 45 %. The presence of WECs altered nearshore hydrodynamic conditions, promoting sediment deposition and enhancing beach accretion. However, the effectiveness of these erosion mitigation measures was influenced by the specific design of the WECs, farm layout, and wave climate conditions.

Despite the promising findings, the heavy reliance on numerical models in current research presents a major limitation, as these models often use simplified representations of WECs and wave conditions. Moreover, there is a significant gap in long-term morphodynamic assessments, with existing studies primarily focusing on short-term storm events. Future research should prioritize field-based validations, long-term simulations, and multi-objective optimization approaches to address the dual goals of maximizing energy output and enhancing coastal protection. By addressing the identified challenges and gaps, future developments in wave farm technology could play a crucial role in enhancing coastal protection. These developments will also support the wider deployment and long-term success of wave farms.

CRediT authorship contribution statement

Avinash Boodoo: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Tatsuya Wakeyama:** Writing – review & editing. **Jeffrey S. Cross:** Writing – review & editing, Supervision, Resources.

Declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of competing interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2025.107807.

Data availability

No data was used for the research described in the article.

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