Journal of *Marine Science and Engineering*

MDPI

Systematic Review

Bioactive Coatings and Engineered Settlement Interfaces for Artificial Coral Reefs: A Systematic Review of Advances, Challenges, and Future Perspectives

Alberto Elizalde-Mata [1], M. E. Trejo-Caballero [1], Marlen A. González-Reyna [1], Rodolfo Silva [2] and Miriam Estevez [1,*]

[1] Centro de Física Aplicada y Tecnología Avanzada, Ingeniería Molecular de Materiales, Universidad Nacional Autónoma de México, Boulevard Juriquilla 3001, Querétaro 76230, Mexico; aelizalde@pceim.unam.mx (A.E.-M.); mtrejo@pceim.unam.mx (M.E.T.-C.); marlengonzalez@fata.unam.mx (M.A.G.-R.)

[2] Instituto de Ingeniería, Edificio 17, Universidad Nacional Autónoma de México, Ciudad Universitaria, Coyoacán, Mexico City 04510, Mexico; rsilvac@iingen.unam.mx

* Correspondence: miries@fata.unam.mx

Abstract

The use of concrete in artificial reefs presents a "recruitment paradox": its inherent hyperalkalinity and delayed natural neutralization severely impair coral larval settlement. Functional surface coatings can mitigate this cytotoxicity and actively provide biological settlement cues. Following PRISMA 2020 guidelines, this systematic review evaluates 16 years of experimental evidence on cementitious surface modifications across Web of Science, Scopus, and ScienceDirect up to September 2026. From 6436 screened records, 127 studies were assessed for full-text eligibility, with a strictly filtered subset of 12 experimental studies included for quantitative data extraction. To systematically categorize these technologies, we propose a novel dual classification framework mapping engineered interfaces by restoration approach (Classes I–IV) and Interfacial Activity Mode (A0–A4). The review evaluates relationships between coating architecture, bio-interfacial stability, and biological performance, identifying current technological bottlenecks. Addressing the need for scalable solutions, we propose a research roadmap integrating circular bioeconomy models and green biomaterials. Methodological quality was assessed by requiring biological validation of coatings in realistic larval settlement models, excluding purely theoretical material simulations. This systematic review was not prospectively registered. Ultimately, this materials-oriented framework clarifies bio-interfacial interactions and identifies research priorities for developing durable, biologically compatible substrates for coral reef restoration.

Keywords: Functional polymer coatings; cementitious substrates; coral restoration; larval settlement; biopolymer hydrogels; bioinspired adhesives; PRISMA 2020

Check for updates

Academic Editors: Enrico Montalbetti, Yohan Didier Louis and Davide Seveso

Received: 5 October 2026
Revised: 22 October 2026
Accepted: 27 October 2026
Published: 2 November 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

1. Introduction

Coral reef ecosystems are recognized as global marine biodiversity hotspots, providing essential habitat for a vast array of species and sustaining significant economic value; they also serve as natural barriers that mitigate coastal erosion and hurricane impacts [1]. However, they are declining at an unprecedented rate due to ocean warming, acidification, and localized anthropogenic pressures [2–4], as recent regional baselines show a severe

reduction in active reef-builders across the Pacific [5]. Additionally, thermal tolerance and adaptive capacity to climate change vary significantly by latitude, even among resilient species like *Porites lutea* [6]. This crisis is evident in major reef networks worldwide, including the Mesoamerican Barrier Reef System in the Mexican Caribbean and the reef communities of the Mexican Pacific. In these regions, the synergistic effects of thermal anomalies, aggressive coastal development, emergent epizootics such as the Stony Coral Tissue Loss Disease (SCTLD), and recurrent massive *Sargassum* spp. influxes have severely degraded hard coral cover [7,8]. As natural recovery mechanisms are increasingly outpaced by the frequency of these stress events, an urgent global mandate exists to shift from passive conservation to large-scale, active ecological intervention.

Over the years, researchers have proposed various reef restoration strategies to combat this rapid degradation. Early interventions relied largely on asexual propagation, or "coral gardening," which involves fragmenting and transplanting fast-growing species. This technique is effective for rapid biomass recovery, but it often yields coral populations with narrow genetic diversity, leaving them highly vulnerable to future environmental shocks [9]. Consequently, the field is shifting toward sexual propagation strategies: capturing gametes during mass spawning events, rearing larvae in nurseries, and seeding competent planulae back onto the reef. This sexually derived approach is crucial for promoting genetic recombination and long-term resilience, but its success fundamentally depends on providing optimal benthic environments for larval settlement [7,10,11].

Larval propagation requires deploying artificial substrates or seeding units that integrate seamlessly into degraded reef matrices. Historically, ordinary Portland cement (OPC) and concrete have been the materials of choice for constructing these large-scale artificial reefs. Concrete offers unparalleled engineering and logistical advantages: it is globally accessible, highly cost-effective, easily moldable into complex 3D macro-topographies that dissipate wave energy, and has the specific gravity needed to withstand oceanic hydrodynamic forces. While alternative micro-substrates, such as 3D-printed alumina ceramics, calcium carbonate frameworks, and specialized clay seeding devices, are highly valuable for experimental coral aquaculture and larval rearing, they are often too brittle, lightweight, or prohibitively expensive to deploy directly as massive, hectare-scale breakwater structures.

Therefore, concrete remains the foundational base material for large-scale reef engineering. However, these alternative substrates (ceramics, carbonates, and composite seeding devices) remain highly relevant and are deliberately included within the scope of this review. They serve as critical ecological analogs and experimental benchmarks; understanding how larvae settle on these specialized matrices provides the biomimetic blueprints needed to design functional coatings, composite layers, and topographical interfaces ultimately applied to structural marine concrete. Unfortunately, despite their structural necessity, bare concrete structures do not guarantee coral settlement. Pelagic coral larvae rely on highly specific topographic and biochemical cues to transition into benthic calcifying polyps. Conventional concrete inherently fails to provide an optimal interface for this delicate ontogenetic transition. Cementitious materials generate a highly alkaline surface environment during hydration. The continuous leaching of calcium hydroxide ($Ca(OH)_2$) into the boundary layer causes sharp interfacial pH spikes that are toxic to coral planulae and actively inhibit the settlement of Crustose Coralline Algae (CCA), which are the primary natural biological inducers for coral metamorphosis [2,3,12–14].

As a direct consequence of this chemical incompatibility, unconditioned concrete substrates are highly susceptible to opportunistic biofouling. In the dynamic marine environment, bare concrete is rapidly colonized by filamentous turf, fleshy macroalgae, and goose barnacles. These fast-growing organisms thrive on the surface, monopolizing the available benthic space and outcompeting slow-growing calcifying organisms. By the

time the pH of the concrete surface naturally neutralizes over several months or years, the substrate is usually permanently dominated by non-reef-building taxa, undermining the restorative purpose of the artificial reef [15,16]. In this review, we introduce the term "recruitment paradox" to conceptualize this fundamental bottleneck. While concrete is the most structurally and economically viable material for building artificial reefs, its unconditioned physicochemical interface inherently repels the very biological recruitment it is intended to promote.

Due to the inherent constraints associated with using bare concrete in artificial reef construction, a multidisciplinary research field integrating materials science and marine ecology has rapidly evolved. This field supports a critical paradigm shift: transitioning from passive structural concrete to bioactive interfaces engineered specifically to enhance coral settlement and post-settlement survival. This reflects a broader trend in marine materials engineering, which has evolved from toxic antifouling paints that release biocides to non-toxic, biomimetic, stimulus-responsive surface coatings [17–19].

While previous reviews have provided valuable insights into artificial reef construction, they do not systematically address the critical role of engineered surface coatings at the micro-ecological scale. For instance, Ozanam et al. [2] recently evaluated substrate choice for coral restoration, but their analysis primarily focused on macroscopic material selection (e.g., concrete vs. ceramic vs. metal) and broad ecological suitability rather than the chemical functionalization of the surfaces. Similarly, Liu et al. [3] conducted a comprehensive review of coral concrete, but their scope was largely limited to the material's bulk mechanical properties, structural integrity, and hydration chemistry, without exploring the biological interface required for larval recruitment. Currently, the existing literature lacks a comprehensive, interdisciplinary synthesis of how active interfacial modifications (such as biopolymers and hydrogels) can mitigate cement toxicity and actively deliver morphogenic cues to coral larvae.

To address this significant knowledge gap, this systematic review provides a state-of-the-art analysis, critically evaluating technological advances over the last 16 years in developing functional surface coatings for marine concrete. By systematically analyzing the evolution, coating architecture, mechanistic function, and translational scalability of these materials, ranging from traditional inorganic passivation to advanced biopolymeric matrices and bio-inspired adhesives, we propose a classification framework based on their mode of interfacial activity. Ultimately, by synthesizing progress and identifying current bottlenecks, this review aims to establish a clear future perspective and a strategic roadmap for engineering next-generation biosubstrates that maximize larval recruitment.

This review employs a dual-structured approach. Sections 4 and 5 comprise a narrative synthesis that establishes the theoretical framework of bio-interfacial interactions and the physicochemical limitations of marine concrete. Building on this foundation, Sections 2, 3, and 6 present the systematic component, rigorously extracting and classifying state-of-the-art coating technologies by their mode of interfacial activity. Specifically, this review addresses the following explicit research questions: (1) What are the fundamental physicochemical and biological mechanisms that inhibit coral settlement on uncoated raw concrete? (2) How can engineered marine coatings be systematically classified based on their restoration approach and mode of interfacial activity? (3) What are the principal bioactive coating technologies (e.g., controlled-release hydrogels, engineered living materials) developed for marine concrete over the last 16 years? (4) How do these specific interfacial modifications mechanistically influence coral larval settlement and early post-settlement survival? (5) What are the primary technological, ecological, and economic bottlenecks preventing the large-scale deployment of these advanced coatings in global reef restoration efforts?

2. Materials and Methods

2.1. Study Design and Search Strategy

This systematic review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines to ensure transparency [20] (see the full checklist in Supplementary Data S1), rigor, and reproducibility. We conducted a comprehensive literature search to identify peer-reviewed studies examining surface coatings and functional modifications on concrete substrates to promote coral larval settlement.

The primary literature search was performed in September 2026 across three major scientific databases: Scopus, Web of Science (Core Collection), and ScienceDirect. The search was restricted to English-lenguage articles published between January 2010 and September 2026 to capture the recent paradigm shift toward advanced biomaterials, smart interfaces, and green chemistry in marine restoration.

Due to the specific search syntax requirements and limitations of each database, the search strings were adapted as follows:

- For Scopus, an advanced search was conducted using:
  TITLE-ABS-KEY ((“coral” OR “larva*” OR “planula*” OR “settlement” OR “recruitment” OR “metamorphosis”) AND (“coat*” OR “surface modification” OR “thin film” OR “hydrogel” OR “eutectogel” OR “biopolymer” OR “bioadhesive” OR “functionalization” OR “Smart” OR “cue*” OR “foul*” OR “active*” OR “compound*”) AND (“concrete” OR “cement*” OR “artificial reef*” OR “substrate*” OR “reef*” OR “composite*”)) AND PUBYEAR > 2009 AND PUBYEAR < 2027
- For Web of Science (Core Collection), the advanced search string was:
  TS=((“coral” OR “larva” OR “planula” OR “settlement” OR “recruitment” OR “metamorphosis”) AND (“coating” OR “surface modification” OR “thin film” OR “hydrogel” OR “eutectogel” OR “biopolymer” OR “bioadhesive” OR “functionalization” OR “smart” OR “active”) AND (“concrete” OR “cement” OR “artificial reef” OR “substrate” OR “reef” OR “microhabitat” OR “composite” OR “groove” OR “roughness” OR “mineral” OR “ion release” OR “carbonate”) AND (“bioinspir*” OR “foul*” OR “settlement cue” OR “chemical cue” OR “biochemical” OR “exometabolite” OR “crustose coralline alga” OR “CCA”))
- For ScienceDirect, due to character limits on Boolean operators, the search was split into three targeted queries within Title, abstract or author-specified keywords:
  (1) (“coral” OR “larva”) AND (“coating” OR “surface modification”) AND (“concrete” OR “artificial reef”) AND “bioinspired”
  (2) (“planula” OR “settlement”) AND (“thin film” OR “hydrogel”) AND (“substrate” OR “microhabitat”) AND “chemical cue”
  (3) (“recruitment” OR “metamorphosis”) AND (“biopolymer” OR “bioadhesive”) AND (“composite” OR “roughness”) AND “CCA”

To ensure maximum coverage and overcome ScienceDirect’s search engine limitations, this manual search was supplemented using LeapSpace, an AI-powered literature discovery tool developed by Elsevier. A comprehensive conceptual string was input into LeapSpace: (“coral” OR “larva” OR “planula” OR “settlement” OR “recruitment” OR “meta-morphosis”) AND (“coating” OR “surface modification” OR “thin film” OR “hydrogel” OR “eutectogel” OR “biopolymer” OR “bioadhesive”) AND (“concrete” OR “cement” OR “artificial reef” OR “substrate” OR “reef” OR “microhabitat” OR “composite” OR “groove” OR “roughness” OR “mineral” OR “ion release” OR “carbonate”) AND (“bioinspir*” OR “foul*” OR “settlement cue” OR “chemical cue” OR “biochemical” OR “CCA”).

