Royal Netherlands Institute for Sea Research

No-regret programme

Nature Enhancement North Sea

NIOZ work:

Developing SeaD-bombs (reef structures) to rebuild marine biodiversity

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Commisioned by

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Contents

Summary

Background: In the past, the sea was full of complex structures, such as moorlog fields and flat oyster reefs. To date, wind farms add habitat complexity in the near-shore zone, while over time, flat-oyster reef restoration projects may do so further out at sea. While oyster reef restoration is slowly gaining momentum, there is a need to create off-shore complex reef-like structures *now*, to boost marine biodiversity *now* and to offer substrate on which reef-building organisms like oysters can settle and use to expand their reefs.

Objectives: In this project, we call for the development of low-cost, easy-to-deploy, and fully-biodegradable SeaD-bombs (i.e., Sea-Diversity bombs) to rapidly scale up marine biodiversity recovery, with the following specific research objectives:

1. Demonstrating the necessity of developing SeeD-bombs.
2. Identifying key challenges that need to be addressed in SeaD-bomb development.
3. Establishing a set of principles for SeaD-bomb development and deployment.
4. Compiling a list of potential materials for constructing SeaD-bombs.
5. Exploring suitable approaches for the preliminary assessment of SeaD-bomb stability.

Methods: The following specific methods are tailored to our research objectives and are presented in the order below:

1. **Literature studies**, including *i*) literature review on the scale and cost of contemporary reef restoration, *ii*) literature review on the application trends of reef structures in sea restoration, *iii*) meta-analysis on the effectiveness of reef structures in supporting marine life.
2. **Workshop**. Gathered feedback and suggestions on the current challenges in developing SeaD-bombs from experts involved in North Sea restoration, including ecologists, civil engineers, legal scholars, environmental consultants, and NGOs. The workshop took place in Utrecht on November 27, 2024, with 20 participants from 13 institutions attending in person.

3. **Documentation**. Based on the outcomes of the workshop, perspectives from across the full knowledge chain were integrated into six general principles to guide the development and deployment of SeaD-bombs.
4. **Resource integration**. Collected and compiled information on locally available materials, summarizing their degradation rates, costs, carbon footprints, and potential harmful releases.
5. **Application development**. Explored mathematical equations suitable for the preliminary assessment of SeaD-bomb stability across different designs, taking into account specific storm wave conditions, and ultimately developed a user-friendly web application.

Main results: The following results were obtained based on the above methods, corresponding respectively to the five objectives mentioned above:

1. **Necessity**: The literature review on contemporary reef restoration revealed that most projects are small in scale and cost-intensive, limiting broader impact. This is further supported by the second review on Artificial Reef (AR) deployment trends, which highlights the growing recognition of ARs as a component of active restoration. However, 70% of AR deployments globally covered less than 1 ha, and individual modules were typically smaller than 10 m^2, indicating a generally minimal deployment scale. In addition to their limited size, most current ARs still rely on non-degradable materials that are not environmentally compatible, undermining restoration goals. Despite these challenges, meta-analyses demonstrate that ARs can yield strong positive ecological effects, particularly by enhancing community richness and population abundance. One aspect that could be improved is their performance in supporting organism fitness (e.g., growth and survival), which still falls short when compared to natural reefs. These findings underscore the urgent need for innovative, scalable, biodegradable reef structures, such as SeaD-bombs, to effectively support biodiversity and ecological function in offshore environments.
2. **Key challenges**: Major challenges include selecting appropriate biodegradable materials with predictable degradation timelines, ensuring short-term structural stability under wave action, securing regulatory approval, and guaranteeing species recruitment in areas with limited larval supply.

3. **Guiding principles**: Six principles were developed to guide SeaD-bomb design and deployment:
    - Principle I: Providing effective Window of Opportunity — enable settlement of reef-builders
    - Principle II: Designing for durability — support reef formation
    - Principle III: Prioritizing biodegradability — aim for no-regret
    - Principle IV: Enabling upscaling — facilitate mass impacts
    - Principle V: Allowing permit-friendly deployment — toward global scope
    - Principle VI: Embracing reef-favored locations — maximize success.
4. **Material list**: A comprehensive list of locally available natural and composite biodegradable materials was compiled. These materials were summarized for their mechanical properties, cost-efficiency, degradation rates and environmental impacts.
5. **Stability assessment approach**: A mathematical model based on the Morison equation was developed for SeaD-bomb stability evaluation. Based on this mathematical model, a web application (accessible via link：https://nioz.shinyapps.io/OffshoreStability_V2/) was developed to assist users in estimating the sliding, overturning, and floating risks of different SeaD-bomb designs under specific site conditions.

Conclusions: SeaD-bombs are designed to create opportunities for natural reef formation, enhance habitat quality, and gradually degrade to minimize human impact. These features support the transition from active intervention to spontaneous recovery, facilitating upscaling and promoting sustainable biodiversity recovery by improving organism fitness. The development of guiding principles, material list, and stability assessment approach lays the groundwork for SeaD-bomb prototyping and pilot testing. SeaD-bombs align with the Nature Enhancement policy of the Netherlands and have strong potential to contribute to scalable, no-regret marine restoration efforts.

General introduction

Structurally complex marine habitats are fundamental to sustaining marine biodiversity and ensuring the proper functioning of ocean ecosystems (Duarte et al., 2020). However, over the past several centuries, human activities have profoundly altered marine environments, leading in particular to the large-scale loss of natural reef structures such as oyster reefs and coral reefs (McAfee and Connell, 2021). Globally, approximately 85% of oyster reefs and nearly 50% of coral reefs have disappeared (Bersoza Hernández et al., 2018; Hughes et al., 2023). This has resulted in the simplification of seafloor substrates, a decline in biodiversity, and a diminished capacity of marine ecosystems to resist disturbances associated with climate change and human impacts.

The Dutch North Sea: background and challenges

In the Dutch North Sea, formerly rich benthic habitats have also undergone substantial degradation. Structurally complex environments such as flat oyster reefs, once widespread, have now almost entirely vanished (Thurstan et al., 2024). The current seafloor landscape is dominated by homogeneous sandy and muddy substrates, offering limited support for marine life. Meanwhile, the Dutch North Sea is undergoing rapid spatial development, including the expansion of offshore wind farms, which brings both new challenges and opportunities for ecological restoration (Bos et al., 2023; Kamermans et al., 2018). On one hand, these wind farm zones, where bottom trawling is typically prohibited, offer potential refuges for biodiversity recovery. On the other hand, effectively restoring habitats in these high-energy, dynamic environments requires technological and strategic innovation.

At the policy level, the Netherlands places strong emphasis on Nature Enhancement in the marine domain, integrating ecological restoration into spatial planning processes (Kingma et al., 2024). There is an explicit requirement for biodiversity enhancement to be achieved in tandem with infrastructure development, such as offshore wind energy projects. Despite this favorable policy landscape and urgent restoration needs, existing reef restoration projects are often small in scale, costly, and rely on non-degradable materials, which significantly limits their functionality and scalability—especially in the energetically dynamic conditions of the North Sea.

SeaD-bombs: an innovative solution

To address these challenges, we have proposed an innovative ecological restoration approach: SeaD-bombs (Sea Diversity bombs). This approach is specifically designed for highly dynamic offshore environments such as the Dutch North Sea, providing a low-cost, easily deployable, and fully biodegradable reef structure. By creating "Windows of Opportunity", SeaD-bombs support the settlement and expansion of reef-building species, such as flat oysters, and gradually transition into self-sustaining natural reefs with full ecological functionality. This transition not only enables rapid biodiversity recovery but also allows the structures to fully degrade and integrate into the natural environment without requiring post-deployment intervention—achieving "No-regret" ecological restoration.

Compared to traditional artificial reefs, SeaD-bombs offer distinct innovations and critical advantages:

- *Clear functional objectives*: Focused on facilitating the recruitment and expansion of reef-building species (e.g., flat oysters), thereby promoting natural reef recovery.
- *Ecologically compatible materials*: Use of biodegradable materials avoids long-term environmental burden and simplifies the permitting process.
- *Scalability*: Designed for industrial production and deployment, SeaD-bombs offer cost-efficiency and the potential for large-scale offshore restoration.
- *Wind farm compatibility*: Suitable for co-deployment with offshore wind infrastructure, thereby enhancing the ecological value of nearshore development zones.

Report structure

This report systematically presents the development and application of SeaD-bombs through the following core components:

1. Articulating the necessity of developing SeaD-bombs in the context of the Dutch North Sea and global restoration challenges;
2. Identifying the key challenges encountered in the development and deployment of SeaD-bombs;
3. Proposing a set of guiding principles for the design and implementation of SeaD-bombs;

4. Collecting and evaluating potential materials for constructing SeaD-bombs, balancing ecological suitability with practical feasibility;
5. Exploring methods for assessing the stability of SeaD-bombs under offshore conditions, and developing a practical evaluation tool.

This report aims to lay the groundwork for scaling up SeaD-bombs in the Dutch North Sea, while also providing insights and reference for similar ecological restoration initiatives worldwide.

1. Demonstrating the necessity of developing SeeD-bombs

1.1 Literature review on the scale and cost of contemporary reef restoration

1.1.1 Summary

Oyster and coral reefs have historically thrived in seas worldwide, spanning from coastal zones to the deep sea. However, the profound impact of human activities over recent centuries has resulted in substantial changes to reef habitats on an expanding spatial scale (Dietzel et al., 2021; McAfee and Connell, 2021). It is estimated that 85% of global oyster reefs have vanished (Beck et al., 2011), with coral reef cover worldwide experiencing a roughly 50% decline (Eddy et al., 2021). Despite the enduring history of reef restoration and the continual emergence of new initiatives, a growing body of research emphasizes a significant mismatch between the scope of present-day reef restoration endeavors and the global decline of reefs (Duarte et al., 2020; Hemraj et al., 2022; Hughes et al., 2023). To illustrate, the 53-year restoration efforts in the United States managed to rebuild only 4.5% of the lost oyster reefs within the designated regions (Bersoza Hernández et al., 2018).

To examine the latest trends in the area and costs associated with global reef restoration, we compiled and analyzed existing records through literature research (n = 1576). The results reveal that the total area of reef restoration worldwide is 6,307 ha (Fig. 1a), comprising 6,219 ha of oyster and 88 ha of coral reefs. The median area achieved by individual oyster reef restoration projects globally is 0.5 ha, while that for coral reefs is 0.007 ha (Fig. 1a). Both values indicate the nearly trivial scale of current reef restoration efforts, notably falling well short of their naturally occurring population size (typically over 1 ha; Hughes et al., 2023; Zaneveld et al., 2016), highlighting the urgent need for upscaling. Despite the limited number of studies (n = 189) reporting the costs of reef restoration, a significant positive linear relationship between the area of reef restoration and the associated costs was identified, with a slope of 0.45 for oyster reefs and 0.51 for coral reefs (Fig. 1b). This implies a trend where larger restoration projects tend to incur comparatively lower costs per unit area. Specifically, the median cost for oyster reef restoration is $163,490 per hectare, whereas for coral reef restoration, it is $790,000 per hectare (Fig. 1b). We caution against the notable variability and uncertainty in the reported costs, stemming from the diverse methods employed in reef restoration projects and discrepancies in labor prices and other construction-related expenses across different countries (Bersoza Hernández et al., 2018; Hughes et al., 2023). Nevertheless, this rudimentary analysis somewhat highlights the potential cost-effectiveness of scaling up and emphasizes the necessity of cost reduction in future sea restoration practices.

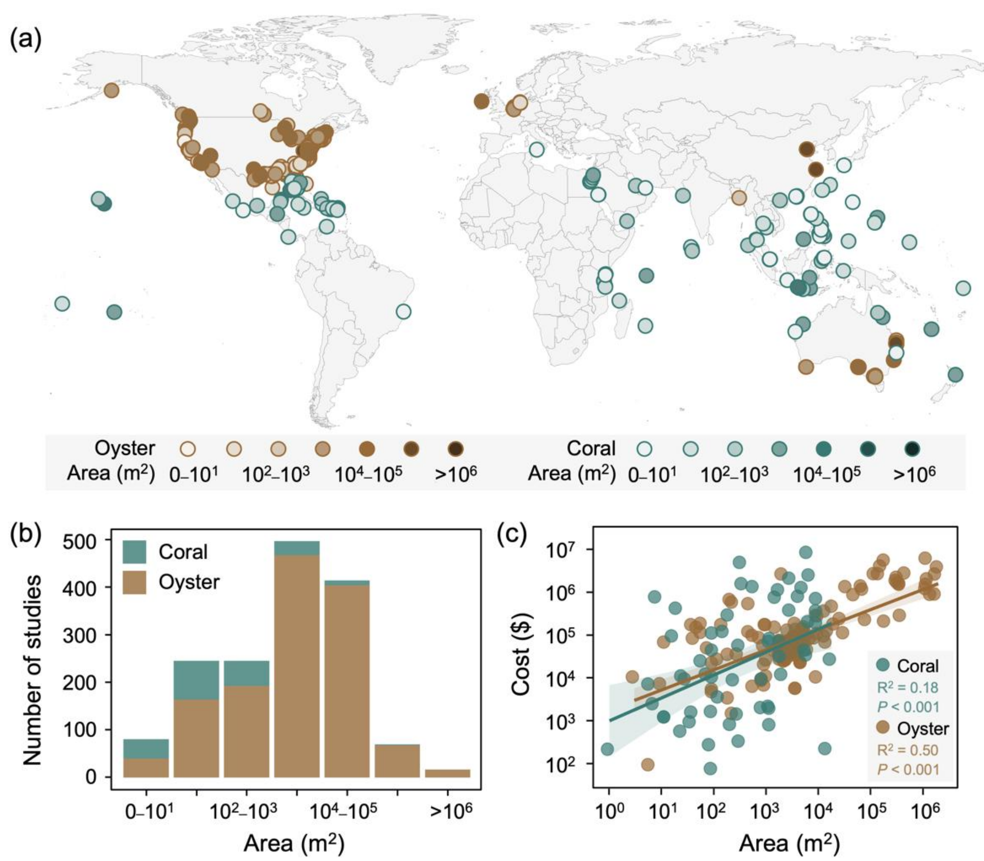

Fig. 1 (a) Geographic distribution of reef restoration endeavors around the world (n = 1576). (b) Frequency distribution of reported reef restoration areas (n = 1576). (c) Relationship between reef area restored and associated costs (n = 189).

1.1.2 Related methods

The dataset on contemporary reef restoration areas and costs used in this study is an update of the latest relevant datasets, including the U.S. oyster restoration dataset published in 2018 (covering 1964-2017 with 1,176 records reporting restoration areas, 89 of which reported costs; Bersoza Hernández et al., 2018) and the global coral restoration dataset published in 2023 (covering 1979-2022 with 221 records reporting restoration areas, 58 of which reported costs; Hughes et al., 2023). To fill in gaps regarding *i*) oyster restoration in the U.S. after 2017; *ii*) oyster restoration in other global regions up to and including 2024; and *iii*) coral reef restoration worldwide in 2024, we searched the Web of Science Core Collection on October 20, 2024. The search terms used were: Keyword = oyster restoration, Period = 1978-2024; and Keyword = coral restoration, Period = 2024. This search resulted in 1,258 publications on oyster restoration and 224 publications on coral restoration.