The AI was prompted to summarize the literature and identify studies matching the review's strict inclusion and exclusion criteria. The references cited in the LeapSpace report were then downloaded and merged with the conventional database results.

2.2. Eligibility Criteria

To maintain a strict focus on the interfacial engineering of artificial reefs, studies were evaluated against predefined inclusion and exclusion criteria based on the PICO (Population, Intervention, Comparison, Outcome) framework:

Inclusion criteria:

1. Substrate: studies utilizing concrete, Portland cement pastes, geopolymers, or analogous cementitious materials intended for marine deployment.
2. Intervention: application of active chemical modifications, synthetic polymer layers, natural biopolymer matrices (e.g., polysaccharides, proteins), bio-inspired adhesives, or functional hydrogels/eutectogels on the substrate surface.
3. Outcomes: quantitative evaluation of coral larval settlement rates, metamorphosis success, post-settlement survival, or interfacial adhesion metrics.
4. Theoretical context: highly specialized systematic or narrative reviews focusing directly on cementitious artificial reefs, marine bio-adhesion, or coral recruitment microenvironments, to be included exclusively in the qualitative narrative synthesis.

Exclusion criteria:

1. Studies focusing exclusively on non-cementitious substrates (e.g., pure plastics, glass, or unconditioned terracotta) without direct relevance to artificial reef structures.
2. Research evaluating passive concrete curing or weathering without the addition of an interfacial coating or chemical functionalization.
3. General marine biofouling studies lacking specific quantitative assays involving coral larvae or crucial settlement-inducing organisms like CCA.
4. Preprints, conference proceedings (e.g., conference abstracts), editorial letters, patents, and broad, non-specific general marine biofouling reviews lacking direct relevance to targeted coral settlement engineering.

2.3. Study Selection Process

All citations retrieved from the databases, including the supplementary curated list from LeapSpace, were exported to Mendeley Reference Manager, where automated and manual deduplication were performed. The screening phase was conducted in two sequential steps. First, titles and abstracts were independently screened by three reviewers (A. EM, M.E. TC, and M.A. GR) to discard clearly irrelevant records. Disagreements were resolved through discussion and consensus with a senior reviewer (R. S. and M.E.). Inter-reviewer reliability for study inclusion was high (**mean** Cohen's kappa = 0.85). Second, the full texts of the remaining articles were retrieved and thoroughly evaluated against the eligibility criteria. The reasons for excluding full-text articles were systematically recorded to construct the PRISMA flow diagram.

2.4. Data Extraction and Synthesis Protocol

Three reviewers (A. EM, M.E. TC, and M.A. GR) systematically extracted data from the included studies independently into a standardized matrix designed to evaluate both the materials science parameters of the engineered interfaces and their resulting biological performance. Any discrepancies during the data extraction phase were cross-checked and resolved through consensus with a senior reviewer (R. S. and M.E.). To systematically categorize these technologies, the extracted variables explicitly align with our proposed classification framework and include:

- Coating technology: the specific chemical nature, formulation, or structural design of the engineered interface (e.g., nanocarrier hydrogels, living microbial inks, inorganic additives, 3D-printed topographies, or foul-release coatings).
- Classification: the restoration approaches were defined by determining whether a component or function of the natural settlement environment is reproduced, replaced, modified, or supported, organizing the articles into biofilm and microbiome cue-mimicry (I), biomineral/ionic (II), physical/hydrodynamic (III), or benthic competition and spatial regulation (IV). Category IV represents the ecological imperative of maintaining available settlement space by mitigating aggressive benthic competition (e.g., algal overgrowth), securing fragments by acting as adhesives, or protecting established corals.
- Mode of interfacial activity (A0–A4): to distinguish the biological resource being addressed from the material mechanism used to provide it, we use the question "how does its interface operate?" to assign A0 to passive or static; A1 to bioactive; A2 to smart or controlled release; A3 to living mechanisms; and A4 to electroactive.
- Biological endpoints: explicit differentiation between reversible attachment, irreversible metamorphosis, overall settlement, and post-settlement survival (as formally defined in Section 5.2 of this review).
- Reference control conditions: identification of the specific baseline substrate used for comparison (e.g., bare concrete, pure ceramic) and its pre-conditioning status (e.g., sterile/unconditioned versus seawater-conditioned) to ensure accurate interpretation of reported fold-changes.

Given the expected methodological heterogeneity in substrate formulations and biological assays across literature, a quantitative meta-analysis was inappropriate. Instead, a narrative synthesis with quantitative benchmarking was performed. The selected studies were mapped by dual classification (restoration approach and interfacial activity) to critically evaluate current technological bottlenecks, economic viability, and future translational scalability. To enable meaningful comparisons across highly heterogeneous experimental designs, quantitative settlement outcomes were standardized whenever the original data permitted. Specifically, raw settlement counts or percentages were converted into relative effect sizes (expressed as fold-changes or relative percentage differences) normalized against the respective unconditioned baseline control of each individual study.

2.5. Methodological Quality and Risk-of-Bias Assessment

Because traditional risk-of-bias tools (e.g., Cochrane Risk of Bias, MINORS) are designed for clinical interventions, they are not directly applicable to materials science and marine ecology. Consequently, methodological quality was assessed using a custom 5-criterion Quality Assessment Framework (QAF) tailored for this interdisciplinary overlap. As detailed in Supplementary Table S1, each included study was evaluated on a 0–5 scale based on: (Q1) substrate and interfacial relevance, (Q2) physicochemical characterization, (Q3) biological control and baseline, (Q4) assay rigor and replicates, and (Q5) endpoint definition. High-quality studies were defined as validating coatings in realistic biological systems or models (e.g., in vivo field deployments, mesocosms, or ex situ flow chambers) with actual larval settlement assays. Studies presenting mere proof-of-concept material characterizations or theoretical simulations without real larval settlement evaluation were deemed at high risk of biological irrelevance and were excluded from the quantitative matrix. Finally, due to the extreme methodological heterogeneity in reporting settlement metrics (e.g., absolute counts versus percentages), reporting bias (such as publication bias) could not be formally assessed via funnel plots, nor could a standardized certainty of evidence framework (like GRADE) be universally applied. Highly specialized review

articles retained to construct the theoretical framework and qualitative narrative synthesis were, by definition, excluded from the quantitative data extraction matrix, ensuring that only primary empirical data populated the final comparative analysis.

2.6. Protocol and Registration

This systematic review protocol was not prospectively registered in platforms such as PROSPERO, as its scope pertains strictly to materials engineering and marine ecology rather than human health outcomes.

3. Systematic Search Results (Study Selection)

The systematic literature search retrieved an initial gross total of 7466 records across the three conventional databases. Specifically, Scopus yielded 7155 records (6117 articles, 365 reviews, 333 conference papers, 256 book chapters, and 84 conference reviews). ScienceDirect yielded a total of 119 records across the three split manual searches (29 articles, 62 reviews, 17 book chapters, 2 conference abstracts, 4 encyclopedia entries, and 5 others). Web of Science yielded 192 records (172 articles, 16 reviews, 2 book chapters, 1 early access, and 1 proceeding paper). Prior to formal screening, ineligible document types (such as conference abstracts, book chapters, editorials, and non-peer-reviewed notes) along with language restrictions were excluded using the native automated filters built into each database, effectively narrowing the yield. To ensure academic rigor, results were strictly limited to peer-reviewed articles and reviews published in English, which reduced the conventional database yield to 6404 eligible records. Along with 61 additional records identified through the AI-assisted LeapSpace search, a combined total of 6465 records was retrieved prior to deduplication.

After exporting these records to Mendeley Reference Manager, 29 records were removed before screening. These included 12 duplicates from the conventional searches, and 17 records from the LeapSpace results (15 duplicates already captured by other databases and 2 non-English articles). Consequently, 6436 unique records remained for title and abstract screening. Most of these records (n = 6311) were discarded as “off-scope” during the first screening phase. These were primarily false positives captured by broad keywords (e.g., “hydrogel,” “coating,” “active”), which retrieved literature unrelated to marine ecology, such as studies on biomedical tissue engineering, oncology, industrial antifouling for ship hulls, or microplastics pollution.

Figure 1 presents the complete systematic search and selection process as a PRISMA flow diagram. After thorough screening, 126 articles were deemed highly relevant and retained for full-text eligibility assessment. From this pool, 41 reports were excluded from the strict quality assessment but retained solely for the overall qualitative synthesis, providing the foundational literature for the theoretical framework and biological mechanisms discussed in this review. Consequently, 85 full-text articles were rigorously assessed for eligibility using a custom 5-domain Quality Assessment Framework. Following this evaluation, 46 publications were excluded: four failed to meet the primary scope or eligibility criteria; one met all quality domains but lacked direct validation with coral material; and 41 were retained separately as analog evidence. Ultimately, 39 publications met the five-domain inclusion criteria and were included in the main extraction matrix: nine in category I, five in category II, 13 in category III, and 12 in category IV. Based on the quality framework, 35 of these studies received an overall Low Risk rating, while four received an Unclear Risk rating. From these 39 publications, a highly refined subset of 12 peer-reviewed experimental studies met all strict PICO eligibility criteria, specifically the use of cementitious or analogous marine substrates and direct biological evaluation of coral larvae or spat, and were included in the final quantitative data extraction matrix. To avoid

methodological bias, 27 studies were excluded from this final quantitative matrix because they evaluated coatings on pure plastics or glass, tested chemical compounds dissolved in multi-well plates without a functional coating on a relevant substrate, lacked quantitative coral settlement metrics, or lacked sufficient control baselines.

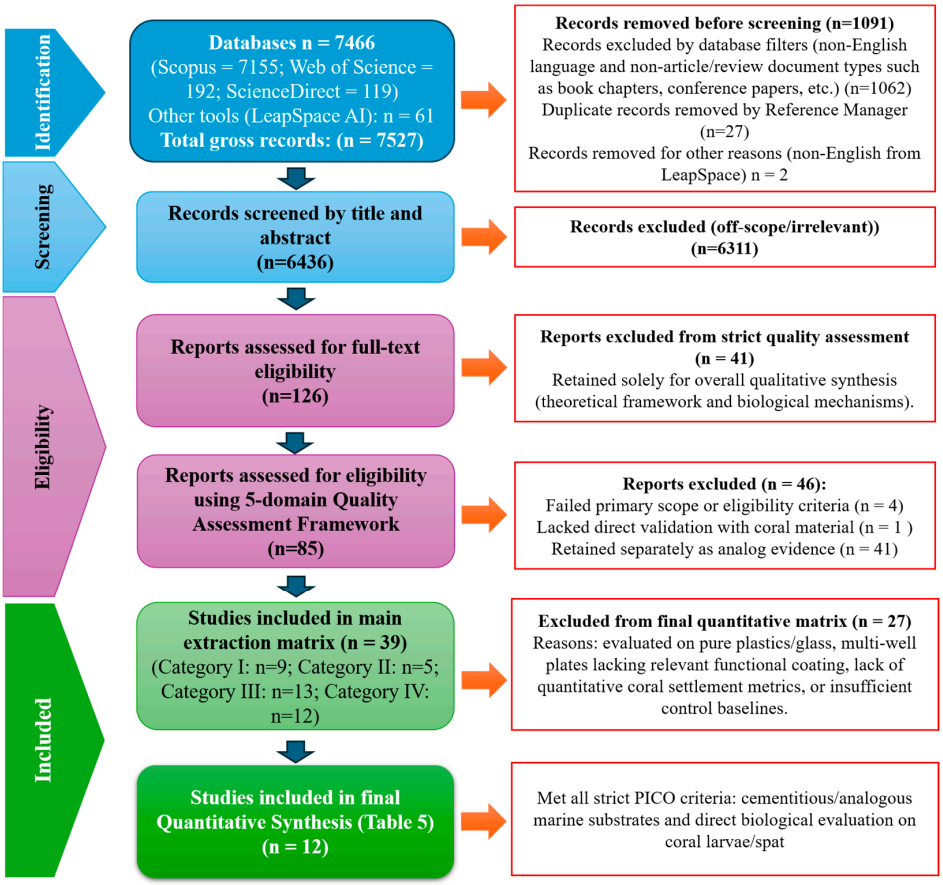

Figure 1. PRISMA 2020 flow diagram of the systematic literature search and study selection process.

4. Physico-Chemical Limitations of Marine Concrete

The widespread use of OPC in marine artificial structures stems from its structural mechanics and economic feasibility, but its bulk hydration chemistry severely compromises the biocompatibility of the biological interface. The hydration of tricalcium silicate (C_3S) and dicalcium silicate (C_2S) produces a poorly crystalline, nanostructured calcium silicate hydrate (C-S-H) gel alongside substantial quantities of crystalline portlandite ($Ca(OH)_2$), as described by Equation (1):

$$2Ca_3SiO_5 + 7H_2O \rightarrow 3CaO{\cdot}2SiO_2{\cdot}4H_2O + 3Ca(OH)_2 \quad (1)$$

Similarly, the hydration of the slower-reacting belite phase also contributes to the formation of the C-S-H gel and releases additional calcium hydroxide, as described in Equation (2):

$$2(2CaO{\cdot}SiO_2) + 5H_2O \rightarrow 3CaO{\cdot}2SiO_2{\cdot}4H_2O + Ca(OH)_2 \quad (2)$$

As both Equations (1) and (2) show, the continuous generation of $Ca(OH)_2$ (portlandite) is fundamental to hydration. The dissolution of this portlandite, together with dissolved alkali species (primarily Na^+, Ca^{2+}, and K^+), contributes to the highly alkaline pore solution. Consequently, the internal fluid of freshly cured concrete typically exhibits an equilibrium pH of 12.5 to 13.5. Therefore, when an unconditioned concrete unit is submerged in

seawater, a steep chemical concentration gradient drives ions outward across the substrate-water boundary layer. Although seawater has substantial buffering capacity governed primarily by the carbonate system ($CO_2/HCO_3^-/CO_3^{2-}$), boundary-layer transport can locally constrain its ability to neutralize highly alkaline effluents rapidly. This produces localized interfacial pH spikes exceeding 9.5 to 10.5 during early deployment [21,22].

This localized alkaline microenvironment exerts immediate cytotoxic stress on pelagic coral planulae because they lack keratinized or rigid cuticular barriers. At this stage, the coral larvae's outer surface consists of a delicate, ciliated pseudostratified epithelium equipped with sensory cells and mucocytes. Contact with hyperalkaline micro-zones disrupts transmembrane electrochemical gradients and intracellular pH regulation, causes osmotic shock that leads to epidermal cell lysis and excessive mucus hypersecretion, and impairs ciliary beating, directly impeding substrate exploration and crawling behavior, causing premature larval mortality before attachment [23,24].

Simultaneously, leached OH^- can react with seawater Mg^{2+} to promote brucite precipitation, whereas Ca^{2+} released from the cement pore solution can interact with dissolved inorganic carbon species to promote $CaCO_3$ precipitation at the concrete–seawater interface and within near-surface pores. Although this mineralization gradually attenuates ion leaching by blocking pores, surface alkalinity can persist for extended periods. The rate of natural pH attenuation depends strongly on concrete composition, porosity, curing history, the surface-area-to-volume ratio of the artificial structure, and local hydrodynamic conditions. For instance, while small experimental settlement tiles may reach a biologically viable surface pH and develop inductive microbial biofilms within 4 to 8 weeks, large-scale artificial reef modules possess a significantly greater internal reservoir of portlandite. These massive structures can require several months of in situ seawater conditioning before their surfaces safely support sensitive coral larval settlement. Ultimately, this delayed neutralization may create an extended window during which larval settlement and early post-settlement survival are substantially impaired [3,25,26]. Figure 2 visually summarizes the physicochemical conflict detailed above.

To evaluate material compatibility accurately, it is crucial to distinguish the distinct spatial pH environments associated with marine concrete. The internal pore solution of standard ordinary Portland cement (OPC) is highly alkaline (pH 12.5–13.5). However, biological interactions occur at the substrate-water boundary layer (interfacial surface pH). While fresh OPC can produce initial boundary-layer spikes (pH 9.5–10.5), extended seawater curing or modified low-alkalinity cements significantly reduce this surface emission. Consequently, the pH values reported for comparative material assessments (as is discussed in Section 5) strictly refer to the interfacial surface pH measured after specific curing periods, reflecting the actual microenvironment encountered by exploring coral larvae.

Furthermore, in seawater, concrete surfaces develop a dynamic net negative zeta potential due to the dissociation of silanol groups ($\equiv Si-OH \rightleftharpoons \equiv Si-O^- + H^+$) and the adsorption of multivalent anions (such as SO_4^{2-}). During the first few minutes of immersion in seawater, this charged surface adsorbs a film composed of dissolved organic matter, including glycoproteins, polysaccharides, and humic substances [27]. Given that untreated concrete lacks the biochemical selectivity to promote settlement, this film acts as an open ecological niche, colonized primarily by opportunistic fouling organisms (micro- and macro-foulers) (as is illustrated in Figure 3). This colonization is often exacerbated in inland coastal waterways, where terrestrial runoff, turbidity, and nutrient pollution severely degrade water quality, facilitating rapid macroalgal overgrowth before concrete neutralization occurs [28,29]. In the first seven days, a rapid colonization occurs by fast-dividing benthic diatoms, heterotrophic bacteria, and cyanobacteria, forming an amorphous extracellular polymeric substance matrix [3,16,30]. After 1–4 weeks, filamentous green algae,

cyanobacterial mats, and opportunistic turf algae compete with the slow-growing CCA; however, turf algae thrive in elevated nutrient regimes and unbuffered concrete surfaces, expanding rapidly, trapping particulate sediments, and forming a layer that coats and smothers concrete surfaces, generating localized microenvironments of hypoxia and acidity in dark conditions [3,16,30,31].

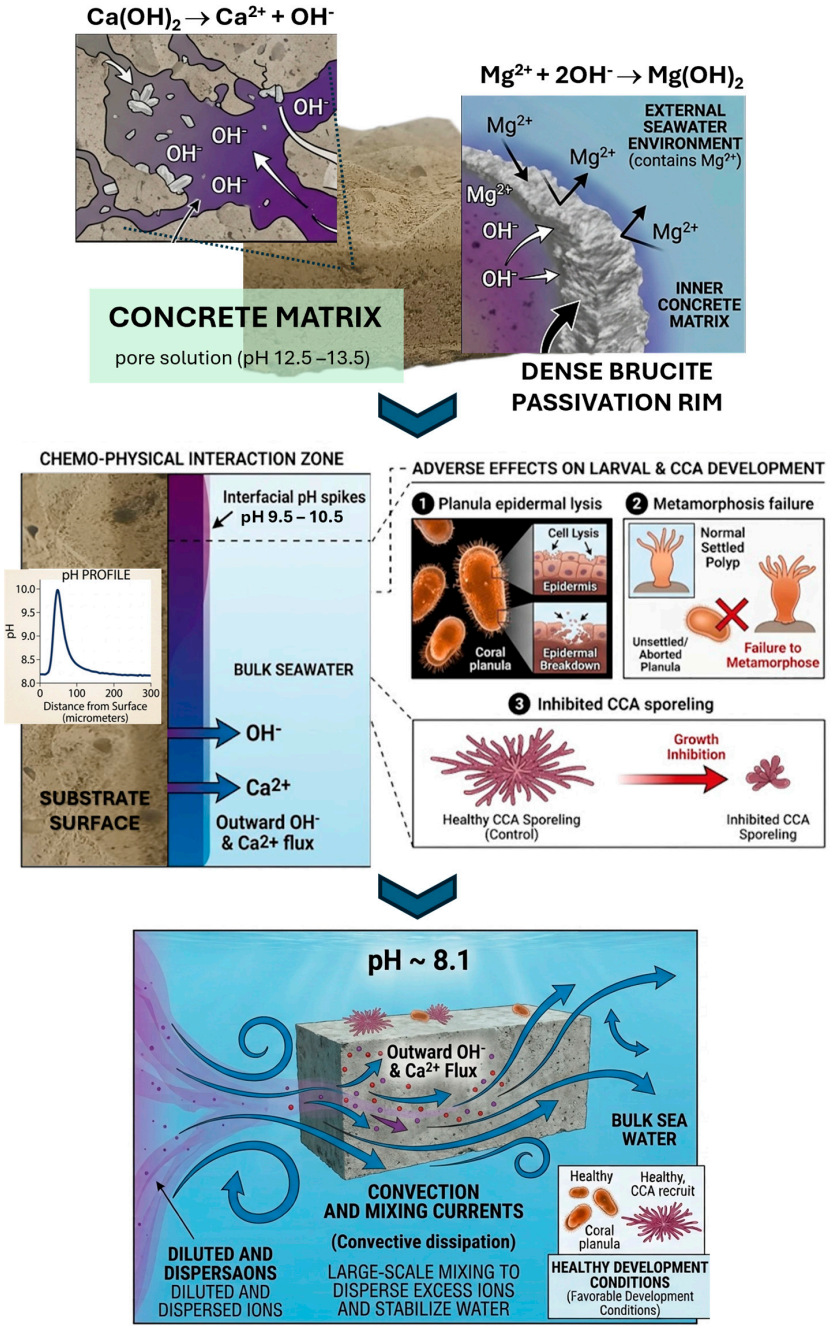

Figure 2. Schematic representation of physicochemical interactions and biological consequences at the bare concrete-seawater interface. The conceptual pH profile illustrates the outward flux of OH^- and Ca^{2+} ions from the highly alkaline concrete pore solution (pH 12.5–13.5), leading to inorganic precipitation reactions (e.g., Mg^{2+}). The middle physicochemical interaction zone exhibits interfacial pH spikes (9.5–10.5) that directly induce planula epidermal lysis, metamorphosis failure, and severe growth inhibition of crustose coralline algae (CCA). Finally, large-scale convective dissipation is required to dilute excess ions and return the boundary layer to a biologically favorable ambient pH (~8.1). *Note: all representative pH values are derived from the primary literature referenced in the main text.*

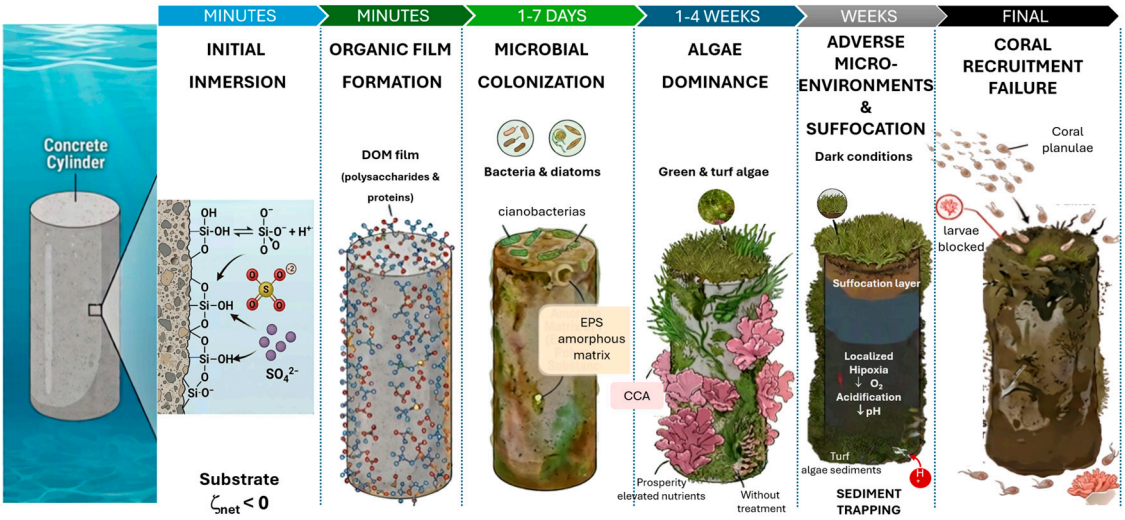

Figure 3. Conceptual model of the biofouling succession and physicochemical limitations on unconditioned marine concrete leading to coral recruitment failure. *Note: The specific biological mechanisms and primary literature references supporting each temporal stage are detailed in the accompanying text.*

When coral planulae encounter a concrete substrate dominated by dense algal turf or unconditioned biofilms, recruitment fails because the sediment-trapping nature of the turf prevents the larval aboral pole from establishing direct physical contact with the underlying solid matrix (see Figure 3). In addition, filamentous algae produce allelopathic secondary metabolites that deter larval probing. For these reasons, when the concrete has chemically neutralized via passive seawater leaching, non-calcifying, competitive organisms fully monopolize the available benthic space, establishing an alternative stable state that permanently excludes scleractinian coral colonization [32–34].