The following criteria were applied to further filter these publications: *i*) projects or experiments involving proactive reef restoration rather than natural reef recovery; *ii*) studies conducted in intertidal, subtidal, or offshore areas rather than in laboratories, mesocosms, or aquariums; *iii*) studies reported the area and/or cost of reef restoration. Ultimately, 55 publications on oyster reefs and 0 publications on coral reefs were retained. For the selected publications, we extracted the reported study sites and implementation years. If a publication reported data from multiple sites, each site was treated as a separate record. Records from the same site and year were considered the same restoration project/experiment, and duplicates were removed, leaving only unique records. For valid records, we documented the following variables: title, study site (country and region), latitude, longitude, restoration species, implementation year, restoration area, and involved cost (if reported). When coordinates were not provided, we obtained latitude and longitude data by locating the study site on Google Earth. The final integrated dataset contains 1,355 records reporting oyster reef restoration areas and 221 records reporting coral reef restoration areas, including 131 records reporting oyster reef restoration costs and 58 records reporting coral reef restoration costs. Visualizations were created using R studio (version 4.3.2).

1.2 Literature review on the application trends of reef structures in sea restoration

1.2.1 Summary

Artificial reefs (ARs), hard structures submerged intentionally or accidentally by humans (Bracho-Villavicencio et al., 2023), have transitioned from tools originally developed for fishing and aquaculture to promising active interventions for accelerating sea restoration (Lee et al., 2018; Vivier et al., 2021). By relieving habitat pressures and providing opportunities for marine life to colonize, shelter, feed, and reproduce, ARs offer potential to counteract habitat degradation and foster diverse, productive ecosystems (Higgins et al., 2022; Tickell et al., 2019). The practice of using ARs spans thousands of years, with materials, sizes, designs, and purposes varying across time and regions (Bracho-Villavicencio et al., 2023).

Our systematic review compiled 494 peer-reviewed scientific publications from 1980 to 2024. While this number does not fully capture the total deployment of ARs, it reflects the overall research interest in ARs worldwide. Since the early 21st century, studies on ARs have proliferated across five continents and 55 countries (Fig. 2a), with the highest research intensity in the United States (n = 126), followed by China (n = 59) and Australia (n = 37). Most ARs examined were deployed in marginal seas within 10 km of the coastline and at depths shallower than 30 m, while only a few were placed in rivers or lakes (n = 6). Regardless of their objectives or materials, 70% of AR deployments globally covered less than 1 ha (Fig. 2b), and individual modules were typically smaller than 10 m^2 (Fig. 2c). These findings suggest that ARs remain minimal in scale—especially in comparison to natural benthic habitats such as oyster reefs and coral reefs, which commonly exceed 1 ha (Hughes et al., 2023; Thurstan et al., 2024)—highlighting the urgent need for scaling up.

The deployment of ARs has historically been dominated by socioeconomic-oriented applications (Fig. 2d), with 275 ARs examined primarily aimed at boosting commercial fisheries, supporting marine aquaculture, and promoting tourism. Since the 2010s, there has been a notable shift toward restoration-oriented ARs (n = 162; Fig. 2d), designed to protect specific habitats, mitigate habitat degradation, or facilitate habitat recovery. This transition has accelerated in the 2020s (Fig. 2e), with publications on restoration-oriented ARs over the past five years (n = 84) surpassing the total from the previous 40 years (n = 78). As a result, restoration-oriented ARs have now overtaken socioeconomic-oriented ones as the dominant focus, underscoring the growing recognition of ARs as a key element in ecological restoration. The drivers behind this transition include mounting public concerns about overfishing (Yan et al., 2021), ecosystem degradation (Duarte et al., 2020), and climate change (Urban, 2015), coupled with increased support from international and regional policies, legislation, and funding dedicated to ecological restoration (Fischer et al., 2021; Hermoso et al., 2022; Techera and Chandler, 2015). Additionally, a smaller yet rising number of ARs (n = 42) have been deployed for research-oriented purposes (Fig. 2d, e), such as evaluating different AR designs, tracking biological responses, or assessing changes in abiotic conditions.

Materials have been a central focus in AR studies (n = 481), as their physicochemical properties, texture (e.g., micro-roughness), and color influence AR costs, structural performance, and carbon footprint (Bracho-Villavicencio et al., 2023; Grasselli et al., 2024; Vivier et al., 2021). From 1980 to 2024, inorganic and metal components, such as cement, lime, clay, slag, and steel, have consistently been the predominant materials for the main structure of ARs (n = 409), with their adoption steadily increasing over time (Fig. 2f, g). Such ARs typically involve various custom-made concrete structures, rock piles, intentionally or accidentally submerged ships and vehicles, and decommissioned oil rigs. The second most widely used materials are synthetic and composite (n = 42; Fig. 2f), such as plastics, PVC, glass, ceramics, and discarded tires. Their application peaked before 2010 (86%; Fig. 2g) but has since declined due to environmental risks (e.g., toxic substance release, heavy metals, and microplastics; Bracho-Villavicencio et al., 2023; Techera and Chandler, 2015) and legislative restrictions (e.g., dumping laws; *London Convention, 1972*). Relatively few ARs (n = 30) have been constructed using natural and degradable materials (Fig. 2f), such as wood, shells, and biopolymers derived from underutilized biomass, with 50% of such ARs appearing in the past five years (2020–2024) and 67% within the past decade (2015–2024; Fig. 2g). Notably, successful applications of ARs using such materials have recently emerged (Carral et al., 2023; Dickson et al., 2023; Talekar et al., 2024), highlighting their significant yet underutilized potential (e.g., minimizing environmental harm and simplifying permitting procedures) in advancing marine restoration.

Overall, a clear paradox emerges in AR evolution from our analysis: while ARs are increasingly aimed at ecological restoration, the continued reliance on traditional materials incompatible with the marine environment may undermine this goal and hinder scaling up.

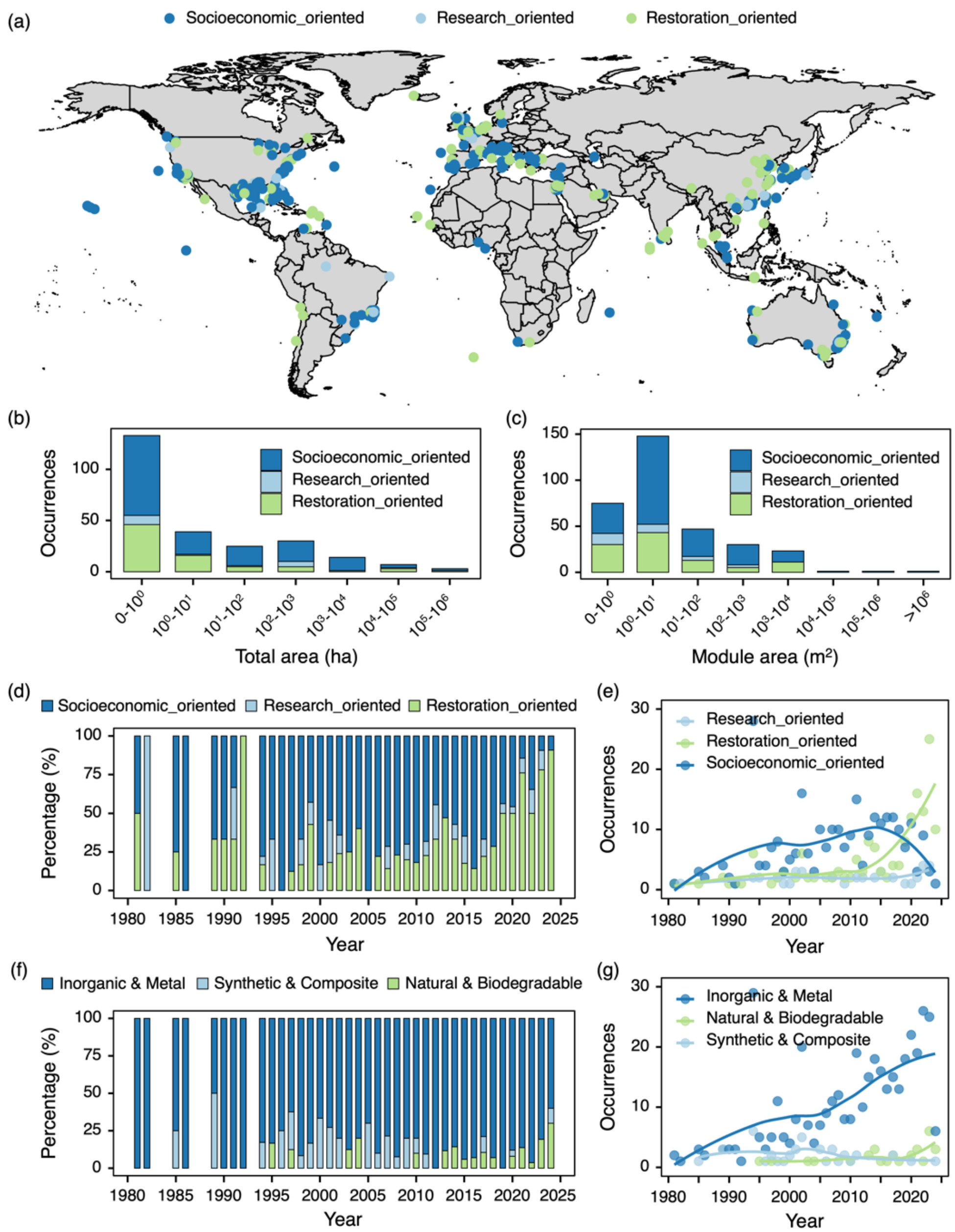

Fig. 2 Overview of artificial reef (AR) studies from 1980 to 2024. (a) Global distribution of AR studies (n = 494) by application purpose: Socioeconomic-oriented (e.g., fisheries, aquaculture, tourism); Research-oriented (e.g., AR design, biological monitoring, abiotic assessment);

Restoration-oriented (e.g., habitat protection, degradation mitigation, recovery). (b) Frequency distribution of AR deployment area per study. (c) Frequency distribution of AR module area per study. (d) Annual percentage of AR applications by purpose. (e) Trends in AR applications over time by purpose. (f) Annual percentage of AR applications by primary material: Inorganic and metal (e.g., cement, lime, clay, slag, steel); Synthetic and composite (e.g., plastics, PVC, glass, ceramics, discarded tires); Natural and degradable (e.g., wood, shells, biopolymers). (g) Trends in AR material use over time.

1.2.2 Related methods

The literature search was conducted on 22 December 2024 using ISI Web of Science with the terms: TITLE (“artificial reef” OR “artificial habitat” OR “man-made reef”). Reference lists and databases from reviews were also examined for additional studies. A total of 13,694 potentially relevant publications were evaluated for inclusion following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) screening procedure (Fig. 3), leading to 494 publications that underwent full-text review. Key descriptors extracted included publication details (i.e., journal, publication year); year of AR deployment; purpose of AR deployment; AR deployment location (i.e., continent, country, latitude, longitude); AR deployment scale (including individual module area and/or total deployment area); and primary material of deployed ARs. Given variations in terminology and descriptions across studies, AR deployment purposes and primary materials were further clustered to identify overarching trends. AR deployment purposes were categorized into 1) socioeconomic-oriented, 2) restoration-oriented, and 3) research-oriented, while AR primary materials were grouped into 1) inorganic and metal, 2) synthetic and composite, and 3) natural and degradable. See Table 1 for specific content (i.e., purposes and materials) under each category.

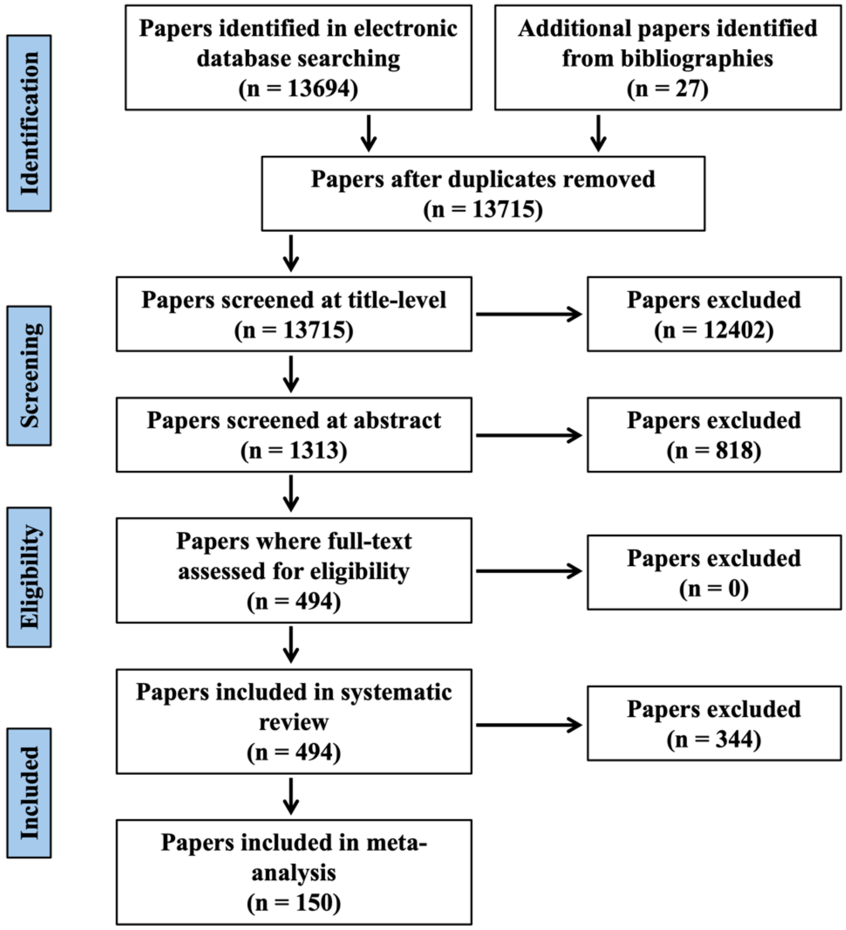

Fig. 3 PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram depicting the study selection process for the systematic review and meta-analysis.

Table 1. Artificial reef deployment purposes and primary materials were categorized based on statements from each study during the systematic literature review.

Items	Grouping categories	Number of papers	Related keywords
Purposes	Socioeconomic-oriented	275	Production, Fisheries, Aquaculture, Tourism, Recreational fishing
	Restoration-oriented	162	Mitigation, Restoration, Protection, Conservation, Management

	Research-oriented	42	Research, Monitoring, Impacts, Effectivity, Material
Materials	Inorganic and metal	409	Concrete, Cement, Metal, Steel, Slag, Ash, Cinder, Limestone, Clay,
	Synthetic and composite	42	Fibreglass, Plastic, Tires, PVC, Acrylic, Polyrthylene
	Natural and degradable	30	Shells, Wood, Timber, Bamboo, Biomass, Biogenic

1.3 Meta-analysis on the effectiveness of reef structures in supporting marine life

1.3.1 Summary

Today, artificial reefs (ARs) are widely present in global seas and are proliferating rapidly (Ramm et al., 2021), evolving from accidental ARs like sunken ships to purpose-built conventional ARs tailored to ecological needs (Carral et al., 2023). However, conventional ARs often face criticism for their reliance on unsustainable materials and the generation of harmful waste (Carral et al., 2023; Grasselli et al., 2024). In response, green ARs featuring a reduced carbon footprint have emerged, starting to take environmental and sustainability issues into account (Carral et al., 2023; Huang et al., 2016). Nonetheless, beyond a few high-profile cases of success or failure, the biodiversity benefits surrounding ARs have not been widely examined (Bracho-Villavicencio et al., 2023; Higgins et al., 2022; Vivier et al., 2021). Given indications that ARs could be altering marine ecosystems on a massive scale (Folpp et al., 2020; Paxton et al., 2024), it is imperative to critically assess their effectiveness in enhancing biodiversity, addressing both opportunities and challenges to optimize their role in advancing marine biodiversity recovery.