Beyond the foregoing, coral larval settlement is not a stochastic physical landing; it is a genetically hardwired, signal-mediated cascade. Competent planulae navigate their fluid environment by actively probing benthic surfaces using specialized neurosensory ciliary complexes located at their aboral pole. Specific exogenous chemical inducers (morphogens) trigger the cessation of swimming, contraction along the oral-aboral axis, adherence, and irreversible metamorphosis into a calcifying primary polyp [35–37].

The principal natural sources of these inductive cues are CCA, such as species of *Lithothamnion*, *Porolithon*, and *Neogoniolithon,* and their associated surface-bound bacterial biofilms (e.g., specific strains of *Pseudoalteromonas*) [35,38–40]. Among the identified biochemical stimuli, the most prominent are:

- Cell-wall-associated sulfated polysaccharides and complex glycans.
- Brominated pyrrole derivatives, with particular emphasis on tetrabromopyrrole (TBP).
- Hydrophobic signaling macromolecules (peptides/esters) that trigger neurosensory pathways via G-protein-coupled receptors (GPCRs) in the planula larva.

The intrinsic surface chemistry of bare concrete systematically neutralizes these chemosensory dynamics. First, the hyperalkaline boundary layer chemically alters or denatures sensitive bioactive *morphogens* via alkaline hydrolysis, rendering signaling peptides and glycans functionally inert. Second, beneficial marine bacteria that induce settlement fail to form stable monocultures or functional consortia on fresh concrete, as high alkalinity allows only alkali-tolerant microbial strains that do not induce settlement [2,16,41,42].

Finally, conventional untreated concrete typically has a smooth macroscopic surface, creating two distinct disadvantages: one chemical and one physical. Chemically, a smooth surface possesses a low specific surface area. This limited contact interface restricts ion exchange with seawater, slowing the leaching of internal alkalinity and delaying natural

surface carbonation and pH neutralization. Physically, a smooth surface lacks the tailored sub-millimeter microtopographical grooves (optimally 250–500 μm) required to provide hydrodynamic shelter for planulae against oceanic boundary shear stress. Because microfeatures smaller than 250 μm are effective only under static conditions, they fail to protect larvae in dynamic environments while their basal calicoblastic ectoderm synthesizes the initial aragonite proto-skeleton [21,23,42,43].

In summary, this tripartite incompatibility (alkaline cytotoxicity, rapid biofouling preemption, and chemical cue inactivation) defines the fundamental bottleneck of bare concrete, demonstrating that applying engineered, biocompatible, and bioactive surface coatings is an absolute physiological and ecological requirement for effective coral larval recruitment.

However, it is important to avoid overgeneralizing the negative effects of untreated concrete as an absolute, permanent barrier. Historical field observations demonstrate that given sufficient time (often several years) and highly favorable local hydrodynamic flushing, massive bare concrete structures can eventually neutralize and support natural reef succession [15,25]. The core issue is temporal: during this extended, uncontrolled neutralization window, the unconditioned substrate remains highly vulnerable to aggressive spatial monopolization by competitive macroalgae.

5. Integration of the Coating and Settlement of Larvae

Despite its disadvantages, concrete offers advantages in formability, availability, and strength. For these reasons, this investigation focuses on designing functional coatings that leverage concrete substrates while considering material stability and interactions with larvae and benthic communities [25,44,45]. One of the most studied topics is the development of polymeric coatings, which can partially decouple the biological surface from the concrete volume, but their function is not limited to barrier formation. Their composition, thickness, wettability, porosity, stability, and ability to release compounds determine how the interface with seawater and organisms is established. Consequently, the relevant functional unit is the concrete–coating–boundary layer–organism system, whose response emerges from interactions among material properties, biological signals, and environmental conditions [35,46,47].

The mechanisms of coating–concrete integration are fundamental to the stages of coral settlement, from transport and substrate recognition to metamorphosis and post-settlement survival. The evidence is interpreted by distinguishing studies conducted directly on corals and concrete from those that provide adhesion or durability principles from other cementitious or marine systems.

5.1. Integration of the Coating with the Concrete Substrate

Effective integration of bioactive coatings with the substrate is critical to successful larval settlement, as it determines the spatial and temporal availability of inducing signals, coating adhesion under marine conditions, and physicochemical compatibility with the base surface. Preparing concrete before applying a coating has two related but distinct objectives: improving chemical compatibility with the marine environment and creating a surface capable of forming a stable bond with the polymer matrix. Preconditioning by immersion in seawater can gradually reduce the surface alkalinity associated with cement and promote the formation of a conditioning film. In cementitious substrates evaluated for restoration, seawater conditioning has been linked to larval settlement viability, although its effectiveness depends on concrete composition, exposure time, and test conditions [25].

In addition to passive seawater conditioning, more direct surface treatments may be employed when a greater degree of substrate modification is required. Mild acid washing

and fast-setting pre-coatings have been studied as alternatives to modify the surface and improve the performance of aggregates or concretes intended for reef applications. However, treatment intensity must be controlled: excessive modification can alter the surface layer, increase porosity, or compromise the material's cohesion. Therefore, measure final pH, mass loss, roughness, and strength together, rather than assuming further neutralization is always beneficial [45].

Chemical functionalization can provide additional control over coating–substrate interactions. Molecular surface chemistry, including the behavior of functional groups like catechols, carboxylates, and phosphates, fundamentally dictates wet adhesion mechanisms and bioadhesion at the solid/liquid marine interface [48]. Hydroxylation, using chemical, oxidative, or plasma treatments, can increase the availability of surface hydroxyl groups and generate reactive sites for subsequent modifications. Silanization uses these groups to form a coupling layer between the mineral and organic phases. However, researchers must validate the transfer of these methods to immersed concrete for each formulation, as surface chemistry, pH, solvent, moisture, and deposition conditions affect interface formation and stability [49–51].

Adhesion between the coating and the concrete may involve mechanical anchoring in pores and asperities, intermolecular interactions, and, when the chemistry of both phases permits, chemical bonds. Mechanical anchoring depends on the polymeric matrix's ability to wet and penetrate surface irregularities before it gels or cures. Coupling agents can reinforce the chemical bond, provided the promoter's functional groups are compatible with both the mineral surface and the polymer. In cementitious systems, silanes have been studied as modifiers of the interfacial transition zone and as adhesion promoters; however, evidence from mortars or fibers does not, by itself, demonstrate a biological benefit in coral restoration [47,51].

Moreover, strong initial adhesion is only the first requirement, because the interface must remain stable after prolonged exposure to marine conditions, including immersion, swelling, thermal cycling, and flow action. Water ingress can induce plasticization, hydrolysis, loss of cohesion, or interfacial separation, depending on polymer chemistry and layer design. Therefore, an initial dry adhesion measurement cannot predict field behavior; retention tests are required after seawater exposure and, where relevant, under hydrodynamic or abrasive load [52].

Primer systems or tie-coats can be useful when the concrete and the external coating are incompatible. Silane promoters are an option, while polydopamine, inspired by mussel adhesive chemistry, has been investigated as a bonding layer on complex surfaces. Its performance must be compared with abrasion resistance, seawater stability, and potential component release. PDMS-epoxy systems and self-layered coatings provide fouling protection and control strategies, but their relevance for coral substrates depends on demonstrating ecological compatibility, not only anti-corrosion durability [53–57]. To visualize how these interfacial layers and adhesion promoters physically converge on an engineered artificial reef, Figure 4 conceptually illustrates a multilayered substrate architecture designed for optimal larval settlement.

Rather than relying on bare cement, this hierarchical design employs a transitional silane primer and an antifouling polymer layer. This interfacial barrier effectively mitigates alkaline leaching and uncontrolled macroalgal overgrowth while preserving the substrate's sub-millimeter microtopography [58,59]. Within these sheltered topographic niches, favorable conditions allow for the rapid establishment of inductive bacterial biofilms and encrusting CCA, creating a synergistic interface where physical protection meets biochemical signaling.

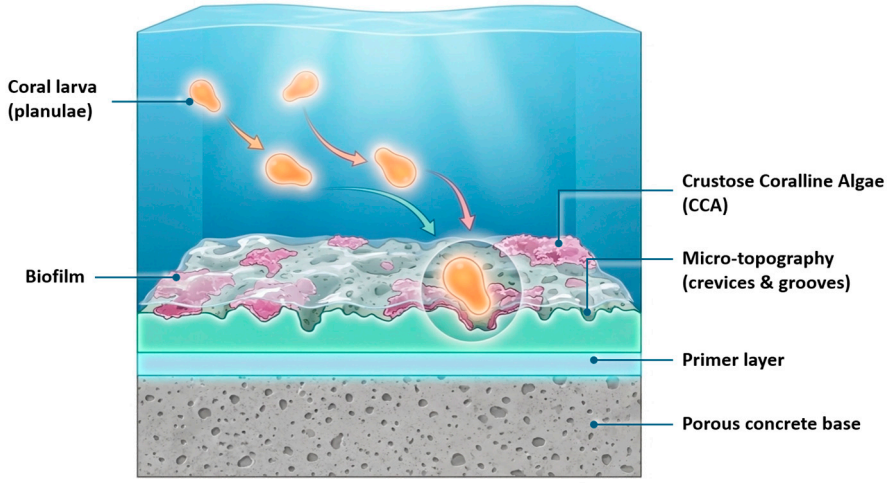

Figure 4. Larval settlement mechanism on multilayer artificial substrate. Representative diagram of the process of coral larva (seedling) fixation in the microtopography (cracks and grooves) of the surface. The substrate consists of a porous concrete base coated with a silane primer and an antifouling polymer layer. Previous CCA colonization and biofilm formation provide the chemical and structural signals needed to induce successful larval settlement.

Wettability also determines initial contact between the aqueous coating and the substrate, as well as how the formulation distributes on the surface. A hydrophilic surface can facilitate aqueous hydrogel spread, but overall contact angle is not a universal predictor of coral settlement. Larval responses to mineral composition and local signals have been observed on composite substrates, even though average wettability or roughness does not fully explain the preference [60].

Surface energy also influences polymer and microbial wetting and adhesion. Furthermore, surface structuring at the micro- and nano-scale, often achieved through anisotropic nanoparticles or tailored topographies, can significantly modulate initial bacterial adherence and subsequent fouling-release properties [61]. Plasma or corona treatments can modify surface energy in certain polymers. Still, the usefulness of these techniques in concrete coating must be judged by actual improvements in bond strength and stability after immersion. Similarly, porosity can facilitate mechanical anchoring and modify the diffusion of water, ions, and bioactive molecules, but high porosity can also favor water ingress or sediment accumulation. Pore architecture should be designed considering both mechanical and biological function [62–64].

Beyond adhesion, coating design must consider thickness, swelling, permeability, degradation, mechanical strength, and signal release (see Table 1). These variables are coupled: swelling can facilitate molecule diffusion but also generate interface stresses; a highly cross-linked matrix can retain integrity, but it can limit inductor availability; and rapid degradation can expose the concrete before the settling window ends. Therefore, the formulation must balance retention, transport, and stability based on the expected stimulus duration and site conditions.

The marine durability of smart coatings, including self-healing or anti-corrosion systems, offers useful principles for preserving material integrity. However, self-healing or corrosion resistance should not be considered proxy indicators of biocompatibility. Degradation products, leachate, additives, and curing agents require specific assessment against larvae, biofilms, and non-target organisms [65–67].

A critical materials engineering consideration for polymer-coated restoration substrates is matching the polymer matrix's degradation kinetics and dynamic stability to the temporal biological window of larval settlement. Hydrogels and biopolymeric networks subjected to continuous marine immersion undergo water uptake, swelling-induced

chain relaxation, and hydrolytic or enzymatic cleavage. If matrix degradation or surface erosion occurs too rapidly (i.e., within days), the immobilized biochemical morphogens or functional topographies are prematurely lost before competent planulae can complete irreversible metamorphosis. Conversely, overly stable or densely crosslinked synthetic matrices may permanently entail bio-inductive cues, preventing their diffusion into the boundary layer. Therefore, optimizing interfacial performance requires tuning polymer crosslinking density and degradation profiles to ensure structural and chemical stability throughout the critical 2-to-4-week settlement and early post-settlement window.

In engineered coatings for marine concrete, key physical parameters operate as coupled variables: coating thickness typically ranges from thin functional films (~10–100 μm) to thick hydrogel layers (0.5–2 mm); interfacial shear adhesion strength varies widely between 0.5–4.5 MPa depending on surface silanization or catechol priming; equilibrium hydrogel swelling ratios range from 120–450%; and water vapor/ionic permeability coefficients span 10^{-9}–10^{-7} cm^2/s. Not all reviewed literature reports specific quantitative ranges for certain experimental biopolymers or living materials; this lack of standardized parameterization is noted as a primary reporting limitation.

Table 1. Factors that affect coating adhesion to a cement substrate.

Factor/Parameter	Typical Quantitative Operational Ranges *	Physicochemical & Biological Implications	Ref.
Coating Thickness	10–100 μm (thin functional films) 0.5–2 mm (hydrogels & bioinks)	Physicochemical: Thicker layers increase bioactive morphogen loading capacity, but excessive thickness elevates internal swelling stress and delamination risk under wave shear. Biological: Thin films preserve substrate sub-millimeter microtopography (250–500 μm refugia), while thick gels create soft, compliant interfaces that facilitate planula probing and attachment.	[33,35,68–70]
Interfacial Adhesion Strength	0.5–4.5 MPa (shear/pull-off strength)	Physicochemical: Governs coating retention against hydrodynamic drag and wave abrasion. Interfacial coupling agents (silanes or catechol/L-DOPA primers) dramatically increase bond durability on alkaline concrete. Biological: Shear strength < 0.5 MPa causes premature coating detachment in dynamic environments, resulting in recruit loss before basal aragonite skeleton formation.	[47,49,54,71,72]
Swelling Ratio	120–450% (hydrogel mass expansion)	Physicochemical: Water uptake relaxes the polymer network, driving Fickian or non-Fickian diffusion of entrapped signaling molecules into the boundary layer. Biological: Controlled swelling lowers local interfacial stiffness to match native biological tissues, but hyper-swelling (>450%) degrades mechanical cohesion and creates sediment-trapping pockets.	[35,52,73]

Table 1. *Cont.*

Factor/Parameter	Typical Quantitative Operational Ranges *	Physicochemical & Biological Implications	Ref.
Permeability/Release Kinetics	10^{-9}–10^{-7} cm^2/s (diffusion coefficient) Sustained window: 2–4 weeks	Physicochemical: Regulates the outward flux of chemical morphogens (e.g., CCA exometabolites or bacterial LPS) while acting as a barrier against alkaline (OH^-) leaching from bulk concrete. Biological: Sustained release across 14–28 days bridges the competency window of broadcast-spawning larvae, preventing rapid burst leaching and premature cue depletion.	[35,73]
Surface Chemistry and pH	Surface pH: 7.8–8.5 (vs. 12.5–13.5 in raw OPC)	Physicochemical: Passivates outward OH^- ion flux and prevents localized alkaline spikes at the water-substrate boundary layer. Biological: Eliminates planula epidermal cell lysis and excessive mucus secretion, restoring normal ciliary beating and promoting rapid colonization by inductive CCA and bacterial biofilms.	[16,23,25]
Surface Roughness & Microtexture	Micro-grooves: 250–500 µm (RMS roughness: 1.8–12 µm)	Physicochemical: Alters the fluid boundary layer to generate localized flow recirculation vortices (Q-criterion zones) that reduce fluid velocity. Biological: Provides essential physical refugia that shelter attached planulae from wave-driven shear stress, resuspension, and sediment burial during initial calcification.	[12,42,60,68,74]

* Note: Where specific quantitative values or ranges were not explicitly reported in primary studies for certain experimental coatings (e.g., novel living materials or bio-inspired gels), this lack of standardized parameterization is noted as a primary reporting limitation in current literature.

5.2. Bioreceptivity and Signals That Regulate Settlement

In this review, these biological endpoints are strictly distinguished: attachment refers to the initial, reversible physical adhesion to the substrate; metamorphosis is the irreversible morphological transition into a primary polyp; and settlement encompasses both permanent attachment and successful metamorphosis. Finally, post-settlement survival indicates the long-term retention and growth of the recruit.

Settlement studies use different strategies to separate substrate effects from biological signals and environmental conditions. Choice/no-choice designs are particularly useful for studying coatings, as they allow researchers to distinguish an absolute effect on settlement from a true preference of larvae for a given surface area [75,76]. Furthermore, for practical restoration applications, post-settlement monitoring is equally critical; it determines whether a surface that successfully induces initial attachment also supports long-term recruit permanence and survival [77–80].

To interpret these experimental outcomes accurately, researchers must account for intrinsic developmental differences among target coral species. Corals are broadly classified into two reproductive groups (brooders and broadcast spawners) whose larvae have distinct ontogenetic timelines and rely on specific triggers, such as CCA, bacterial biofilms, or dissolved chemical signals, to initiate fixation and metamorphosis [76,81,82].

Brooding species incubate their embryos and release well-developed planulae that are fully or nearly competent. Because these larvae require little to no additional development, they settle rapidly. For example, *Heliopora coerulea* planulae can crawl and affix to a substrate within hours, whereas in *Porites astreoides*, settlement success and spatial competition depend heavily on local site conditions and initial larval size [11,39].

Conversely, broadcast-spawning corals release gametes directly into the water column, producing larvae that require a longer and more variable planktonic phase before achieving settlement competency [37]. While the larvae of species like *Platygyra daedalea* and *Goniastrea favulus* may become competent to settle within a few days, others necessitate considerably longer developmental periods [31,83,84]. These varying competency windows directly dictate how long an engineered coating must remain chemically active and physically stable underwater to bridge the gap between larval deployment and irreversible settlement successfully.

As was mentioned previously, settlement is an ontogenetic process that includes substrate encounter, exploration, initial adhesion, microhabitat selection, and metamorphosis into the benthic phase. The duration of larval competition and the timing of planulae responses to cues vary by species and reproductive strategy. In brooder corals, larvae may be released in relatively advanced stages and have brief settling windows; in broadcast spawner species, the planktonic phase and competition may be more variable. Consequently, the benefits of functional coatings cannot be generalized categorically. A specific biochemical cue, polymer formulation, or surface topography that significantly enhances the settlement of a brooding species in a static laboratory assay may prove entirely ineffective, or even deterrent, to the larvae of a broadcast spawner under dynamic field conditions. Successful settlement induction is governed by the complex interplay between the target species' unique sensory biology and the specific hydrodynamic test environment [33,84–86].

Temporary attachment does not equate to permanent settlement. Stable attachment is usually associated with metamorphosis and establishment of the juvenile polyp, but high mortality may still occur after this transition. Consequently, the percentage of larvae present on a surface at any given time is not sufficient to describe restoration success: it is necessary to distinguish initial adhesion, metamorphosis, retention, and early survival [11,78,87].

Because CCAs are important signals for many coral species, they can serve as a physical substrate and a source of chemical signals from the tissue, exudates, and microbial communities that live on them. Larval responses are not uniform; they depend on CCA identity, coral species, and whether living tissue is preserved. Some studies show that extracts or associated metabolites can induce responses even without live algae, opening the possibility of incorporating signals into polymeric matrices and presenting them locally [39,76,81,88,89].

Metabolomic and microbiological characterization of articulated coralline algae (ACAs) has enabled us to link differences in settlement induction to variations in their metabolites and microbiomes. Researchers have identified classes of lipids and other algal metabolites as potential signaling molecules. Importantly, CCA settlement-inducing capacity is fundamentally linked to the distinct, highly specific bacterial communities they harbor on their surfaces [38,39], which can be highly susceptible to environmental stressors such as coralline algal diseases [90]. However, identifying a chemical association does not, by itself, demonstrate that an isolated compound is sufficient or universal for inducing settlement; its activity must be validated for each species under controlled experimental conditions [35,67,91].

In biofilms, these communities progressively modify the chemistry and biology of submerged surfaces. Their effects on larvae depend on community composition, maturity, developmental conditions, and coral species. Researchers have identified bacteria and

metabolites that can induce settlement in certain systems, including TBP produced by biofilm-associated bacteria and signals linked to bacteria of the clade Roseobacter. However, it is not appropriate to attribute the response of all biofilms to a single taxon or metabolite: entire communities can exert inducing, neutral, or inhibitory effects [82,92–95].

Light and other environmental conditions during biofilm formation can modify its composition and ability to induce settlement. In addition, ACAs and their bacterial communities should be considered related, but not equivalent, components of the microhabitat. A bioreceptive coating should not necessarily seek a sterile surface but rather favor a community compatible with recruitment and selectively limit organisms that compete with recruits [38,96].

Beyond biological signals, mineral composition can directly influence settlement. In composite substrates, calcium carbonate-based materials and certain mineral additives can alter larval responses. Some studies suggest that soluble ions, such as silicate or strontium, act as signals in certain coral systems. This result indicates that material composition and the release of chemical species in the boundary layer may matter more than average macroscopic properties. For coatings, this highlights the need to control ion diffusion and local concentration, avoiding both insufficient release and potentially harmful exposure [97].

Responses to extracts of specific corals and to signals from other benthic organisms have also been described. The effect can be positive, neutral, or inhibitory, depending on the organism's identity, concentration, and ecological context. Therefore, selecting inducers should account for biological specificity and recognize that a signal favorable to one species may not benefit another [82,95]. Furthermore, larval settlement preference for CCA over other substrata is dynamic and highly dependent on the availability of bare space, indicating that larvae evaluate complex spatial and competitive cues during recruitment [98].

Incorporating CCA or microbial signals into polymeric matrices turns transient environmental stimuli into localized release sources. For example, SNAP-X is a commercial biomimetic chemical microhabitat based on polyethylene glycol hydrogel with methacrylate groups and nanoparticles loaded with CCA metabolites. It is designed to deliver signals and, in reported trials, has maintained release for more than one month and increased coral settlement compared to controls, illustrating the potential of release systems. However, it does not eliminate the need to evaluate species specificity, stability, and performance under natural conditions [35,81].

Microbial living materials represent another biomimetic strategy, as they seek to maintain or generate biological signals at the interface. Their application poses additional challenges of compositional control, stability, containment, and ecological response. In both approaches, the goal should be to regulate the spatial and temporal presentation of the signals, and not simply to maximize their initial concentration [35,68].