We extracted 500 response ratios from 150 studies to assess how ARs benefit marine organisms at different biological levels (Methods see below). The distribution of response ratios varied considerably across habitat types and taxonomic groups, with the highest representation from soft-bottom seabeds (n = 291) and vertebrates, primarily fish (n = 264). Most studies compared AR sites with either natural reef reference sites (47.6%) or unstructured control sites (e.g., adjacent bare substrate; 44%), while only 8.4% used pre-deployment degraded sites as controls (i.e., before vs. after). Over 90% of the studies focused on community-level (e.g., diversity, richness; 41.6%) and population-level responses (e.g., abundance; 49%), whereas individual-level (e.g., size, biomass; 3.4%) and fitness-level responses (e.g., survival, condition, reproduction; 6%) received less attention. This imbalance highlights that existing AR research has largely focused on immediate biodiversity responses, while the long-term sustainability of rebuilt biodiversity remains underexplored.

Compared to unstructured and before controls, AR areas consistently exhibited higher values across different biological levels (Fig. 4). The impact of ARs on population enhancement was particularly strong, with abundance 144% higher than in unstructured controls and 142% higher than in before controls (Fig. 4). Among these, ARs deployed on hard-bottom seabeds showed the greatest population gains, especially for fish and bivalves (Fig. 5). ARs also led to notable improvements in community metrics, with diversity and richness 97% higher than in before controls and 41% higher than in unstructured controls (Fig. 4). The strongest community-level effects were detected in reef-based habitats (e.g., coral reefs and oyster reefs), primarily benefiting fish and bivalves (Fig. 5). Individual metrics in AR areas were 42% higher than in before controls and 34% higher than in unstructured controls (Fig. 4), with little variation across habitat types and taxonomic groups (Fig. 5). Fitness indicators in AR areas were 180% higher than in unstructured controls (Fig. 4), suggesting that marine organisms in AR areas can survive, reproduce, and recruit successfully. No data regarding fitness were available for comparison with before controls.

Compared to natural reef reference sites, AR deployment also demonstrated a population-level enhancement effect (20%; Fig. 4), particularly in vegetation-based habitats (e.g., seagrass beds) and among fish populations (Fig. 5). Community (-4%) and individual (1%) metrics were comparable between AR areas and reference sites (Fig. 4), indicating that ARs have promoted similar community diversity and individual size. Unexpectedly, fitness indicators in AR areas were much lower than in reference sites (-42%; Fig. 4), with the most pronounced negative response ratios observed in soft-bottom seabeds, particularly for fish and invertebrates (Fig. 5). Notably, negative response ratios signify that AR areas had lower metric values than reference sites but do not imply a negative effect.

Overall, our analysis suggests that ARs consistently benefit marine organisms across multiple levels, including supporting biodiversity, increasing population abundance, and enhancing individual size. Nonetheless, the evaluation of fitness highlights a limitation: while AR deployment improves the habitat quality of unstructured and pre-deployment degraded sites and provides favorable conditions for the survival, growth, and reproduction of marine organisms, it has not yet achieved the ecological equivalence of natural reef habitats. This may be because some degradation drivers, such as pollution, hydrodynamics, and sediment dynamics, still persist.

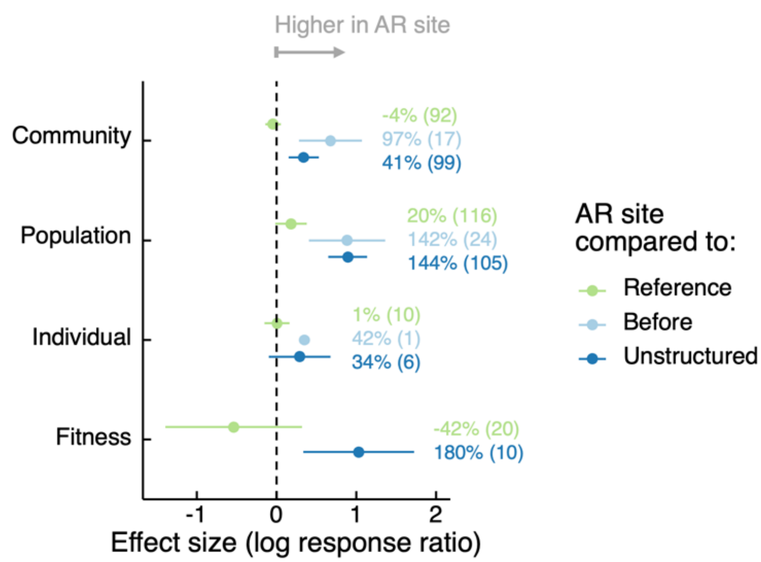

Fig. 4 Forest plots of response ratios (with 95% confidence intervals) for biological metrics affected by artificial reefs (ARs), pooled across habitat types and taxonomic groups. Metrics are categorized into community-level (e.g., diversity, richness), population-level (e.g., abundance), individual-level (e.g., size, mass), and fitness-related (e.g., survival, condition, reproduction). A positive response ratio indicates that the metric at AR sites is higher than at natural reefs (reference), nearby unstructured habitats (unstructured), or pre-installation conditions (before), whereas a negative response ratio indicates it is lower. Labeled values represent the average percentage difference between AR sites and the reference, unstructured, or before controls, with sample sizes shown in parentheses.

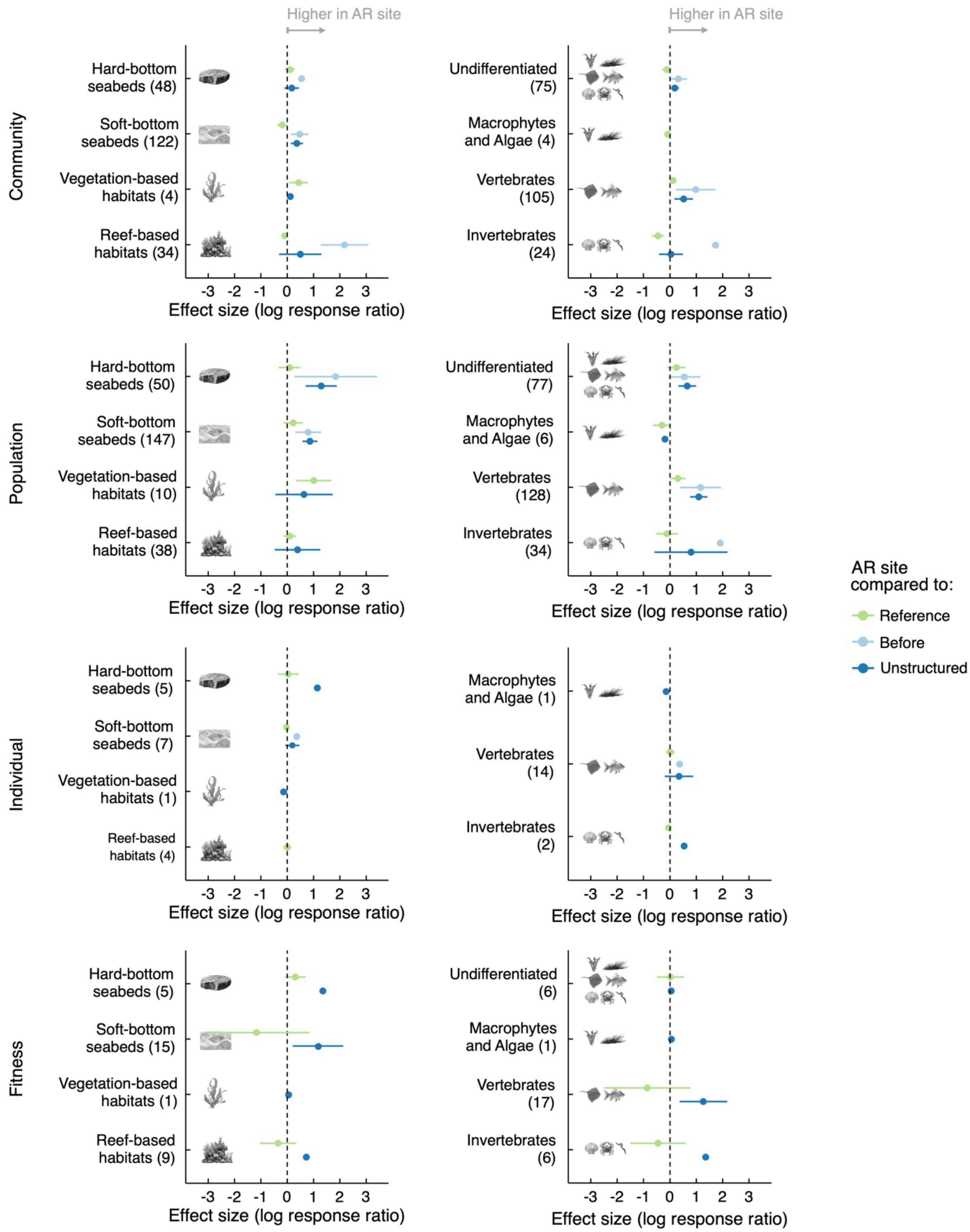

Fig. 5 Forest plots of response ratios (95% confidence intervals) for community, population, individual, and fitness metrics affected by artificial reefs (ARs), grouped by habitat type (left

panels) and taxonomic group (right panels). Habitat types are classified as hard-bottom seabeds, soft-bottom seabeds, vegetation-based habitats (e.g., seagrass beds, kelp forests), and reef-based habitats (e.g., coral reefs, oyster reefs). Taxonomic groups are categorized as invertebrates (e.g., bivalves, crustaceans, gastropods), vertebrates (e.g., fish, nekton), macrophytes and algae, and undifferentiated organisms. A positive response ratio indicates that the metric at AR sites is higher than at natural reefs (reference), nearby unstructured habitats (unstructured), or pre-installation conditions (before), whereas a negative response ratio indicates it is lower. Numbers in parentheses indicate the sample size for each analysis.

1.3.2 Related methods

Additional exclusion criteria were applied to screen reviewed publications (n = 494; Fig. 3) for meta-analysis: *i*) studies that lacked comparisons with reference habitats, including natural reference sites, unstructured control sites (e.g., bare sand), or degraded sites before AR installation; *ii*) studies from which response ratios could not be calculated, such as those using stable isotope analysis, solely performing multivariate analyses of community composition, or reporting responses as percentages. A total of 150 publications were included (Fig. 3), and the following descriptors were extracted: taxonomic classification of monitored organisms, type of measured response, experimental design (e.g., control vs impact, before vs after), and type of control habitat (i.e., natural reference, unstructured control, or pre-installation condition). Response types were grouped to facilitate systematic comparisons across biological levels: 1) community, 2) population, 3) individual, and 4) fitness. Specific response types under each group are detailed in Table 2. Open-source graphical digitizer software (i.e., PlotDigitizer; https://plotdigitizer.com/) was employed to extract data from figures and tables in the included publications to calculate the log response ratio (lnRR) using the equation below. Species-specific data were extracted when possible; otherwise, taxonomic group averages (e.g., all fish) were used.

$$\ln[RR] = \ln[B\ or\ R] - \ln[A\ or\ C]$$

Here, R represents the mean value at the AR installation site, C represents the mean value at the control site, A represents the mean value after AR installation, and B represents the mean value before AR installation. For studies with multiple unpaired control sites, the raw data from control sites were averaged to calculate the lnRR for each AR installation site.

Table 2. Organism response types to artificial reef installation were classified into four groups, corresponding to four biological levels, for use in the meta-analysis. The recorded numbers do not equal the number of scientific publications, as a single study may report multiple response metrics.

Response group	Response type	Number of records
Community	Diversity	59
(n = 208)	Evenness	22
	Richness	127
Population	Abundance	186
(n = 245)	Density	1
Individual	Size	13
(n = 17)	Mass	62
Fitness	Survival	3
(n = 30)	Growth	11
	Reproduction	5
	Recruitment	11

1.4 Conclusion

Lack of scale makes that restoration endeavors fall greatly short of compensating for the historical loss of marine habitats and biodiversity. The overall ecological effects of artificial reefs (ARs), as an element of active restoration, are strongly positive (Fig. 4, Fig. 5), but their small size and limited deployment highlight the need for a paradigm shift in AR approaches to achieve significant upscaling. Moreover, restoration-oriented AR applications could be more effective in promoting sustainable biodiversity recovery by bridging the gap between physical habitat provision and organism fitness, with the integration of complementary active reef restoration techniques holding great promise for further enhancing habitat quality.

Active reef restoration and AR deployment have so far remained two relatively independent strategies. The former targets historically degraded coastal habitats with minimal natural recovery, where unreliable larval supply and the lack of suitable settlement substrates are the primary bottlenecks hindering the establishment of reef-building species (Rinkevich, 2014, 2015a). Common techniques include adult/spat transplantation (Rinkevich, 2015b), substrate modification (Goelz et al., 2020), positive species interactions (Reeves et al., 2020), acoustic enrichment (Gordon et al., 2019), and integrated multi-trophic aquaculture (Giangrande et al., 2021). However, these approaches are often constrained to small-scale applications due to limited cost-effectiveness (Bersoza Hernández et al., 2018; Hughes et al., 2023). Furthermore, reef formation is inherently a long-term process (e.g., ~10 years for oyster reefs, Bersoza Hernández et al., 2018; ~30 years for coral reefs, Rooper et al., 2011), providing minimal biodiversity support until sufficient relief height is reached (Hemraj et al., 2022; Schulte et al., 2009). In contrast, AR efforts have largely focused on enhancing the physical structure of habitats (Lemoine et al., 2019; Ramm et al., 2021), a feature immediately contributing to biodiversity recovery. However, static AR structures alone are insufficient to generate a gradually developing and expanding living ecosystems, as is the case for active reef restoration. Integrating active reef restoration techniques into AR innovation can maximize the benefits of both components, delivering immediate and mid-term biodiversity gains comparable to conventional AR designs while also fostering the gradual development of reef-building species to enhance habitat quality, thereby promoting sustainable biodiversity recovery by addressing bottlenecks that limit the fitness of resident organisms (Fig. 2, Fig. 3). The latter is particularly ensured by the ecological functions of reef-building species, such as water filtration, hydrodynamic attenuation, and sediment stabilization (Wu et al., 2024; zu Ermgassen et al., 2013), which are crucial for the survival, growth, reproduction, and recruitment of most marine organisms (Adams and Greeley, 2000; Duarte et al., 2020). Therefore, the objective of AR applications should shift from offering permanent physical structure toward enabling the establishment of living functional reef-habitats in degraded or naturally barren areas. A key mechanism behind this approach is the ability of such ARs to create Windows of Opportunity (WoO; Appendix A1) for the successful establishment of reef-building species by *i*) providing attractive and stable substrates that mimic natural reef structures or seabed topography and *ii*) ensuring both current and future reproductive capacity through adult addition and larval/spat settling.