5.3. Topography and Hydrodynamics: From Transport to Contact

As was established previously, the presence of chemical signals does not guarantee that a larva will reach or remain above the surface. Transport to the substrate depends on local hydrodynamics and the interaction between flow and surface geometry (see Table 2). Topography can modify the benthic boundary layer, generate recirculation zones, and change the probability of contact. In oscillatory flow experiments, millimeter-scale structures produced low-velocity zones and were associated with marked increases in settlement compared with flat surfaces. The effect depends on the height, spacing, and geometry of the structures, so it should not be generalized to any roughness pattern [60,99].

It is useful to distinguish functional scales. Millimeter structures can modify larval flow and retention; microcracks, cavities, and depressions can provide refuges from shear

stress, resuspension, sedimentation, or herbivory; and microscopic scale characteristics can influence coating or biofilm contact and retention. However, roughness does not have a universal effect: some rough surfaces favor settlement, while others can accumulate sediment or facilitate competitor growth [42,84,100–102].

Additive manufacturing and porous matrices allow control of the shape, size, and distribution of surface structures. Studies with porous ceramics and 3D-printed substrates show that three-dimensional architecture can modify settlement and growth. For polymeric coatings on concrete, design the topography with the understanding that the applied layer can fill or smooth substrate irregularities. Therefore, characterize the concrete geometry and the coating's final topography separately [63,64,91,103,104].

Physical topography plays a crucial role in attachment processes, but its optimal scale is strictly dictated by local hydrodynamics. Sub-millimeter features smaller than 0.25 mm (250 µm) assist initial attachment under static conditions but become ineffective in dynamic scenarios. While 250–500 µm micro-grooves provide necessary shelter from moderate boundary shear stress, high-energy environments involving wave-driven flow require macro-topography. In these scenarios, millimeter-scale structures, such as 2.5 mm ridges, are essential for dissipating fluid velocity and creating localized recirculation zones (eddies), enabling larvae to swim downward and attach. Additionally, substrate chemistry and biofilm co-dependencies are vital; the physical shape must be combined with low-alkalinity materials to promote rapid colonization by inductive bacterial biofilms.

Table 2. Geometries, topography, and transport in cement specimens.

Substrate Geometry	Surface Topography & Fluid/Larval Transport	Advantages	Disadvantages	Ref.
Flat or Smooth (Standard square or circular tiles/slabs)	Topography: Smooth without macrostructures; low microscopic roughness (RMS ~1.88 µm). Transport: Laminar boundary layer without flow recirculation. Under oscillatory flow, generates high local velocities (>5x larval swimming speed), reducing "settlement windows" to brief periods (<0.6 s).	• Easy and cost-effective to mold and manufacture commercially. • Allows evaluating the pure effect of material chemistry without physical shape interference.	• Near-zero larval settlement (<5%) under dynamic flow or wave conditions. • High initial interfacial surface alkalinity (pH * > 8.7) in standard Portland cement (CEM I) that inhibits inductive biofilm formation.	[16,60]
Millimeter-scale Ridges & Grooves (Ridged/Grooved Surfaces; ~2.5 mm ridges separated by 7.5 mm or 1 mm grooves)	Topography: Combined micro- and macroroughness with millimeter-scale ridges or channels. Transport: Breaks oscillatory flow, creating recirculation zones (Q-criterion > Qthresh), redirects larvae to the base, and extends settlement windows by up to 300% (3.7 s per cycle).	• Increases larval settlement 10- to 20-fold over flat substrates in active flow. • Creates protected microhabitats and retains chemical cues.	• Requires precision molds, CNC machining, or 3D bioprinting. • Potential sediment accumulation within low-energy hydrodynamic pockets.	[35,60,68]

Table 2. *Cont.*

Substrate Geometry	Surface Topography & Fluid/Larval Transport	Advantages	Disadvantages	Ref.
Biomimetic Modular Coral Polyp Structures (Inspired by *P. rugosa*, Coelastrea, Astrea; crater patterns, pockets, and protrusions)	Topography: Complex 3D patterns with pockets (few mm to ~1 cm) and protrusions (1 mm to 2.5 cm). Transport: Induces local micro-turbulence and dissipates direct wave energy, trapping fluids within protected pockets.	• Excellent for coral fragment attachment through micro-fragmentation and larval settlement. • High surface area; oyster-concrete versions significantly boost bioreceptivity.	• Complex manufacturing requires custom silicone molds or 3D printing. • Oyster concrete can develop micro-cracks if the mix design is not optimized.	[62]
Sustainable Low-Carbon Formulations (CEM III, CSA, Xiriton-E0 in 40 × 40 × 10 mm square tiles)	Topography: Intrinsic roughness from organic fibers (*Miscanthus*) and shell gravel (in E0) or porous mortar surfaces. Transport: Modifies the chemical boundary layer (reduced interfacial surface pH * to ~8.1–8.6) and facilitates bacterial biofilm adhesion.	• Significantly higher larval settlement with biofilm presence (up to 30% on CEM III and 26% on CSA). • Considerably lower carbon footprint compared to conventional cement.	• Requires seawater pre-conditioning (3–4 weeks) to develop inductive biofilms. • Geopolymers and sediment mixes may leach trace soluble compounds.	[16]
Structural Cylindrical & Block Specimens (20 mL molds or 150 × 150 × 150 mm cubic blocks for underwater setting & adhesives)	Topography: Smooth on curved or flat surfaces with central mechanical/adhesive coupling. Transport: Designed to evaluate stability against drag currents and outplanting hydrodynamics.	• High mechanical stability for testing underwater settings (Portland cement and Epoxy Putty). • Enables standardized tensile, pull-out, and corrosion resistance testing.	• Primary design focuses on physical attachment/mechanical bonding rather than active larval settlement trapping. • Higher weight and bulk for diver handling and transport.	[72,105]

* Reported pH values indicate the interfacial surface pH measured after respective curing periods, strictly representing the boundary-layer environment encountered by larvae, not the internal pore solution pH. As a systematic review synthesizing heterogeneous literature, specific measurement methodologies (e.g., flat-bulb electrodes, spectrophotometry) and exact sampling times (typically 3 to 8 weeks of immersion) vary across studies; readers are directed to the primary references provided in the corresponding 'Ref.' column for exact experimental conditions.

As shown by the intersection of biological cues (Section 5.2) and hydrodynamic topography, successful coral larval recruitment is not driven by a single environmental variable; rather, it is a complex, multi-modal chemosensory and biomechanical cascade. To effectively break the recruitment paradox of bare concrete, these isolated variables must be engineered as a coupled system. Table 3 provides a comprehensive synthesis of these multi-modal mechanisms, categorizing them from fundamental physical and inorganic cues to advanced biotechnological interventions.

This synthesis highlights a clear evolutionary trajectory in substrate design. While traditional approaches rely on passive physicochemical modifications, such as macro-roughness to exploit Q-criterion recirculation zones or alternative cement to reduce alkalinity, the frontier of reef remediation relies on active bio-instruction. By integrating the topographical refuges detailed in Table 2 with the biomimetic signal delivery systems detailed in Table 3 (e.g., SNAP-X hydrogels and living microbial materials), researchers

can explicitly control both the spatial and temporal availability of settlement cues. Ultimately, these mechanisms determine whether a larva attaches temporarily or permanently transitions into a calcifying benthic organism.

Table 3. Comparison of larval settlement mechanisms.

Mechanism Category	Specific Mechanism & Operating Principle	Effect on Settlement/Recruitment	Example/Innovation	Ref.
Chemical Biochemical	**Soluble CCA exometabolites:** Exuded organic acids, lipids, and amino acids acting as chemotactic cues in the water column.	Induce larval attachment and metamorphosis even in the physical absence of algae.	Exudates from *Hydrolithon reinboldii*.	[35,81]
	Bacterial biofilms & macromolecular inducers: Synthesis of lipopolysaccharides (LPS; O-antigen polysaccharide chain) and TBP by Gram-negative bacteria.	Significantly increases settlement compared to sterile substrates (e.g., from 4–10% to 26–30% with a 4-week biofilm).	Strains of *Cellulophaga lytica*, *Thalassotalea euphylliae*, and *Pseudoalteromonas*.	[16,68,82]
Chemical Inorganic	**Soluble inorganic ion leaching:** Diffusion of cations and inorganic salts from the substrate matrix into the fluid boundary layer.	Creates inorganic chemical gradients that attract larvae via active chemotaxis.	Soluble cations of Ca^{2+}, Mg^{2+}, Sr^{2+}, and $SrCO_3$.	[10,97]
Physical/Hydrodynamic	**Flow recirculation zones (Q-criterion):** Millimeter-scale ridges (2.5 mm) break the boundary layer in oscillatory flow, generating recirculation vortices where rotation exceeds strain.	Actively redirects larvae from the main current toward the substrate; 90–98% of settlement occurs beneath these zones.	Millimeter-scale ridge topography on lime mortar or concrete substrates.	[12]
Physical Topographic	**Microtopographic refuges (attachment point theory):** Millimeter/micrometer crevices, pores, and depressions that maximize physical contact points.	Protects attached larvae against fluid shear forces, wave abrasion, and sedimentation.	Micro-striations, grooves, and rough texture on tiles.	[99,106–108]
Physicochemical	**Low cement alkalinity & bioreceptivity:** Reduction in initial interfacial surface alkalinity (pH * 8.1–8.6 vs. pH > 8.7 in standard Portland cement CEM I).	Promotes rapid development of inductive bacterial biofilms and increases larval settlement up to 8-fold compared to CEM I.	Alternative cements: CEM III, CSA (calcium sulfoaluminate), and Xiriton E0 fiber mixes.	[16,23,74]
Optical/Spectral	**Spectral cues (substrate color):** Visual discrimination of surface reflectance and emitted wavelength.	Larvae show a strong settlement preference for red surfaces, which mimic the spectral signature of crustose coralline algae.	Surfaces are pigmented with red iron oxide or pink/red PETG filaments.	[62,109,110]

Table 3. *Cont.*

Mechanism Category	Specific Mechanism & Operating Principle	Effect on Settlement/Recruitment	Example/Innovation	Ref.
Biotechnological Biomimetic	**Biomimetic chemical microhabitats (SNAP-X):** Hydrogel nanoink (GelMA/PEGDA) encapsulates silica nanoparticles loaded with CCA exometabolites.	Slow, continuous cue release (>1 month), generating a chemical "halo" (>10 cm) that increases larval settlement up to 20-fold under flow conditions.	3D-printed light-crosslinkable SNAP-X nanoink applied to the substrate.	[35]
Biotechnological Living Material	**Microbial living materials (brink-bacterial reef ink):** Hydrogel emitter matrix (PEGDA-GelMA) immobilizes and cultivates live inductive bacteria.	Bacteria function as biofactories, continuously releasing LPS and increasing larval settlement by more than 5-fold compared to controls.	Brink bioink with *Cellulophaga lytica* or *Thalassotalea euphylliae*.	[62,68,83]

* Reported pH values indicate the interfacial surface pH measured after respective curing periods, strictly representing the boundary-layer environment encountered by larvae, not the internal pore solution pH. As a systematic review synthesizing heterogeneous literature, specific measurement methodologies (e.g., flat-bulb electrodes, spectrophotometry) and exact sampling times (typically 3 to 8 weeks of immersion) vary across studies; readers are directed to the primary references provided in the corresponding 'Ref.' column for exact experimental conditions.

5.4. From Settlement to Survival and Recruitment

Permanent settlement and metamorphosis are necessary but not sufficient stages for recruitment. After establishment, juvenile polyps face sedimentation stress, macroalgal overgrowth, competition for space, predation, and fluctuations in temperature and salinity. Microcracks and refugia may decrease some pressures, but their benefit depends on them not becoming clogged or covered by competing organisms. Post-settlement mortality can be high even when initial settlement is successful [11,78,80,101,111–113].

Gregarious settlement can favor interactions between recruits and, in certain species, the formation of chimeras, with possible consequences for survival or symbiont acquisition. However, aggregation can also increase intraspecific competition and limit growth when density exceeds the microhabitat's capacity. Therefore, recruit density and spatial distribution are relevant variables when evaluating designed surfaces [80,83,114,115].