Therefore, we advocate an innovative AR approach, termed SeaD-bombs (i.e., Sea Diversity bombs), emphasizing the creation of WoO for transition to natural reefs, gradual degradation to minimize human impact, and scalable applications as defining features of innovative ARs. Despite emerging attempts (Bersoza Hernández et al., 2018; Ramm et al., 2021; Vivier et al., 2021), advancing AR innovation by optimizing materials and deployment strategies remains a trial-and-error process. To ensure the effective implementation of SeaD-bombs for sustainable biodiversity recovery, a clear manifest outlining ecologically, economically, and legally sound guiding principles must be established.

2. Identifying key challenges that need to be addressed in SeaD-bomb development

To promote the development of SeaD-bombs, a workshop (Fig. 6) was held in Utrecht on November 27, 2024, with 20 participants from 13 institutions attending in person, including ecologists, civil engineers, legal scholars, environmental consultants, and NGO representatives (see Appendix A2 for participant details). The workshop focused on key challenges related to material selection, stability calculations, and cost-effective deployment, with key takeaways summarized below:

Fig. 6 A photo from the SeaD-bombs workshop (held in Utrecht on November 27, 2024).

2.1 Discussion 1: How to select materials for SeaD-Bombs?

2.1.1 Key considerations defined in workshop

- *Objective-dependent base material*
  - To facilitate reef-builder establishment, the material should allow for attachment and growth.
  - To facilitate reef-community development, the material should ideally have a high structure (to prevent burial) and great habitat complexity (fractal structure to provide hiding spaces).
- *Degradation rate:*
  - Many natural materials degrade slowly, with exact values being material dependent (e.g., debarked wood, tree wood, limestone). This suits medium long-term stability that fits reef restoration.
  - Synthetic biodegradable materials *can* be designed to degrade faster, making them also suitable for shorter-term ecological goals.
- *Lifespan vs Usage:*
  - Material lifespan must balance structural tasks (e.g., anchoring must last longer than settling substrate) with ecological functional tasks (e.g., reef-builders establishment or reef-community develop).
  - If material lifespan matches wind farm operations (20 years), it can serve dual purposes during the wind farm's lifecycle.
  - In non-wind farm environments, lifespan requirements are more flexible and can be tailored to specific ecological goals.
- *Ecological requirements:*
  - Reef formation may for some species require specific ecological inputs, such as e.g. adding live oysters for natural reef establishment.
- *Ecotoxicity:*
  - Materials must avoid potential environmental toxicity to ensure usability and ecological safety.

To consolidate the interdisciplinary perspectives gathered during the SeaD-bombs workshop, we summarize the five key material selection considerations in Table 3. This table outlines their core insights and corresponding design implications.

Table 3. Comparative overview of material selection criteria for SeaD-bombs

Criterion	Description	Design Implication
Base material	Material should enable reef-builder attachment and promote reef-community structure (e.g., relief, shelter).	Select textured, complex forms with vertical elements to reduce burial and increase habitat complexity.
Degradation rate	Natural materials degrade slowly and suit mid- to long-term use; synthetics can be tuned for faster breakdown.	Match degradation speed to ecological goals—shorter for temporary aid, longer for full reef succession.
Lifespan vs. usage	Lifespan should balance structural (e.g., anchoring) and ecological functions (e.g., settlement substrate).	For co-use with wind farms, aim for ~20 years; elsewhere, tailor to specific restoration timelines.
Ecological requirements	Some reef-building species may require additional biological inputs (e.g., live oysters for recruitment).	Consider species-specific needs when selecting materials or integrating biological cues.
Ecotoxicity	Materials must avoid environmental toxicity to ensure ecological safety and legal compliance.	Exclude waste-derived, chemically treated, or heavy-metal-containing materials.

2.1.2 Recommendations

- *Using core-periphery design strategy for large-scale projects (e.g., 10×1 hectare).*
  - Long-lived core: use long-lasting materials in core areas to provide stable structures..
  - Short-lived periphery: use faster-degrading materials in peripheral areas to create ecological corridors and enable dynamic ecological adaptation.
- *Leverage legal frameworks.*
  - Use decommissioning laws as a reference to define the maximum acceptable degradation time of materials.

2.1.3 Challenges

- More a point of attention than challenge: To ascertain that materials selected cannot be perceived as “waste dumping”, be certain to avoid controversial materials like e.g., steel-slag (staalslakken).

2.2 Discussion 2: What affects SeaD-Bomb stability?

2.2.1 Key considerations

- *Seabed types:*
  - Sandy seabeds: Prone to burial, sandbank coverage, and scouring; require increased friction or embedded substrate design.
  - Rocky seabeds: May need interlocking structures to prevent slippage or loss in rock crevices.
- *Deployment location:*
  - Near wind farms: Account for accelerated hydrodynamic forces and turbulence around turbine structures.
  - Away from wind farms: Address wave shear stress and seabed morphodynamics.
- *Biofouling effects:*
  - Work with standard shapes to approximate hydrodynamic changes.
  - Use structures with higher safety factors to compensate for biofouling impacts.
  - Biofouling may sometimes increase stability by "gluing" (small) structures to hard substrates.
- *Ecological vs. Economic stability:*
  - Define stability thresholds that are acceptable from an ecological perspective (e.g., biodiversity outcomes) versus economic considerations (e.g., cost-efficiency, durability and preventing damage).
    - While from an ecological perspective some movement may be tolerable, often in/near economic zones (like windfarms) zero movement is the norm.
    - Too much movement will however hamper ecological use and development. For this reason an ecological stability norm is needed. This may require case by case (i.e., depending on nature-targets) discussion with ecological experts.
  - Prioritize ecological stability in areas with high conservation value, while balancing economic feasibility in other areas.
- *Allowable mobility:*
  - For some structures, tumbling (e.g., rolling) may be acceptable from an ecological perspective. Large-scale horizontal displacement should always be avoided.

- Select for the stability calculation the appropriate design-load cases, based on storm return periods (e.g., 10, 100, or 1000 years).

2.2.2 Recommendations

- *Overall design:*
  - Increase weight: Increase underwater density and solid volumes.
  - Reduce drag: Use compact, permeable designs.
  - Increase friction: Add rough surfaces or embed structures into the substrate.
- *Weight distribution:*
  - Heavy bottom and light top for rocky seabeds; weight distribution may be less critical for sandy seabeds.
- *Anchoring design:*
  - Where needed, structures can be linked together with anchors to enhance overall stability. But if such lines can be avoided, it will greatly benefit large-scale deployment.
  - When needed,
    - anchor lines must always be positioned carefully to avoid high-disturbance zones.
    - anchor weights should ideally be attached using ropes instead of chains, to prevent damage to soft structures.
- *Stability assessment:*
  - Apply the Morrisson equation to evaluate instability risks for large structures (e.g., cages), focusing on toppling and sliding forces. See examples from EcoFriend project.

2.2.3 Challenges

- How to define the allowable mobility of degraded elements?
- How to identify the disintegration forces that make things fall apart?

2.3 Discussion 3: How to optimize deployment while reduce costs?

2.3.1 Key considerations

- *Cost drivers:*

- Vessel operation is the largest cost factor (~€50,000/day), so key to minimize ship time and optimize usage of deck-space:
  - Optimizing requires making critical choices between e.g., offshore on deck construction (to maximize deck-space usage) *versus* onshore before shipping assembly (to minimize ship-time at sea).
  - Higher structures and more complex designs (as needed for ecology) may greatly increase deployment costs (by requiring more deck-space)

- *Multi-project integration:*
  - If SeaD-Bombs align with the lifespan of wind farms, resources can be shared during deployment, reducing overall costs.

2.3.2 Recommendations

- *Site selection:*
  - Identify the most suitable areas for SeaD-Bombs based on seabed morphology and bed shear stresses.
  - Use insights from projects like e.g., FutureMARES to locate sites with optimal carrying capacity for reef development.
  - Assess site-specific conditions to ensure deployment efficiency and ecological compatibility.
- *Deployment optimization:*
  - Pre-treat materials (e.g., pre-soaking wood) to reduce weight requirements and simplify assembly.
  - Simplify modular designs to minimize offshore assembly time and complexity.
  - Combining long-lived core structures with short-lived peripheries to create ecological gradients.

2.3.3 Challenges

- How to balance cost-effectiveness and ecological functionality in modular designs?
- How to prevent conflicts between multi-project integration (e.g., wind farms vs. reef ecosystems)?

3. Establishing a set of principles for SeaD-bomb development and deployment

The involvement of relevant stakeholders is a key component in sea rewilding practices to ensure that all required knowledge and expertise from various disciplines are covered. Finding mutual ground and reaching agreement on achievable ambitions between all parties is essential to establish effect at a system-scale (ter Hofstede and van Koningsveld, 2024). Incorporating input from ecologists, civil engineers, legal scientists, environmental consultants and NGOs, we propose six golden principles to guide the development and application of SeaD-bombs, aiming to enhance the effectiveness and scalability of reef restoration when active intervention is required, thus truly initiating the rewilding of our seas (Fig. 7).

3.1 Principle I. Providing effective WoO — steer larvae settlement

Reef-building larvae tend to thrive on hard and rough substrate surfaces (Johns et al., 2018; Vivier et al., 2021), which necessitates the main construction material of SeaD-bombs being rigid and preferably possessing a complex surface texture, particularly in terms of roughness and curvature (Carlson et al., 2024). To attract preferred reef-building larvae, thereby increasing the likelihood of forming target reefs, SeaD-bombs could be fashioned to closely mimic natural reefs in structure and morphology while incorporating shells or fragments of target species to serve as settling cues (Hanke et al., 2021; Schulte et al., 2009). Live individuals of the targeted species might in some cases (e.g. larvae-limited species) be included, but only if guaranteed disease-free and free of contaminating species (Pogoda et al., 2019). It is advisable to carefully time the installation of SeaD-bombs with consideration given to species-specific life history traits, such as deploying them during the optimal spawning season of target species, to minimize competition with other opportunistic colonizers (van den Brink et al., 2020).

3.2 Principle II. Designing for durability — support reef formation

The goal of rewilding is to minimize human intervention (Perino et al., 2019; Svenning, 2020), implying that once SeaD-bombs are installed, no additional procedures (e.g., maintenance) are recommended to further guide the recovery outcomes. Hence, SeaD-bombs must possess sufficient stability over time to resist displacement under the maximum instantaneous hydrodynamic impact in the target area (Vivier et al., 2021; Wellman et al., 2022). It is advisable to explore structural designs rather than merely increasing mass (Schmidt-Roach et al., 2023). This could, for example, involve incorporating holes in the main structure or introducing irregular extensions both vertically and horizontally to overall create porous structures with restricted drag. Swift accumulation of sediments may occur during/after intense hydrodynamic events (Caretti et al., 2021; Colden and Lipcius, 2015), particularly on soft-bottom systems, posing another challenge for SeaD-bombs to turn into self-sustaining reefs. It is thus essential to incorporate suitable vertical reliefs into the design criteria to ensure that SeaD-bombs can maintain functionality even when partially buried. Both requirements are highly site-specific, and addressing them necessitates site suitability assessments precede on-site deployment (see Principle VI).

3.3 Principle III. Prioritizing biodegradability — aim for no-regret

SeaD-bombs are essentially temporary, leveraged to facilitate oyster or coral recruitment opportunities. Once they result in living reefs hosting self-sustaining populations of adults, the SeaD-bombs should either actively or passively disappear, allowing natural forces to take precedence in subsequent development (Svenning, 2020). The resulting successful restoration would also greatly benefit the pristine character of the ecosystem. It is therefore essential to use biodegradable materials in the production of SeaD-bombs, with the expectation that they serve in providing WoO for reef formation over the required time span, gradually degrading thereafter until complete disappearance. Even in the worst-case scenario where SeaD-bombs fail to initiate reef formation post-installation, their biodegradable nature eliminates the necessity for retrieval and their crafted three-dimensional structure may also foster biodiversity as a temporary benefit before complete degradation, leaving no regrets after installation. The specific minimum degradation period depends on the timespan required for the functional recovery of the targeted reef-dominated habitats; for instance, oyster reefs may take 10 years (Bersoza Hernández et al., 2018), while coral reefs may require 30 years (Rooper et al., 2011). In cases where SeaD-bombs involve different components, their logical degradation sequence should be considered, such as: main structure lifespan < connector lifespan < anchor weight lifespan. This helps cut costs while ensuring effectiveness (see Principle IV). Additionally, the incorporation of biodegradable materials in general aids in streamlining the necessary permissions for deploying SeaD-bombs (see Principle V).

3.4 Principle IV. Enabling upscaling — facilitate mass impacts

Scalable strategies are indispensable for achieving more effective sea rewilding through reef restoration, with the key necessity being the mass-production and mass-deployment of SeaD-bombs at lower costs. Concerning mass-production, viable implementation approaches involve utilizing locally sourced biodegradable materials (e.g., economically unviable fruit trees; Dickson et al., 2023), affordable commercial bio-based materials (e.g., BESE®; Temmink et al., 2020), and industrially mass-manufactured products (e.g., transport pallets). These can be seamlessly integrated as components for SeaD-bombs without significant alterations to their dimensions, resulting in SeaD-bombs of varying sizes, whose deployment can enhance habitat diversity and cater to a broad spectrum of reef-dwelling species. Nevertheless, essential structural and stability designs remain imperative to ensure their functionality in steering larval settlement and supporting reef formation (see Principle I and II). Regarding mass-deployment, the wise choice is to leverage the industrial experience of local offshore operations (ter Hofstede et al., 2023), as they have discovered economies of scale and can provide technological advancements in terms of reducing transportation costs, streamlining deployment processes, and rationalizing deployment tools, thereby enhancing scalability efficiency. A content-depended reference is the utilization of connectors to assemble multiple SeaD-bombs and dropping them in a side-cast manner. This approach ensures controlled spacing between SeaD-bombs and offers lower costs compared to traditional crane installation, while also imposing fewer requirements on operating vessels. The challenge lies in making the SeaD-bombs robust enough in material and structure to maintain integrity during deployment. Note, special attention should be given in mass-deployment to expand the distance between deployment arrays to prevent the creation of "traps" that may affect other (larger) marine organisms (Komyakova et al., 2021), but it should still fall within the dispersal range of reef-building larvae to ensure connectivity between multiple deployment arrays.

3.5 Principle V. Allowing permit-friendly deployment — toward global scope

Artificial reefs may be considered unpopular and hence strictly regulated under marine legislation (e.g., legislation regulating the dumping of materials; *London Convention, 1972.*) in most countries, particularly due to concerns like improper material usage (Ramm et al., 2021; Techera and Chandler, 2015). Even if deployment is possible, this involves an intricate permitting process and often requires proposing dismantling arrangements (Techera and Chandler, 2015). The United Nations Convention on the Law of the Sea (UNCLOS; *United Nations Convention on the Law of the Sea, 1982*) and relevant conventions (*London Convention, 1972*) dealing with the prevention of marine pollution by dumping explicitly exclude the placement of matter for a purpose other than mere disposal, provided that such placement is not contrary to their aims, indicating that the placement of SeaD-bombs in principle is not dumping. Moreover, the "degradation" of SeaD-bombs is essentially synonymous with "dismantling" and occurs spontaneously without incurring costs or effort. Meanwhile, the deployment of SeaD-bombs is subject to rules of international law for the protection and preservation of the marine environment, such as the UNCLOS (*United Nations Convention on the Law of the Sea, 1982*) and the Convention of Biological Diversity (*Convention on Biological Diversity, 1992*). However, within that framework, there is nothing preventing coastal States from establishing national procedures that enable the initiation of sea-rewilding through large-scale reef restoration. Constructing SeaD-bombs using appropriate biodegradable materials with optimized degradation rates may provide a solution to mitigate these legal restrictions and simplify the permitting process. The selection of biodegradable materials must take into account factors such as having no negative effect on water quality, a low to negligible carbon footprint, and overall compatibility with the marine environment. The degradation rate of targeted materials must strike a balance, ensuring it is neither too short (in terms of days/weeks/months), resulting in inadequate support for reef development and resultant waste, nor too long (spanning hundreds of years), leading to redundant presence beyond reef formation (also see Principle III). Additionally, the judicious selection of deployment sites for SeaD-bombs represents a pivotal stride in advancing permit-friendly deployment (see Principle VI).

3.6 Principle VI. Embracing reef-favored locations — maximize success

Where to deploy is an essential consideration for applying SeaD-bombs, and strategically evaluating in this regard will undoubtedly bring a greater chance of success. In general, areas meeting three core criteria concurrently should be prioritized for SeaD-bombs deployment: *i*) suitable ecological niche where the target reef-building species currently or historically existed (i.e., conducive to reef growth; Hylkema et al., 2023); *ii*) larval sink of nearby or remote reef populations (i.e., larval availability; Ushijima et al., 2018); *iii*) human stressors such as trawling are impossible or strictly prohibited (e.g., in MPAs; Grorud-Colvert et al., 2021). On this basis, locations with the following attributes are anticipated to augment the cost-effectiveness of SeaD-bomb applications: nearby aquaculture farms cultivating target species; coastal or marine facilities incorporating nature-inclusive designs; well-regulated tourist and sightseeing zones. Subject to conditions and budget, detailed site suitability assessments based on in-situ monitoring and/or model simulations are advisable for further pinpointing optimal locations within these prioritized areas. Possible site-specific evaluation indicators include: *i*) maximum instantaneous hydrodynamic intensity, such as shear stress from currents and waves, which should not surpass the stability threshold of SeaD-bombs; *ii*) maximum sediment accumulation, which should fall significantly below the relief height of SeaD-bombs; *iii*) water conditions during extreme events, such as temperature during heatwaves and turbidity during storms, which should remain within the tolerance range of target reef-building species. Note, for the application of SeaD-bombs in scenarios where larvae are unavailable due to the extinction of target reef-building species, measures to provide a substantial supply of larvae need to be implemented in tandem. Concrete steps designed specifically for this purpose have already been suggested (ter Hofstede et al., 2023).

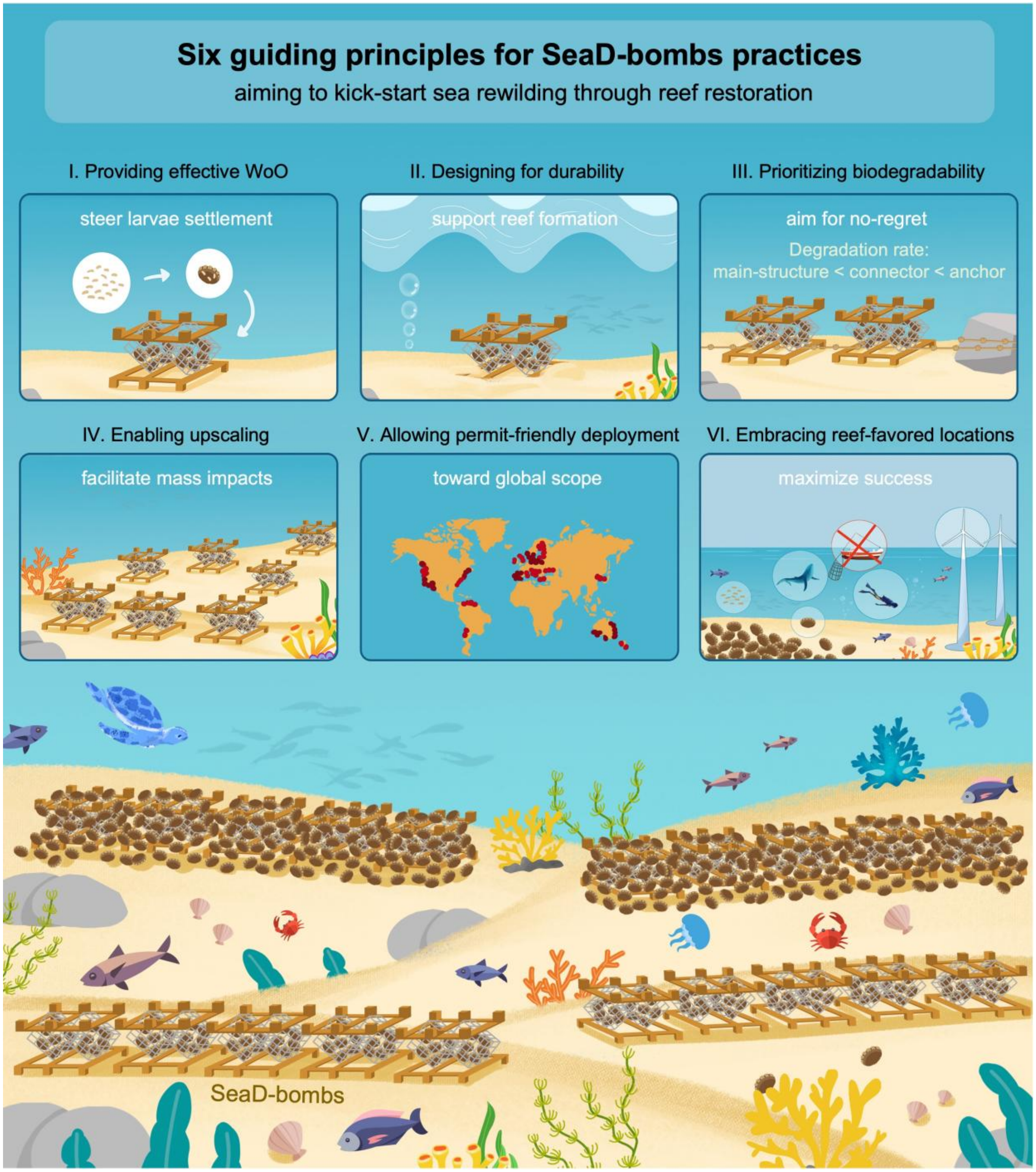

Fig. 7 Conceptual diagram illustrating the six guiding principles for SeaD-bombs development and application, showcased by oyster reef restoration. By adhering to these principles, SeaD-bombs are poised to effectively upscale reef restoration efforts, thus truly kick-starting sea rewilding. In the first subplot, WoO stands for Windows of Opportunity (see introduction in Appendix A1).

4. Compiling a list of potential materials for constructing SeaD-bombs

Selecting appropriate materials is a critical step in the design and construction of SeaD-bombs, ensuring ecological compatibility, structural functionality, and cost-effectiveness. To guide material choices, a list of potential options has been compiled, focusing on biodegradable, locally sourced, and low-cost materials suitable for either the main structure or accessories. These include not only natural materials like shells and untreated wood, but also agricultural byproducts such as hemp board, rice husk blocks, and jute products. Additionally, bio-based innovations like BESE-elements® and biodegradable mesh provide versatile, marine-safe alternatives. Each material offers unique advantages—ranging from promoting biodiversity to ease of deployment—while also presenting challenges such as durability or anchoring needs. Potential environmental releases from these materials are generally minimal, with most substances being naturally derived, biodegradable, or designed for ecological safety. This diverse material portfolio supports flexible design approaches tailored to specific ecological goals and site conditions.

Table 4. Potential materials for manufacturing SeaD-Bombs (main structure or accessories).

Type	Material	Description	Advantages	Disadvantages	Examples	Degradation rate (empirical)	Cost	Carbon footprint	Potential releases under high-density use	Tip
Shell	Shells	from wild collection or restaurant waste	**Natural Habitat**: Promotes marine life growth. **Eco-Friendly**: Integrates into the ecosystem.	**Limited Structure**: lack complex habitat features. **Displacement**: May scatter in currents. **Disease Risk:** May carry pathogens if not cleaned. **Source Concerns**: Collection may harm natural ecosystems.	 Clam/ Cockle	5-15 years	Around €150 per m^3 (ca. 800 kg)	**Collecting** (equipment emissions) **Processing** (cleaning, energy use) **Transport** (fuel use)	**Organic residue** may be released initially but is generally biodegradable. **Calcium carbonate dissolution** may cause slight, localized pH changes, but risks are minimal under typical use.	
					 Oyster	5-15 years	Around €100 per m^3 (ca. 500 kg)			
Wood	Untreated Wood Pilings	Wood that has not been treated for preservation, with high durability	**Durable**: Naturally resistant to moisture. **Sustainable**: Uses raw wood materials with minimal processing.	**Pest Susceptibility**: Vulnerable to insect and fungal damage. **Heavy**: Difficult to transport and install.	 Chestnut poles	10-15 years in moist soil or waterlogged environments	(15 cm diameter, 3 m long): around €33 each	**Harvesting** (machinery use) **Processing** (cutting, shaping) **Transport** (fuel use; Robinia is heavier than chestnut, so transportation may slightly increase its footprint)	Wood may slowly decompose, releasing small amounts of **organic acids** with minimal ecological impact**.** Robinia wood can release **tannins**, which may slightly influence local water chemistry;	Naturally grown wood; trees sequester carbon during growth.
					 Robinia pole	20-25 years in moist soil or waterlogged environments	(15 cm diameter, 3 m long): around €57 each			

									effects are typically negligible.	
	Low-stem fruit tree	These trees are often by-products of orchard management and would otherwise be disposed of.	**Eco-Friendly:** Repurposes discarded orchard trees sustainably. **Habitat Complexity:** Branches and trunks provide shelter for marine life.	**Variable Decomposition:** Different decay rates may affect reef consistency**.** **Anchoring Required:** Extra weights needed for stability, increasing setup complexity.		***Apple***: 12-15 years ***Pears***: 20-80 years ***Prune***: 12-20 years ***Peaches***: 8-15 years ***Cherry***: 10-20 years	around €5 to €20 per tree, depending on the species and availability	**Harvesting** (machinery use) **Processing** (cutting, shaping) **Transport** (fuel use)	Trace pesticide residues may exist depending on prior orchard use. **Test results indicate very low pesticide residues, well below ecological concern thresholds.**	Reuses waste wood, sequestered carbon remains stored in the material.
	Bamboo	Fast-growing, durable natural material, primarily harvested from sustainable plantations	**Lightweight**: Easy to handle and deploy. **Natural Habitat**: Its texture and hollow structure provide good shelter for small marine life.	**Limited Durability**: Less resistant to marine conditions. **High buoyancy**: May need anchoring to prevent drifting.	 Bambusa	1-3 years	(15 cm diameter, 3 m long): around €35 each	**Harvesting** (machinery use) **Processing** (cutting, drying) **Transport** (fuel use)	Natural **cellulose degradation** may release small amounts of organic acids (e.g., acetic acid), with minimal environmental impact under typical conditions.	Bamboo grows quickly and absorbs significant amounts of carbon during growth.
	Accoya	Created by a non-toxic wood modification process called wood acetylation	**Durable:** Resists moisture and decay. **Stable:** Maintains shape over time. **Eco-Friendly:** No added chemicals.	**Costly:** Relatively more expensive than untreated wood. **High buoyancy**: May need anchoring to prevent drifting.	 Planed plank	25-50 years	(2 cm thick, 9 cm wide, 3 m long): around €50 each	**Wood sourcing** (harvesting) **Acetylation process** (uses energy and acetic anhydride) **Transport** (fuel use)	Acetylated wood is **chemically stable** and does not leach harmful substances under marine conditions.	
Plant Fibers	Hemp Board	Made from compressed hemp fibers, offering eco-friendly alternatives in construction and design	**Sustainable**: Made from renewable resources. **Non-Toxic**: Made with few chemicals, safe for marine use.	**Buoyancy**: May need additional anchoring. **Weakens in Water**: Softens when waterlogged, affecting stability.	 Hempspa® Bio board	2-5 years	(2 cm thick, 0.8 m wide, 1.2 m long): around €30 each	**Hemp cultivation** (minimal, as hemp is low-impact) **Processing** (fiber extraction, compression, and binding) **Transport** (fuel use)	If **synthetic binders** are used, trace chemical release is possible; use of **bio-based or inert binders** is preferred.	Hemp cultivation is highly carbon-efficient, absorbing CO_2 during growth.
	Rice husk block	Eco-friendly building materials made from compressed rice husks	**Sustainable**: Made from agricultural waste. **Lightweight:** Easy to handle and deploy.	**Buoyancy:** May need extra anchoring. **Binder Impact:** Binders can affect environmental compatibility.	 Rice husk block	2-5 years	(10 cm thick, 15 cm wide, 30 cm long): around €1.5 per block	**Rice husk collection** (minimal processing). **Compression process** (energy for binding and shaping). **Transport** (fuel use).	Gradual degradation may release small amounts of **silica and natural organic acids**, with limited ecological impact under typical conditions.	Reuses agricultural waste, avoiding emissions from burning rice husks.
	Jute products	Made from natural jute fibers	**Versatile Application:** Bags can be filled other materials to create a weighted base; Ropes can be used to connect and secure	**Limited Strength:** Not suitable for heavy structures. **Fragmentation Risk:** May release fibers as it decomposes.	 Jute bags  Jute rope	1-2 years	***Bag***: (60 cm wide, 1.0 m long): around €4 each ***Rope***: (2 cm diameter): around €8 per meter	**Jute cultivation** (low, as jute is sustainable) **Processing** (spinning, weaving, or rope making) **Transport** (fuel use)	Natural decomposition releases **plant-based fibers and organic compounds**, typically with negligible ecological impact.	Jute plants absorb large amounts of CO_2 during their growth.