Assessments of coatings should distinguish between settlement induction and subsequent habitat quality. A system may increase initial fixation but not necessarily improve survival if it maintains an unfavorable pH, releases toxic substances, delaminates, or favors sediment accumulation. Measure early survival and juvenile growth over sufficiently long periods and, where possible, under field conditions [87,116,117].

5.5. Selective Control of Biofouling and Bioreceptivity

Biofouling should not be treated as an exclusively harmful phenomenon. As was mentioned above, microbial colonization and the presence of CCAs can provide recognition signals. At the same time, overgrowth of macroalgae or other organisms can compete for space and resources, shade, or suffocate recruits. Consequently, a restorative coating should not aim to eliminate all colonization, but to regulate it selectively and conserve a surface community compatible with settlement [42,77]. Different surface coatings selectively recruit distinct micro- and macrofouling communities depending on substrate orientation and specific polymer chemistry [118]. Antifouling and fouling-release coatings offer different

approaches: the former limit organism adhesion or development, while the latter facilitate shedding, often relying on dynamic surface tension properties and amphiphilic behaviors that reduce protein adsorption [119]. Coral trials have reported that some coatings can reduce algal growth without inhibiting settlement, and that fouling control can improve recruit survival by reducing competition. However, the effect depends on the formulation and the organism being tested, so any strategy must simultaneously test for reduced fouling and the absence of adverse effects on corals and beneficial biofilms [46,117].

6. Classification of Settlement Interface Materials

As established in the previous sections, successful coral larval recruitment relies on a synergistic combination of physical topographies, biomineral properties, and specific biochemical cues. Because these mechanisms are now well understood, recent advances in materials science have sought to reproduce them on artificial reefs. Over the last decade, marine restoration has shifted from predominantly passive modifications of substrate composition (e.g., bulk alkalinity reduction) toward advanced, bioactive marine coatings and engineered living materials (ELMs). These modern interfaces are designed to be dynamic (capable of continuously presenting, releasing, or producing signals that induce settlement directly in the boundary layer).

To systematically categorize these technologies and address limitations in the literature, we propose a novel dual-axis classification framework. Existing classification approaches typically categorize marine substrates based on bulk material composition (e.g., concrete versus ceramics). Our proposed framework brings a significant improvement by shifting the focus to the micro-ecological scale, connecting materials design to the needs of coral larvae, recruits, and transplanted fragments. The first axis classifies materials based on the natural ecological component they mimic: (I) biochemical cue-mimetic interfaces, (II) biomineral and physicochemical interfaces, (III) physical microhabitat and hydrodynamic interfaces, and (IV) benthic competition and spatial regulation, grouping technologies by the restoration task they enable, such as limiting competitive fouling, securing fragments, or protecting established corals. Its organizing principle is functional rather than strictly biomimetic.

The second axis primarily classifies these engineered interfaces by their mode of interfacial activity (A0–A4, defined in Table 4), describing the coating's operational mechanics. In modern multifunctional materials, these categories are not inherently mutually exclusive; a single coating may present topographical features (A0) while simultaneously releasing ions (A1). To resolve these overlaps, clarify the classification criteria, and ensure highly reproducible placement of studies into this framework, we strictly applied the 'dominant mechanism' rule. Under this rule, if an engineered interface exhibits multiple mechanisms, it is assigned exclusively to the category corresponding to the primary experimental variable that the original authors explicitly isolated and evaluated as the main driver of coral settlement.

A supplementary catalog was compiled from the 85 source-matched original research publications included in this review that were rigorously assessed for eligibility using a custom 5-domain Quality Assessment Framework: substrate and interfacial relevance (Q1), physicochemical characterization (Q2), biological control and baseline validity (Q3), assay rigor and replication (Q4), and endpoint definition (Q5). Each domain was rated as satisfied (1), unclear or partially satisfied (0.5), or not satisfied (0). To qualify for methodological inclusion, a publication needed a score of at least 0.5 in every domain; a favorable total score could not make up for failing to meet any individual criterion. The five ratings were added for a maximum score of 5, with review-specific overall bands of High Risk (0–1.5), Unclear (2–3.5), and Low Risk (4–5).

Table 4. Proposal for the classification of coatings for coral settlement according to their mode of interfacial activity.

Code	Mode of Interfacial Activity *	Operational Definition
A0	Passive/static	Function derives from fixed composition, chemistry, texture, or geometry without engineered release or biological activity.
A1	Bioactive	The interface directly presents biologically active chemical, biological, or ionic cues but does not intentionally regulate their release over time.
A2	Smart/Controlled release	The interface is engineered to release settlement-active compounds with spatial or temporal control, or to change its properties or functionality in response to a stimulus, including self-healing behavior.
A3	Living/self-renewing	Living organisms incorporated into the interface continuously generate relevant biological signals.
A4	Electroactive	Interface uses or transmits electrical functionality to alter mineralization, growth, or the local interfacial environment.

* Due to activity modes not being mutually exclusive, where multiple modes apply, materials are classified according to the dominant engineered mechanism responsible for their functionality.

Within the established scope for I-IV restoration approaches, 39 publications met the five-domain inclusion criteria. They were included in the main extraction matrix: nine in category I, five in II, 13 in III, and 12 in IV. 35 received an overall Low Risk rating, and four received an Unclear rating. Of the remaining 46 publications, four were screened out for scope or eligibility reasons before a complete numerical score could be assigned. One publication met all five domains but was not counted as direct validation of coral material, so it was excluded. The remaining publications were retained separately as Analog Evidence (41 publications). The original restoration categories, interfacial activity codes, and biological endpoints were also recorded.

Ultimately, the practical utility of this standardized, biomimetic system is demonstrated in Table 5, where the systematic correlation of these defined classes with available experimental results allows us to identify the specific technological combinations that yield the highest settlement efficacy.

Table 5. Summary of the 12 highly refined experimental studies included in the quantitative extraction matrix, mapping the engineered surface coatings and specific substrate materials to their targeted ecological component (Classes I–IV) and mode of interfacial activity (A0–A4). All studies quantitatively evaluated coral larval settlement.

Coating	Classification	Base Substrate Material	Activity	Species/Settlement Mechanism	Key Findings with Quantitative Outcome
FRCs	IV. Benthic competition and spatial regulation	Concrete/specialized cement seeding devices	A0 (Passive/static)	*Acropora loripes*; post-settlement retention/reduced algal competition	Fouling-release coating lowered fouling to 25% and improved 46-week spat survival to 68%, compared with 59% on uncoated bare concrete seeding devices deployed in situ (naturally conditioned) [69].
Antifouling coatings (CeO_{2-x} nanoparticle coating, Antiadhesive coating, and DCOIT coating)	IV. Benthic competition and spatial regulation	Resin/mineral hardened analog substrates	A0 (Passive/static)	*Acropora tenuis*; settlement preservation under antifouling treatment	DCOIT reduced fouling most strongly, while larval settlement was not significantly reduced versus uncoated, unconditioned hardened resin/mineral analog controls [46].

Table 5. *Cont.*

Coating	Classification	Base Substrate Material	Activity	Species/Settlement Mechanism	Key Findings with Quantitative Outcome
Natural hydraulic lime (NHL) composite substrates (with $CaCO_3$, $SrCO_3$, $MgCO_3$ additives)	II. Biomineral and physicochemical interfaces	Natural hydraulic lime (NHL) composite substrates	A1 (Bioactive)	*Colpophyllia natans*, *Orbicella faveolata*, *Diploria labyrinthi-formis*/Mg^{2+} ion release and soluble mineral cue selection	Soluble Mg^{2+} promoted settlement and metamorphosis mean larval survival remained >97% across treatments, compared to unconditioned baseline NHL substrates (without added specific carbonates/Mg^{2+}) [10].
SNAP-X hydrogel (Silica NPs, biopolymers, CCA exometabolites)	I. Biochemical cue-mimetic interfaces	Standard concrete/OPC tiles.	A2 (Smart/Controlled release)	*Montipora capitata*/Sustained CCA exometabolite release	Increased settlement by up to 20-fold compared to uncoated, unconditioned standard concrete (OPC) controls in outdoor mesocosm trials [35].
LPS Nanocarriers (Liposomes and silica NPs in hydrogel)	I. Biochemical cue-mimetic interfaces	Concrete/Cementitious tiles	A2 (Smart/Controlled release)	*Montipora capitata*/Targeted bacterial LPS delivery	Both nanocarrier platforms increased settlement by >5-fold compared to uncoated, unconditioned bare cementitious tiles [73].
Bacterial Reef Ink (Brink) (Hydrogel with live *C. lytica* & *T. euphylliae*)	I. Biochemical cue-mimetic interfaces	Calcium Carbonate (CaCO3) coated tiles/Standard cement.	A3 (Living/self-renewing)	*Montipora capitata*, *Pocillopora acuta*/Continuous live bacterial cue secretion	Increased settlement >5-fold for *M. capitata* and >4-fold for *P. acuta* compared to uncoated, unconditioned bare standard cement controls [68].
ReefTiles (Stabilized non-living bacterial biomolecules)	I. Biochemical cue-mimetic interfaces	Standard Portland cement (OPC) or concrete discs	A1 (Bioactive)	*Acropora kenti*, *Hydroides elegans*/Stabilized microbial cues	Enhanced settlement rates and normal polyp formation; matched or exceeded settlement of living *P. gallaeciensis* biofilms compared to uncoated, unconditioned bare Portland cement discs [70].
Inorganic additives (SiO_2, $SrCO_3$)	II. Biomineral and physicochemical interfaces	Natural Hydraulic Lime (NHL) composites.	A1 (Bioactive)	Coral larvae/Soluble mineral cue selection	Inorganic composition and specific soluble mineral cues directly contributed to larval substrate selection, compared to unconditioned baseline mortar (without specific additives) [97].
Millimeter-scale benthic topography	III. Physical microhabitat and hydrodynamic interfaces	Lime mortar/Concrete substrates	A0 (Passive/static)	Slow-swimming coral larvae/Flow recirculation	Increased larval settlement by over 10-fold under wave-driven oscillatory flow, compared to flat, unconditioned mortar/concrete substrates [60].
3D-printed concrete with micro-grooves	III. Physical microhabitat and hydrodynamic interfaces	3D-printed concrete or marine mortar	A0 (Passive/static)	Coral recruits/Physical refugia	Micro-grooves effectively supported high recruitment, with recruits actively locating at the bottoms of grooves, compared to smooth, flat unconditioned marine concrete controls [74].

Table 5. *Cont.*

Coating	Classification	Base Substrate Material	Activity	Species/Settlement Mechanism	Key Findings with Quantitative Outcome
3D-printed alumina ceramic (800 µm pores + biological conditioning)	I. Biochemical cue-mimetic interfaces	3D-printed alumina ceramic-containing agar loaded with CCA extract or Hym-248, mounted on concrete	A1 (Bioactive)	*Acropora kenti*/Pores combined with biological cues	In the physical experiment, conditioning produced approximately 47–51% settlement, whereas unconditioned substrates remained below 1% [36].
Commercial Foul-Release Coating (FRC)	IV. Benthic competition and spatial regulation	Concrete/specialized cement seeding devices	A0 (Passive/static)	*Acropora millepora*/Macroalgal fouling reduction	Spat survival doubled (49% vs. 22%) and fouling decreased to 24% after 48 weeks, compared to uncoated seeding devices deployed in the field (naturally conditioned) [120].

This A0–A4 framework is proposed not only to categorize the existing evidence base but also to map future technological trajectories. As demonstrated in the quantitative synthesis (Table 5), the current robust evidence for coral larval settlement (n = 12 strictly filtered studies) is heavily concentrated in passive (A0), bioactive (A1), and smart/controlled-release (A2) modes. In contrast, advanced modes such as living/self-renewing (A3) and electroactive (A4) interfaces are nascent in coral restoration; they are included in this framework as a prospective roadmap derived from other marine materials sectors (e.g., anti-corrosion coatings), requiring substantial future validation with coral larvae before they can be considered broadly established.