	Coir Fiber Logs	made from 100% natural coconut fibers; biodegradable erosion control products	**Erosion Control**: Stabilizes sandy or soft areas. **Customizable**: Available in various sizes for easy use. **Promotes Biodiversity**: Good surface for organisms to attach.	**Less Durable**: Not suitable for strong currents. **Buoyancy**: Floats initially, needs anchoring. **Simple Structure**: Limited habitat complexity.	 Coconut coir logs	2-5 years	(Diameter 50 cm, Length 3 m): around €30-€50 per log	**Coconut harvesting and coir extraction**. **Processing** (shaping and binding into logs) **Transport** (fuel use)	Natural decomposition may release **tannins and small amounts of organic acids,** with minimal impact on local water chemistry.	Coconut trees naturally sequester carbon, and the coir is a waste byproduct.
Bio-based	BESE-elements®	Made of a starch biopolymer derived from potato waste. Shaped into honeycomb structure	**Supports Marine Life:** Honeycomb structure promotes biodiversity. **Reduces Erosion:** Stabilizes surrounding sediment. **Customizable**: Can be molded into various shapes.	**Limited Strength:** Not suitable for heavy structures. **Needs Anchoring:** May require extra stability in strong currents.	 BESE-elements®	***Type 1***: 10-20 years; ***Type 2***: 2-4 years	Around €50 per m^2	**Potato farming and starch extraction** (minimal but involves energy use) **Biopolymer production** (energy-intensive process) **Processing** (shaping into honeycomb structure) **Transport** (fuel use)	Degradation releases **starch-based compounds** that are generally non-toxic and biodegradable in marine environments.	If **additives** are present, their composition determines potential release; current formulations are typically designed for ecological safety.
	BESE-reef paste	Made from crushed waste shells (60-80%) and natural binding agent (20-40%)	**Fast Habitat Growth:** Promotes rapid reef establishment. **Versatile:** Works on various surfaces.	**Application Challenges:** Requires careful handling, which may increase labor costs. **Supply Constraints:** Scarcity of waste shells can restrict production	 BESE-reef paste	1-5 years	Around €100 per kg	**Shell collection and crushing** (minimal but involves energy use). **Mixing and shaping** (energy use) **Transport** (fuel use)	Dissolution of **calcium carbonate** (from crushed shells) may slightly influence local pH, with limited ecological impact.	
	BESE-mesh biopolymer	Made of a starch biopolymer derived from potato waste, and is the biodegradable alternative for plastic mesh	**Easy to Use:** Adaptable for simple customization, e.g., bags of dead oyster shells	**Prone to Breakage**: May crack or tear easily in high-stress conditions.	 Orange type  Black type	***Orange type***: 1-7 years. ***Black type***: 5-20 years.	?	**Potato farming and starch extraction** (minimal but involves energy use) **Biopolymer production** (energy-intensive process). **Mesh manufacturing** (shaping). **Transport** (fuel use).	**Synthetic stabilizers**, if used, are typically selected for environmental compatibility to ensure safe degradation.	
	BESE-zip ties	Made from pure polycaprolactone (PCL); 100% biodegradable	**Quick Installation:** Easy and fast for securing reef components.	**Limited Strength:** Holds up to 8 kg. **Early Breakage Risk:** May degrade faster in high-energy environments.	 BESE-zip ties	12-18 months in terrestrial environments; in marine conditions, it may take a few years.	About €0.30 per tie	**PCL production** (energy-intensive) **Processing** (molding and shaping) **Transport** (fuel use)	Decomposes into **low-molecular-weight compounds** such as hydroxy acids, which are non-toxic and biodegradable.	

Other	Mother Reef (Oyster Heaven)	Made of clay and can be produced cheaply from brick factories	**Scalable**: Mass-produced in brick factories. **Boosts Biodiversity**: Supports various marine species.	**Brittle**: Can crack during deployment or in strong currents.		5-10 years	About €5 per brick	**Clay extraction** (mining and transport) **Processing** (shaping, drying, and possibly firing) **Transport** (fuel use)	Minor release of **fine clay particles** may occur without significant ecological impact.	
	HEMSPAN® Bio Block	Building material made from hemp shiv, hydrated dolomitic lime and probiotics	**Eco-Friendly:** Biodegradable, made from hemp and lime. **Low CO_2 Impact:** Absorbs CO_2, reducing footprint.	**pH Changes:** Lime may alter local pH. **Unpredictable Breakdown**: Lime and probiotics may degrade unevenly in marine conditions.	 HEMSPAN®	5-10 years	About €350 per m³	**Hemp cultivation and shiv processing** (minimal impact) **Lime production** (energy-intensive process) **Mixing and forming blocks** (energy for shaping and drying) **Transport** (fuel use)	Gradual **lime dissolution** may cause slight, localized pH shifts, typically with limited ecological impact.	Hemp absorbs carbon, and lime carbonation during curing can also lock in CO_2.

5. Exploring suitable approaches for the preliminary assessment of SeaD-bomb stability

Ensuring the stability of SeaD-bombs in dynamic marine environments is essential for their long-term functionality and ecological success. As part of this effort, a dedicated R script has been developed to perform preliminary stability assessments of SeaD-bomb structures. This script evaluates three critical failure modes—sliding, uplifting, and overturning—by calculating Unity Check (UC) values, which compare applied hydrodynamic forces to resisting forces. A UC value below one indicates structural stability, while a value above one signals potential instability. The calculations incorporate key structural, hydrodynamic, and soil resistance parameters, using established principles such as Morison's equation and soil friction models. By applying this tool, practitioners can efficiently assess design robustness under various environmental conditions, including extreme scenarios such as 50-year return period wave events. This approach supports the informed selection of SeaD-bomb designs, ensuring both stability and ecological integrity during deployment.

5.1 Principles and governing equations

The approach is based on three unity checks (UC). UC is the ratio of the maximum design load to the allowable load. All UCs below one means the structure passes the stability check.

1. *Sliding stability*

   - Ensures that the structure does not slide due to hydrodynamic forces.
   - The resistance comes from friction and passive soil pressure.
   - Equation:

$$UC_{sliding} = \frac{F_D + F_I}{F_{soil}} \tag{1}$$

   where:

   - F_D = Drag force (Equation 4)
   - F_I = Inertia force (Equation 5)
   - F_{soil} = Total soil resistance (Equations 9-11)

2. *Uplift stability*

   - Ensures that the structure remains in contact with the seabed and does not float upward.
   - Equation:

$$UC_{uplifting} = \frac{F_L + F_B}{W - F_L - F_B} \tag{2}$$

   where:

   - F_L = Lift force (Equation 6)
   - F_B = Buoyancy force (Equation 7)
   - W = Gravity force (Equation 8)

3. *Overturning stability*

   - Ensures that the structure does not tip over due to hydrodynamic loads.
   - Equation:

$$UC_{overturning} = \frac{M_{overturning}}{M_{restoring}} = \frac{F_D \times h_{pivot}}{(W - F_L - F_B) \times \frac{L_{base}}{2}} \tag{3}$$

   where:

- h_{pivot} = Pivot height
- L_{base} = Structure bottom length

4. *Involved equations:*

- Drag force (F_D)

$$F_D = \frac{1}{2}\rho C_D S(u_c + u_w \sin(\omega t))^2 \quad (4)$$

where:

- ρ = Seawater density (kg m^{-3})
- C_D = Drag coefficient (-)
- S = Project area normal to the force direction (m^2)
- u_c = Current velocity (tidal + wind-driven; m s^{-1})
- u_w = Orbital velocity (m s^{-1})
- ω = Wave frequency (1/rad)

- Inertia force (F_I; through the wave cycle)

$$F_I = \rho(1 + C_A)V\dot{u}\cos(\omega t) \quad (5)$$

where:

- C_A = Added mass coefficient (-)
- V = Displaced volume (m^3)
- $\dot{u}$ = Fluid particle acceleration amplitude (only for orbital motion; m s^{-2})

(*The drag and inertia force combined form Morison's load equation which expresses the inline force of a body in oscillatory flow*)

- Lift force (F_L)

$$F_L = \frac{1}{2}\rho C_L S|u|u \quad (6)$$

where:

- C_L = Lift coefficient (-)
- u = Fluid particle velocity (tidal + wind-driven + orbital; m s^{-1})

- Buoyancy force (F_B)

$$F_B = \rho V g \quad (7)$$

where:

- V = Object volume (m^3)

- g = Gravitational acceleration (m s^{-2})

- Gravity force (W)

$$W = mg \tag{8}$$

where:

- m = Object mass (kg)

- Total soil resistance (F_{soil})

$$F_{soil} = F_{friction} + \Delta H \tag{9}$$

$$F_{friction} = (W - F_L - F_B) \cdot \tan(\delta) \tag{10}$$

$$\Delta H = (\tan(\varphi + 0.5 \cdot \varphi)^2 - \left(\frac{1}{\tan(\varphi + 0.5 \cdot \varphi)^2}\right)) \cdot \gamma \cdot D_b \cdot A_h \tag{11}$$

where:

- φ = Internal friction angle of the scour protection layer (= 45 degrees)
- δ = Steel-soil interface friction angle (= φ -5 degrees)
- γ = Effective unit weight of soil (kN m^{-3})
- D_b = Depth below seafloor to base level (m)
- A_h = Embedded vertical cross-sectional area of foundation (m^2)

Input Parameters

The calculation requires the following input parameters, categorized into structural, hydrodynamic, and soil properties.

- *Structure properties*

Parameter	Description	Value	Source
`m`	Structure mass (kg)	--	Measure
`W`	Gravity force (N)	W = m × g	Measure
`frontal_area`	Projected frontal area (m^2)	--	Measure
`structure_height`	Structure height (m)	--	Measure
`h_pivot`	Pivot height (m)	--	Measure
`base_length`	Base length (m)	--	Measure
`base_width`	Base width (m)	--	Measure
`V_structure`	Submerged volume (m^3)	--	Measure
`Db`	Depth below seafloor (m)	--	Measure
`Ah`	Embedded vertical area of foundation (m^2)	--	Measure
`CA`	Added mass coefficient	1.579	Ref. [3]

- *Hydrodynamic properties*

Parameter	Description	Value	Source
`u_total`	Water particle velocity (wave + current; m s^{-1})	2.16	Ref. [1]
`wave_velocity`	Wave particle velocity (m s^{-1})	1.81	Ref. [1]
`T_wave`	Wave period (s)	10	Ref. [1]
`omega`	Wave frequency (rad/s)	2π / T_wave	Ref. [1]
`a_wave`	Fluid particle acceleration amplitude	omega × wave_velocity	Ref. [1]
`Cd_steel`	Drag coefficient (steel)	1.05	Ref. [3]
`Cl`	Lift coefficient	0.2	Ref. [2]

Note: The critical hydrodynamic conditions used for the stability assessment is the 50-year wave-dominated condition with associated currents.

- *Soil Resistance properties*

Parameter	Description	Value	Source
`phi`	Internal friction angle (°)	45	constant
`delta`	Soil-steel interface friction angle (°)	phi - 5	constant
`gamma_soil`	Effective soil unit weight (N m^{-3})	16,000	constant

Output

The script returns three Unity Check (UC) values, each indicating the safety margin of the structure:

Output	Description	Interpretation
`UC_Sliding`	Ratio of hydrodynamic loads to soil resistance	<1: Safe, >1: Unstable
`UC_Uplifting`	Ratio of lift + buoyancy to vertical resistance	<1: Safe, >1: Unstable
`UC_Overturning`	Ratio of overturning moment to restoring moment	<1: Safe, >1: Unstable

Overall, a UC value greater than 1 means the structure fails the stability check.

References

1. WOZ2180106 Metocean Desk Study and Database for Dutch Wind Farm Zones – Hollandse Kust (West).
2. Van Oord (2018), Stability of oyster cages and reef balls at Luchterduinen Technical Memo.
3. DNV-RP-C205: Environmental conditions and environmental loads. RECOMMENDED PRACTICE

5.2 Code Execution

(test on WINOR-frame, measurement parameters see Appendix A3)

```
# Load necessary library
library(dplyr)
# ------------------------------
# CONSTANTS & PARAMETERS
# ------------------------------
# Structure Properties (Measure)
m <- 1500                # Structure mass (kg)
W <- m * 9.81              # Gravity Force (N)
structure_height <- 2.9925  # main structure height (m)
h_pivot <- structure_height / 4 # Pivot height: Centroid of projected
area
base_length <- 3.1167         # Structure bottom length (m)
base_width <- 2.7085        # Structure bottom width (m)
frontal_area <- 0.8244703     # Projected frontal area (m²)
V_structure <- 0.158857  # Submerged volume (m³)
A_h <- 0               # Embedded vertical area of foundation (m²)
D_b <- 0               # Embedment depth (m)

# Environmental Conditions
u_total <- 2.16          # Water particle velocity wave + current (50-
year return period)
wave_velocity <- 1.81    # Water particle velocity wave (50-year return
period)
T_wave <- 10             # Wave period (s)
omega <- 2 * pi / T_wave # Wave frequency (rad/s)
a_wave <- omega * wave_velocity # Fluid particle acceleration amplitude
(m/s²)

# Soil Resistance Properties (Appendix A.1)
phi <- 45                # Internal friction angle of seabed (degrees)
delta <- phi - 5        # Soil-steel interface friction angle (degrees)
gamma_soil <- 16 * 1000  # Effective soil unit weight (N/m³)

# Physics Constants
g <- 9.81                # Gravitational acceleration (m/s²)
rho_water <- 1025        # Seawater density (kg/m³)
Cd_steel <- 1.05         # Drag coefficient for steel
Cl <- 0.2                # Lift coefficient
CA <- 1.579              # Added mass coefficient

# ------------------------------
# STABILITY CALCULATION FUNCTION
# ------------------------------

calculate_stability <- function() {

  # Compute Drag Force (Equation 4)
```

```
  F_D <- 0.5 * rho_water * Cd_steel * frontal_area * u_total^2

  # Compute Inertia Force (Equation 5)
  F_I <- rho_water * (1 + CA) * V_structure * a_wave  # Using max cos(ωt)
= 1

  # Compute Lift Force (Equation 6)
  F_L <- 0.5 * rho_water * Cl * frontal_area * u_total^2

  # Compute Buoyancy Force (Equation 7)
  F_B <- rho_water * g * V_structure

  # ------------------------------
  # SLIDING STABILITY (Equation 1)
  # ------------------------------
  # Frictional Resistance (Equation 10)
  F_friction <- (W - F_L - F_B) * tan(delta * pi / 180)

  # Passive Soil Pressure Increment (Equation 11)
  K_p <- tan((phi + 0.5 * phi) * pi / 180)^2
  K_rd <- K_p - (1 / K_p)
  Delta_H <- K_rd * gamma_soil * D_b * A_h

  # Total Soil Resistance (Equation 9)
  F_soil <- F_friction + Delta_H

  # Sliding UC (Equation 1)
  UC_sliding <- (F_D + F_I) / F_soil

  # ------------------------------
  # UPLIFT STABILITY (Equation 2)
  # ------------------------------
  # Total Vertical Resistance (Equation 9)
  F_vertical <- W - F_L - F_B

  # Uplift UC (Equation 2)
  UC_uplifting <- (F_L + F_B) / F_vertical

  # ------------------------------
  # OVERTURNING STABILITY (Equation 3)
  # ------------------------------
  M_overturning <- F_D * h_pivot
  M_restoring <- (W - F_L - F_B) * (base_length / 2)  # Restoring moment
lever arm

  UC_overturning <- M_overturning / M_restoring

  # ------------------------------
  # RETURN RESULTS
  # ------------------------------
  return(data.frame(
    UC_Sliding = round(UC_sliding, 3),
```

```
    UC_Uplifting = round(UC_uplifting, 3),
    UC_Overturning = round(UC_overturning, 3)))}

# ------------------------------
# COMPUTE STABILITY
# ------------------------------
results <- calculate_stability()

# Print Results
print(results)
```

This script will output a data frame with the three stability indicators:

```
  UC_Sliding UC_Uplifting UC_Overturning
      0.239        0.157          0.078
```

- Here, all values are <1, meaning the structure is stable.

5.3 Web App

Based on the governing equations and implementation code, an interactive web application has been developed (Fig. 8; accessible via link：https://nioz.shinyapps.io/OffshoreStability_V2/; the code for building the web application is provided in Appendix A4). It allows users to obtain a preliminary assessment of the structural stability by inputting specific design parameters. It is important to note that in this application, the structure's drag coefficient (steel) and lift coefficient are from citable literature sources (set as constants), and the hydrodynamic conditions are preset to a 50-year return period storm wave (modifiable upon request). A full and definitive assessment of structural stability should be carried out by qualified third-party experts.

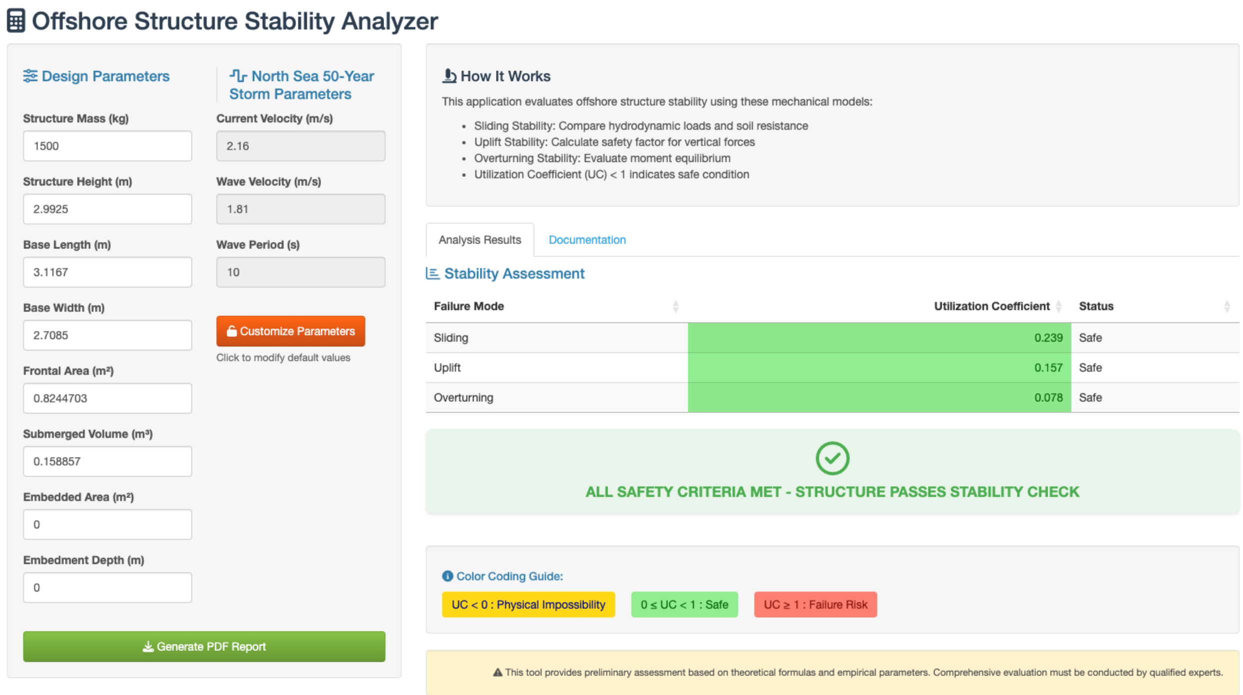

Fig. 8 Interface of the web application for calculating structural stability

General discussion

In recent years, the widespread degradation of marine ecosystems and growing global concern over biodiversity loss have driven the rapid development of various marine ecological restoration technologies. This trend is particularly evident in the Dutch North Sea, where the disappearance of natural reef structures, simplification of seabed substrates, and continuous expansion of offshore wind farms together create a dual challenge and demand for ecological restoration: on the one hand, there is an urgent need to restore marine habitats and enhance ecosystem resilience; on the other hand, restoration measures must adapt to high-energy dynamic environments, comply with low-interference permitting processes, and be suitable for large-scale application.

Historically, marine ecological restoration has relied primarily on two approaches: 1) construction of artificial structures, such as traditional artificial reefs (ARs), aimed at increasing seabed heterogeneity and providing shelter; 2) restoration of living reefs, such as the deployment of oyster spat or adults, intended to rebuild biological structures. However, living reef restoration tends to be costly and slow in effectiveness, making it unsuitable for spatially constrained environments like wind farms, and incapable of supporting rapid biodiversity recovery in the short term. Additionally, our meta-analysis indicates that although ARs can significantly increase biodiversity and species abundance, there remains a marked gap compared to natural reefs in terms of biological fitness, such as survival and reproduction. Our systematic review of AR applications over the past 40 years further reveals that, despite the increasing proportion of ARs with a restoration focus, most deployments remain smaller than 1 hectare and continue to rely on non-degradable materials such as concrete and steel.

The development of SeaD-bombs directly addresses these gaps. Not only do SeaD-bombs support short-term biodiversity enhancement and rapidly triggering the recruitment and expansion of reef-building organisms by providing physical settlement substrates, but their biodegradable materials allow artificial structures to gradually withdraw, enabling natural reefs to take over ecological functions. SeaD-bombs adopt the concept of "Windows of Opportunity", creating physical support at the right time and place to provide critical conditions for the settlement, growth, and expansion of reef-building species, thereby facilitating the self-restoration of natural habitats. To realize this, the project defined six guiding principles, covering material selection, structural design, and deployment strategies, providing comprehensive guidance for the development and application of SeaD-bombs, ensuring ecological functionality while minimizing long-term human intervention.

At the operational level, we screened a range of locally available biodegradable materials from the Netherlands and surrounding regions, including: *i*) natural materials (e.g., wood, shells) — highly ecologically compatible and degradable, though with limited stability; *ii*) biomass composites (e.g., hemp boards, rice husk blocks, BESE-elements®) — good degradability and plasticity, suitable for industrial-scale production; *iii*) functional composites (e.g., biodegradable nylon, starch-based materials) — suitable for detailed components and connectors. Clearly, different materials are suitable for different structural parts of SeaD-bombs (e.g., core load-bearing vs. auxiliary connections) and must be flexibly chosen based on local hydrodynamic conditions and desired restoration timelines. Moreover, the effectiveness of SeaD-bombs depends not only on materials but also on maintaining short-term stability in the deployment environment to ensure that structural functions are realized. To this end, we developed a stability assessment tool based on the Morison equation, allowing multidimensional risk evaluation (sliding, floating, overturning) for different designs under varying hydrodynamic conditions, providing critical reference for pre-deployment design optimization. In addition, during the workshop, we introduced a “core-edge” spatial deployment strategy, combining long-lasting materials with fast-degrading materials to enhance overall structural stability while creating ecological gradients, thereby optimizing the recruitment and expansion of reef-building species.

Despite the wide application potential of SeaD-bombs, several key challenges require further exploration:

- The ecological impact of material degradation needs to be further quantified, particularly regarding the controllability of fragmentation in high-energy environments;
- Accurate site selection requires the integration of field monitoring and modeling to comprehensively assess hydrodynamics and sediment dynamics;
- Species recruitment support mechanisms (e.g., spat release, acoustic attraction) need to be combined with SeaD-bombs to ensure effective restoration in areas lacking natural larval supply;

To translate the SeaD-bombs concept into practical applications, small-scale prototypes and early-stage pilot studies will be essential. These trials will help refine material choices, deployment strategies, and stability predictions under actual hydrodynamic conditions. Furthermore, pilot projects will assess the ecological performance of SeaD-bombs, focusing on species recruitment, substrate stability, and the effectiveness of biodegradable materials in diverse environments. By incorporating iterative testing and feedback, the next phase will provide critical data to optimize SeaD-bombs, ensuring that they not only meet ecological goals but also adapt to specific site conditions and operational constraints. These trials may span a range of offshore zones and sediment types.

Looking further ahead, the successful scaling of SeaD-bombs will benefit from a structured long-term monitoring and evaluation framework tailored to the Dutch North Sea. Such a framework should track settlement success, ecological succession, and substrate persistence, with potential integration of in-situ sensors and AI-supported video monitoring. In parallel, cost-benefit analysis will be crucial to support decision-making and policy integration. This includes not only material and transport costs, but also deployment logistics (e.g., vessel usage) and co-deployment opportunities with offshore wind operations. To support permit-friendly deployment, future work should further define regulatory pathways and spatial planning compatibility. Beyond the Wadden Sea and Voordelta, SeaD-bombs may be suitable for use in various offshore environments, particularly in zones where biodiversity enhancement is prioritized but structural permanence is constrained—such as within or near offshore wind farms or trawling-exclusion zones. However, application in greater depths or high-current areas may require material reinforcement or modified deployment strategies to maintain stability and ecological performance. Limitations primarily relate to hydrodynamic stress, sediment mobility, and access constraints, which must be assessed case-by-case using the developed stability assessment tool.

A key knowledge frontier lies in understanding how temporary SeaD-bomb habitats transition into lasting reef ecosystems. In current concept, oysters and other sessile organisms predominantly settle on the upper and lateral surfaces of SeaD-bombs, especially in crevices, rough-textured zones, or protected niches where shear stress is lower and sedimentation minimal. As materials gradually degrade, these biological colonizers contribute to new biogenic structures, potentially stabilizing loose substrates, thus facilitating the emergence of self-sustaining ecosystems. Understanding the spatial patterns of colonization and how these align with material degradation rates will be central to optimizing SeaD-bomb designs for long-term functionality. SeaD-bombs may also be integrated with other restoration tools, such as larval collectors, suspended mussel or macroalgae cultivation modules. Strategic combinations in mosaic deployments could promote multi-trophic interactions, increase habitat complexity, and enhance ecosystem resilience under changing climate conditions. In particular, co-deployment with mussel or seaweed cultivation modules may introduce shading, nutrient cycling, and trophic linkages. Such hybrid configurations could prove especially beneficial in multi-use marine areas, where diverse ecological functions are desired alongside human activity.

Building on these prospective trials, SeaD-bombs represent a forward-looking, no-regret ecological restoration approach, balancing ecological performance, cost-efficiency, and operational feasibility. Equally critical is sustained stakeholder engagement, which ensures that the development process remains grounded in legal, ecological, and operational realities. In future phases, active collaboration with stakeholders, including ecologists, engineers, legal experts, and policy makers, will be essential for addressing regulatory challenges, optimizing material selection, and scaling deployment. Incorporating local knowledge and community participation will further ensure that SeaD-bombs deliver both environmental benefits and societal relevance.

Appendix

A1. Introducing the concept of Windows of Opportunity

Sea restoration efforts are seldom guided by a well-defined conceptual framework (Hughes et al., 2023; Nyström et al., 2012; Temmink et al., 2021), hindering progress toward achieving expected effectiveness and scalability in biodiversity recovery. Here, we propose elevating the concept of "Windows of Opportunity (WoO)" as crucial, offering key insights into the feasibility and dynamics of initiating sustainable biodiversity recovery.

The WoO can be broadly defined as restricted establishment periods characterized by suitable physical conditions (van Belzen et al., 2022), either consisting of a temporary lack of physical disturbances or the temporary availability of establishment substrate. To illustrate, in biogeomorphic ecosystems such as salt marshes, mangroves, and coastal dunes, where seedling establishment is vulnerable to physical disturbances but crucial for successful recruitment, the WoO is defined as the shortest disturbance-calm benign periods required for stable seedling anchoring (Balke et al., 2014, 2011). Similarly, the successful recruitment of reef-building species relies heavily on stable settlement substrates (Bersoza Hernández et al., 2018; Temmink et al., 2021), which must endure physical disturbances for a sufficient duration to support larval settlement and spat growth (Capelle et al., 2019). WoO in this context can be understood as the critical minimum timeframe during which suitable substrate(s) are available (Capelle et al., 2019).

The availability of WoO is intricately tied to disturbance regimes within the ecosystem (Balke et al., 2014; van Belzen et al., 2022). In reef-dominated marine habitats, high-energy hydrodynamic events such as tropical storms and hurricanes may fragment or dislodge settlement substrates, while associated sediment dynamics may bury them (Gardner et al., 2005; Hanke et al., 2021). These disturbances consequently result in the loss of WoO and subsequent failure in recruitment. In cases of anthropogenic disturbances, such as bottom trawling, both reef-forming species and their underlying substrates are harvested (Beck et al., 2011; Smyth et al., 2009), exposing sediments and terminating WoO. The length of WoO is context-dependent, as different species involve life history stages spanning different durations (Balke et al., 2014; Rooper et al., 2011). For instance, salt marsh seedlings require a few days to anchor successfully (Balke et al., 2014), while oyster larvae settlement occurs during a pelagic stage lasting several weeks

(Davenport et al., 2021). The key is that the WoO provides enough time for organisms to grow beyond a critical size threshold, making them resilient to disturbances (e.g., developing deep roots as a large plant or forming a stable reef; Balke et al., 2014; Capelle et al., 2019). The required WoO for establishment may experience minor fluctuations due to the plasticity of organisms in response to specific habitat conditions that affect settling behavior and growth rate. For reef-forming species, this could include water quality parameters (e.g., temperature, salinity, turbidity, dissolved oxygen, pH; Bigham et al., 2021; Bos et al., 2023; Dias et al., 2019) and geomorphic elements (e.g., depth, bed slope, erosion; Bos et al., 2023; Colden and Lipcius, 2015).

The emergence of WoO in a degraded ecosystem has the potential to kick-start positive shifts between alternative stable states84, setting off positive feedback among system components and thereby reinforcing the overall stability of the ecosystem (Nyström et al., 2012; Temmink et al., 2022). A well-documented instance is the transition from a bare state to a vegetated state initiated by WoO within salt marshes, mangroves and seagrasses (Wang and Temmerman, 2013), facilitated by the positive feedback between plant growth and sediment accretion (Bouma et al., 2009). In reef-dominated ecosystems, we anticipate a comparable shift from a bare state to a reef state as WoO occurs (Fig. B1). The initial substrate (e.g., artificial reefs as active restoration elements) within the WoO facilitates the establishment of reef builders, which expand the substrate (e.g., through shell or fragment formation), allowing for further reef builder establishment and greater substrate extension as a result of mutually reinforcing positive feedback. Given the density-dependent nature of positive feedback mechanisms in maintaining desired states (e.g., vegetated or reef state), the WoO must manifest on a significant scale and support targeted species to surpass the density threshold (Bouma et al., 2009; Temmink et al., 2022).

Notably, dispersal units (e.g., seeds, propagules, and larvae) must effectively reach the establishment site for a WoO to be effective. In case this criterion is not met, maximizing WoO potential requires supplementary measures, such as translocating broodstock and/or adding dispersal units.

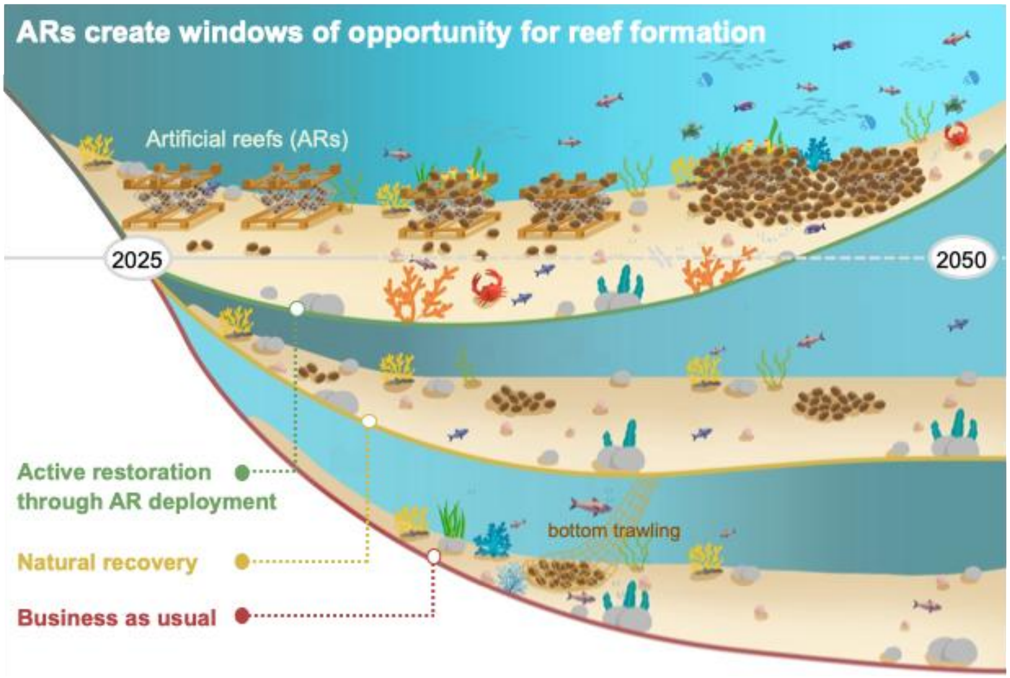

Fig. A1 Conceptual diagram illustrating the kick-starting of sustainable biodiversity recovery through artificial reef (AR) deployment, using a case structure to visualize the ARs. As a temporary proactive intervention, ARs can create windows of opportunity (WoO) for natural reef formation (here, exemplified by oyster reef) at scale, fostering subsequent spontaneous recovery of biodiversity and associated ecological functions. In contrast, natural recovery without WoO is comparatively sluggish and challenging to achieve at the desired scale, while not prohibiting human-induced disturbances (i.e., business as usual) would render biodiversity recovery improbable.

A2. Participants of the SeaD-bombs workshop

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A3. WINOR Frame parameter

WINOR Frame parameter table

Parameter	Description	Value	Source
`m`	Structure mass (kg)	1500	Measure
`W`	Gravity force (N)	14715	Measure
`structure_height`	Structure height (m)	2.9925	Measure
`h_pivot`	Pivot height (m)	2.9925*0.25	Measure
`base_length`	Base length (m)	3.1167	Measure
`base_width`	Base width (m)	2.7085	Measure
`V_structure`	Submerged volume (m^3)	0.158857	Measure
`frontal_area`	Projected frontal area (m^2)	0.8244703	Measure
`Db`	Depth below seafloor (m)	0	Measure
`Ah`	Embedded vertical area of foundation (m^2)	0	Measure

Note: the frame structure is assumed to be a regular quadrangular pyramid to estimate the center of mass height (Pivot height), which is calculated as **Pivot height = Structure height × 1/4**. The projected frontal area and submerged volume are calculated based on the actual frame structure, as explained below. Although some small components are ignored in the calculation, their impact on the overall result is negligible.

Fig. A2 WINOR Frames

Submerged volume calculation

The frame is mainly composed of multiple cylindrical and rectangular components. The volume of each part is calculated separately.

1. Cylindrical components

Formula for cylinder volume:

$$V = \pi \times (\frac{d}{2})^2 \times h$$

- Main vertical support columns (∅76.1 x 6.3)
  - d = 0.0761 m, h = 2.6624 m
  - $V_1 = 0.0121\ m^3$
- Bottom support columns (∅48.3 x 5)
  - d = 0.0483 m, h = 1.7012 m

- $V_2 = 0.0031$ m³

- Other small structures (∅20)
  - $d = 0.02$ m, $h = 0.4237$ m
  - $V_3 = 0.000133$ m³

2. Rectangular components

Formula for rectangular volume:

$$V = L^2 \times h$$

- Bottom rectangular pole 1
  - $L = 0.05$ m, $h = 2.1185$ m
  - $V_{pole1} = 0.00530$ m³
- Bottom rectangular pole 2
  - $L = 0.08$ m, $h = 2.1185$ m
  - $V_{pole2} = 0.013558$ m³
- Bottom plate
  - $L = 0.66334$ m, $h = 0.06$ m
  - $V_{plate} = 0.02640$ m³

Total submerged volume calculation

$$V_{total} = (V_1 \times 1) + (V_2 \times 3.5) + (V_3 \times 1) + (V_{pole1} \times 3) + (V_{pole2} \times 3) + (V_{plate} \times 3)$$

$$V_{total} = 0.1589 \text{ m}^3$$

Projected frontal area calculation

The projected frontal area is calculated based on cylindrical and rectangular components.

1. Cylindrical components

Formula:

$$S = d \times h$$

- Main vertical support columns (∅76.1 x 6.3)
  - d = 0.0761 m, h = 2.6624 m
  - S1= 0.2026 m²
- Bottom support columns (∅48.3 x 5)
  - d = 0.0483 m, h = 1.7012 m
  - S2 = 0.0822 m²
- Other small structures (∅20)
  - d = 0.02 m, h = 0.4237 m
  - S3 = 0.00847 m²

2. Rectangular components

$$S = L \times h$$

- Bottom rectangular pole 1
  - L = 0.05 m, h = 2.1185 m
  - S_{pole1} = 0.1059 m²
- Bottom rectangular pole 2
  - L = 0.08 m, h = 2.1185 m
  - S_{pole2} = 0.1695 m²
- Bottom plate
  - L = 0.66334 m, h = 0.06 m
  - S_{plate} = 0.0398 m²

Total projected frontal area calculation

$$S_{total} = (S_1 \times 1) + (S_2 \times 2.5) + (S_3 \times 1) + (S_{pole1} \times 1.5) + (S_{pole2} \times 1) + (S_{plate} \times 2)$$

$$V_{total} = 0.8245 \text{ m}^2$$

A4. Construction code for the web application that calculates structural stability

```
library(shiny)
library(shinythemes)
library(DT)
library(rmarkdown)
library(markdown)
library(shinyjs)

# UI Interface --------------------------------------------------------
----
ui <- fluidPage(
  useShinyjs(),
  theme = shinytheme("cerulean"),
  titlePanel(div(icon("calculator"), " Offshore Structure Stability
Analyzer",
                 style = "color: #2c3e50")),

  sidebarLayout(
    sidebarPanel(
      width = 4,
      fluidRow(
        column(6,
               h4(icon("sliders"), "Design Parameters")
        ),
        column(6,
               h4(icon("wave-square"), "North Sea 50-Year Storm
Parameters",
                  style = "border-left: 1px solid #ddd; padding-
left:15px;")
        )
      ),

      fluidRow(
        column(6,
               numericInput("m", "Structure Mass (kg)", value = 1500,
min = 100, max = 10000),
               numericInput("structure_height", "Structure Height (m)",
value = 2.9925, min = 1, max = 50),
               numericInput("base_length", "Base Length (m)", value =
3.1167, min = 1, max = 20),
               numericInput("base_width", "Base Width (m)", value =
2.7085, min = 1, max = 20),
               numericInput("frontal_area", "Frontal Area (m²)", value
= 0.8244703, min = 0.1, max = 10),
               numericInput("V_structure", "Submerged Volume (m³)",
value = 0.158857, min = 0.01, max = 5),
               numericInput("A_h", "Embedded Area (m²)", value = 0, min
= 0, max = 100),
```

```
              numericInput("D_b", "Embedment Depth (m)", value = 0, min
= 0, max = 50)
        ),

        column(6,
              disabled(numericInput("u_total",    "Current    Velocity
(m/s)", value = 2.16)),
              disabled(numericInput("wave_velocity",   "Wave   Velocity
(m/s)", value = 1.81)),
              disabled(numericInput("T_wave", "Wave Period (s)", value
= 10)),

              actionButton("unlock_params", "Customize Parameters",
                          icon = icon("unlock"),
                          class = "btn-warning",
                          style = "margin-top:20px;"),
              helpText("Click to modify default values",
                      style = "color: #666; font-size: 0.9em;")
        )
      ),

      downloadButton("report",  "Generate  PDF  Report",  class  =  "btn-
success",
                    style = "width:100%; margin-top:20px;")
    ),

    mainPanel(
      width = 8,
      wellPanel(
        style = "margin: 0 0 20px 0;",
        h4(icon("microscope"),  "  How  It  Works",  style  =  "color:
#2c3e50;"),
        p("This application evaluates offshore structure stability using
these mechanical models:"),
        tags$ul(
          tags$li("Sliding  Stability:  Compare  hydrodynamic  loads  and
soil resistance"),
          tags$li("Uplift   Stability:   Calculate   safety   factor   for
vertical forces"),
          tags$li("Overturning Stability: Evaluate moment equilibrium"),
          tags$li("Utilization  Coefficient  (UC)  <  1  indicates  safe
condition")
        )
      ),

      tabsetPanel(
        tabPanel("Analysis Results",
                h4(icon("chart-bar"), "Stability Assessment"),
                DTOutput("results_table"),
                uiOutput("final_assessment"),
                br(),
                wellPanel(
```

```
                h5(icon("info-circle"), "Color Coding Guide:"),
                div(style = "display: flex; gap: 20px; margin-top:
10px;",
                    tags$div(
                      style = "background: gold; color: darkblue;
padding: 6px 12px; border-radius: 4px;",
                      "UC < 0 : Physical Impossibility"
                    ),
                    tags$div(
                      style = "background: lightgreen; color:
darkgreen; padding: 6px 12px; border-radius: 4px;",
                      "0 ≤ UC < 1 : Safe"
                    ),
                    tags$div(
                      style = "background: salmon; color: darkred;
padding: 6px 12px; border-radius: 4px;",
                      "UC ≥ 1 : Failure Risk")
                )
              ),
              wellPanel(
                style = "margin-top: 20px; background-color:
#fff3cd;",
                tags$small(
                  icon("exclamation-triangle"),
                  "This tool provides preliminary assessment based on
theoretical formulas and empirical parameters. Comprehensive evaluation
must be conducted by qualified experts.",
                  style = "text-align: right; display: block;"
                )
              )
      ),

      tabPanel("Documentation",
              includeMarkdown("documentation.md")
      )
    )
  )
 )
)

# Server Logic --------------------------------------------------------
----
server <- function(input, output) {
  observeEvent(input$unlock_params, {
    shinyjs::toggleState("u_total")
    shinyjs::toggleState("wave_velocity")
    shinyjs::toggleState("T_wave")

    if(input$unlock_params %% 2 == 1) {
      updateActionButton(inputId = "unlock_params",
                         label = "Lock Parameters",
                         icon = icon("lock"))
```

```
  } else {
    updateActionButton(inputId = "unlock_params",
                       label = "Customize Parameters",
                       icon = icon("unlock"))
  }
})

stability_data <- reactive({
  validate(
    need(input$m > 0, "Structure mass must be positive"),
    need(input$V_structure > 0, "Submerged volume must be positive"),
    need(input$frontal_area > 0, "Frontal area must be positive")
  )

  phi <- 45
  gamma_soil <- 16000
  rho_water <- 1025
  Cd_steel <- 1.05
  Cl <- 0.2
  CA <- 1.579

  u_total <- input$u_total
  wave_velocity <- input$wave_velocity
  T_wave <- input$T_wave

  W <- input$m * 9.81
  h_pivot <- input$structure_height / 4
  omega <- 2 * pi / T_wave
  a_wave <- omega * wave_velocity
  delta <- phi - 5

  F_D <- 0.5 * rho_water * Cd_steel * input$frontal_area * u_total^2
  F_I <- rho_water * (1 + CA) * input$V_structure * a_wave
  F_L <- 0.5 * rho_water * Cl * input$frontal_area * u_total^2
  F_B <- rho_water * 9.81 * input$V_structure

  F_friction <- (W - F_L - F_B) * tan(delta * pi / 180)
  K_p <- tan((phi + 0.5 * phi) * pi / 180)^2
  K_rd <- K_p - (1 / K_p)
  Delta_H <- K_rd * gamma_soil * input$D_b * input$A_h
  F_soil <- F_friction + Delta_H
  UC_sliding <- (F_D + F_I) / F_soil

  F_vertical <- W - F_L - F_B
  UC_uplifting <- (F_L + F_B) / F_vertical

  M_overturning <- F_D * h_pivot
  M_restoring <- (W - F_L - F_B) * (input$base_length / 2)
  UC_overturning <- M_overturning / M_restoring

  data.frame(
    Failure.Mode = c("Sliding", "Uplift", "Overturning"),
```

```
      UC.Value = c(UC_sliding, UC_uplifting, UC_overturning),
      Status = ifelse(c(UC_sliding, UC_uplifting, UC_overturning) < 1, 
"Safe", "Unsafe")
    )
  })

  output$results_table <- renderDT({
    datatable(stability_data(),
              rownames = FALSE,
              options = list(dom = 't', pageLength = 3),
              colnames = c("Failure Mode", "Utilization Coefficient", 
"Status")) %>%
      formatStyle(
        'UC.Value',
        backgroundColor = styleInterval(c(0, 1), c('gold', 'lightgreen', 
'salmon')),
        color = styleInterval(c(0, 1), c('darkblue', 'darkgreen', 
'darkred'))
      ) %>%
      formatRound('UC.Value', 3)
  })

  output$final_assessment <- renderUI({
    df <- stability_data()
    all_safe <- all(df$UC.Value < 1) && all(df$UC.Value >= 0)

    color <- ifelse(all_safe, "#4CAF50", "#F44336")
    icon <- ifelse(all_safe, "check-circle", "exclamation-triangle")
    text <- ifelse(all_safe,
                   "ALL SAFETY CRITERIA MET - STRUCTURE PASSES STABILITY 
CHECK",
                   "CRITICAL FAILURE RISK DETECTED - DESIGN REVIEW 
REQUIRED")

    div(class = "final-verdict",
        style = paste0("background-color:", ifelse(all_safe, "#E8F5E9", 
"#FFEBEE"),
                       "; padding:15px; border-radius:8px; margin:20px 
0;",
                       "box-shadow:0 2px 4px rgba(0,0,0,0.1);"),
        div(style = "text-align:center;",
            icon(icon, "fa-3x", style = paste("color:", color, "; 
margin-bottom:10px;")),
            h4(text, style = paste0("color:", color, "; text-
align:center;",
                                    "font-weight:bold; margin:0;"))
        )
    )
  })

  output$report <- downloadHandler(
    filename = "Stability_Report.pdf",
```

```
    content = function(file) {
      report_path <- tempfile(fileext = ".Rmd")
      file.copy("report_template.Rmd", report_path, overwrite = TRUE)

      params <- list(
        inputs = reactiveValuesToList(input),
        results = stability_data()
      )

      render(report_path,
             output_file = file,
             params = params,
             envir = new.env(parent = globalenv()))
    }
  )
}

shinyApp(ui = ui, server = server)
```

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