Nevertheless, by mapping the robust, currently validated literature against this structured framework, we can clearly trace the field's progression from inert structures to highly functionalized biological interfaces. To systematically evaluate how these theoretical frameworks translate into applied materials science, Table 5 summarizes the studies retrieved through our systematic literature search. This matrix catalogs the identified state-of-the-art coating technologies and substrate modifications, assigning them an identification based on our dual classification framework: the ecological component they mimic (Classes I–IV) and their specific mode of interfacial activity (A0–A4). As observed by contrasting the material formulations with their target coral species and quantitative settlement outcomes, several critical technological trends emerge from the literature:

1. The shift from passive to active interfaces: there is a clear evolutionary progression from passive/static mimicry (A0), such as 3D-printed micro-grooves and unconditioned ceramics, toward active biochemical cue-mimetic interfaces (A1 and A2). While static topographies successfully provide hydrodynamic refuges, their settlement efficacy is exponentially amplified when combined with active biological conditioning.
2. Controlled release technology (A2): advanced biopolymeric matrices are successfully addressing the temporal instability of natural cues. Materials using controlled release mechanisms, such as SNAP-X hydrogels loaded with CCA exometabolites or nanocarriers (liposomes and silica nanoparticles) delivering specific bacterial LPS, can sustain settlement signals over time. These engineered delivery systems consistently increase recruitment by 5- to 20-fold compared to uncoated concrete controls.
3. The emergence of engineered living materials (A3): Table 5 highlights the cutting edge of reef biotechnology, employing microbial/biofilm-mimetic interfaces. The development of fully living, self-renewing interfaces (e.g., Bacterial Reef Ink) illustrates a paradigm shift where the hydrogel matrix acts as a continuous "biofactory",

protecting live bacterial strains that actively secrete settlement morphogens directly at the boundary layer.

4. Multifunctional technologies of benthic competition and spatial regulation (Class IV): finally, the synthesis demonstrates that inducing initial settlement is only half the challenge. Technologies within this class, ranging from commercial foul-release coatings (FRCs) to targeted antifouling surfaces (e.g., DCOIT), show that modern engineered interfaces must be designed holistically to combat competitive macroalgae, mitigate fouling overgrowth, and actively preserve available bare space to support long-term juvenile survival.

Beyond these overarching trends, a systematic comparison of the quantitative outcomes in Table 5 reveals critical insights into how experimental conditions and material characteristics dictate coating performance. A prominent, unified trend across the evidence base is that active biochemical and microbial interfaces (Classes I and II) consistently yield the highest absolute settlement fold-changes (often exceeding 5- to 20-fold increases) under static or low-flow laboratory conditions. However, apparent contradictions emerge when evaluating physical topography across different experimental hydrodynamic regimes. For instance, while high micro-porosity (e.g., 800 µm ceramic pores) or millimeter-scale grooves are highly effective at trapping larvae in controlled oscillatory flumes, similar topographies deployed in long-term natural field environments often experience rapid sediment infilling and macroalgal overgrowth, effectively neutralizing their biological advantage if not paired with active fouling-release (FRC) or antifouling mechanisms. Furthermore, the analysis highlights a strict dependence on assay design: studies utilizing static choice/no-choice assays frequently report robust settlement driven purely by chemical gradients, whereas studies evaluating substrates under high fluid shear stress demonstrate that even the most potent biological cues fail to induce settlement if the substrate lacks the necessary macro-topography to disrupt the boundary layer. This comparative analysis shows that discrepancies in reported coating performance rarely stem from failure of the biochemical morphogen itself but are instead driven by varying degrees of hydrodynamic stress and benthic competition in the experimental setup.

However, direct inter-study comparisons of these relative effect sizes must be interpreted with strict caution. The magnitude of a reported fold-change is highly sensitive to the baseline settlement rate of the specific control substrate, the distinct ontogenetic competency windows of different coral species (e.g., brooding versus broadcast-spawning taxa), and the fundamental differences between closed static assays and open-flow mesocosms. Consequently, while these standardized metrics reliably indicate a positive bio-interfacial effect within a given study, they cannot be used to linearly rank the absolute efficacy of disparate coating technologies across different ecological contexts.

Ultimately, this systematic analysis underscores a definitive relationship between material formulation, interface properties, and the resulting biological response. Within the current literature, experimentally demonstrated correlations (Table 5) confirm that specific formulations, such as composite PEGDA/GelMA hydrogels, successfully create a biocompatible, highly hydrated interface capable of the sustained release of CCA exometabolites or bacterial LPS, which directly correlates with significantly enhanced rates of irreversible metamorphosis. Conversely, it is critical to strictly delimit these proven correlations from mechanisms that remain only theoretically proposed. For instance, while bioadhesive coatings, smart/stimuli-responsive coatings, and electroactive interfaces offer compelling theoretical frameworks for mitigating biofouling or accelerating biomineralization based on other marine engineering sectors, their direct effect on coral larval settlement lacks quantitative experimental validation. Consequently, these advanced mechanisms are delimited

in this review strictly as prospective hypotheses for future research, rather than currently established restorative tools.

7. Critical Analysis: Long-Term and Economic Viability of Interface Technologies

While advances in bioactive coatings have largely resolved the challenge of initial larval settlement in controlled environments, translating these technologies to a dynamic oceanic scale creates critical bottlenecks that the scientific community must address. The efficacy of engineered coatings must not be measured exclusively by initial attachment rates; early post-settlement survival remains the true critical hurdle in coral recruitment. Following metamorphosis, juvenile polyps face immense environmental pressures, including benthic spatial competition, sediment smothering, and aggressive biofouling.

Furthermore, when interpreting these advancements, the limitations of the systematic review process itself must be acknowledged. The restriction to peer-reviewed English literature and the exclusion of gray literature (such as governmental or NGO field reports on artificial reefs) may introduce a publication bias. This potentially overrepresents highly successful, high-tech academic interventions while underreporting the long-term field performance of more conventional treatments.

As detailed in Table 5, biomimetic systems like SNAP-X hydrogels sustain exometabolite release for over a month, enhancing settlement up to 20-fold compared to uncoated controls. However, researchers rarely report the physical durability of these hydrogels under the continuous hydrodynamic shear stress and abrasion of marine currents over months. If the matrix degrades before the juvenile coral establishes a robust basal aragonite skeleton, recruitment fails.

Long-term viability appears more promising in materials designed to manage benthic space actively. For example, SLIPS such as reef-PDMS effectively mitigate overgrowth by competing with turf algae. Furthermore, extensive field trials (up to 48 weeks of deployment) have demonstrated that commercial FRCs reduce biofouling to 24% and double the long-term survival of *Acropora millepora* spat.

However, scaling these interventions to restore hectares of degraded reef networks requires a rigorous balance between biochemical sophistication and manufacturing costs [121,122]. For example, ELMs such as Brink and liposome-based nanocarriers for bacterial LPS achieve large increases in settlement (>5-fold). Nevertheless, nanoparticle synthesis, encapsulation of delicate exometabolites, and maintenance of viable bacterial strains require specialized laboratory infrastructure. These high production and logistical costs currently limit their mass application, particularly in developing regions where reef degradation is often most severe.

Conversely, inorganic substrate modifications present a highly economically viable route. For example, composite substrates utilizing natural hydraulic lime doped with soluble inorganic salts actively attract larvae and promote metamorphosis at a fraction of the cost of biopolymeric inks. Similarly, stabilized, non-living biomolecule presentations (e.g., ReefTiles) offer a scalable and shelf-stable alternative to cultivating live biofilms.

8. Future Perspectives and Research Opportunities

The future of coral reef remediation relies on integrating adjacent technologies and adapting materials to regional ecological and economic realities. Future research must pivot away from evaluating coatings on flat, inert substrates. Evidence indicates that micro-structural complexity provides essential hydrodynamic refugia from shear stress. Studies utilizing 3D-printed alumina ceramics demonstrate that while 800 µm pores alone do not induce massive settlement, combining this topography with biological conditioning

results in 100% of spat choosing the bioactive area, with a significant portion nesting safely inside the pores [36]. The frontier of this field lies in mathematically optimizing 3D-printed cementitious topographies and selectively coating only the protected micro-crevices with inductive bioinks.

A critical barrier to the large-scale implementation of bioactive polymeric coatings is their economic viability and their hidden environmental costs. To date, many of the advanced engineered interfaces (such as synthetic hydrogels, epoxies, and fossil-fuel-derived polyurethanes) rely on petrochemical precursors, volatile organic solvents, and potentially toxic crosslinking agents. From a holistic life-cycle perspective, the mass production of these synthetic coatings for hectare-scale reef restoration presents a fundamental ecological paradox: employing high-carbon-footprint manufacturing processes to restore climate-sensitive ecosystems is inherently contradictory. Furthermore, these synthetic matrices can degrade in the ocean, leaching unreacted monomers or generating secondary microplastics. Therefore, to scale these technologies responsibly, researchers must adopt green chemistry principles and rigorously evaluate the coating's environmental impact across its entire life cycle. This need presents a unique opportunity to integrate circular economy models that embed material production systems in cycles that reduce environmental impact, from using renewable resources to reducing toxic by-products. Recent innovations show the potential of using waste biomass, such as agricultural byproducts, raw coral waste and metakaolin, to produce highly durable, 3D-printable artificial reef structures with a significantly lower carbon footprint [123,124].

For instance, green chemistry principles offer immense theoretical potential, particularly through Natural Deep Eutectic Solvents (NADES) to replace toxic conventional solvents. In other materials science domains, substituting conventional solvents with NADES has enabled the green extraction/synthesis of biopolymers with a minimal ecotoxicological footprint. Applying this framework to marine restoration would not only drastically reduce the environmental impact of polymer extraction/synthesis, but NADES could also function as active stabilizing agents within the final material structure.

Building on this green synthesis framework, we propose developing bioadhesive eutectogels (polymeric networks swollen with deep eutectic solvents) as a highly promising future direction. To our knowledge, the current literature has not explored the direct application of NADES-based eutectogels or biorefinery-derived marine biopolymers for coral larval settlement. However, drawing parallels from their success in biomedical drug delivery and tissue engineering, their physicochemical properties offer a compelling theoretical framework for marine restoration. Unlike traditional aqueous hydrogels that may rapidly swell and disintegrate in seawater, polysaccharide-based eutectogels offer robust, tunable matrices that could enable localized wet adhesion and the controlled, sustained release of active marine morphogens (e.g., CCA exometabolites or bacterial LPS).

However, a persistent challenge for polymeric coatings on marine concrete is maintaining strong adhesion in hypersaline, saturated environments. Future material designs should leverage bioinspired wet-adhesion mechanisms, for example, by using catechol chemistry inspired by marine mussels [71,93,125]. Functionalizing polymeric coatings with catechol groups can dramatically enhance the interfacial shear strength between the highly alkaline concrete base and the soft bioactive hydrogel, ensuring the settlement matrix remains anchored during high-energy wave events.

Furthermore, the evolution of responsive marine materials opens unexplored avenues for restoration. Recently developed conductive bio-pastes (formulated from biodegradable soybean oil and graphene nanoplatelets) enable localized MAT application without continuous power supplies, accelerating coral fragment growth. As these electroactive and smart/self-healing materials transition from industrial anti-corrosion applications to

biological interfaces, they hold immense potential not only to induce larval settlement but also to actively stimulate early biomineralization. Looking forward, embracing the philosophy of "extreme biomimetics" could guide the development of next-generation, highly resilient biopolymeric composites capable of withstanding the increasingly harsh, extreme conditions predicted for future oceans [126,127].

9. Conclusions

The transition from passive concrete structures to bioactive engineered interfaces marks a pivotal turning point in artificial reef restoration. As established, deploying bare concrete precipitates a "recruitment paradox": its intrinsic alkalinity and rapid colonization by competitive turf algae actively inhibit coral settlement. To address this, materials science has advanced rapidly, yet it is essential to formulate expectations strictly in accordance with the strength of available evidence. The individual methodological quality assessment revealed that while biological induction assays are rigorously validated at laboratory scales, overall experimental evidence remains methodologically constrained by a lack of prolonged in situ mechanical testing.

Consequently, this systematic synthesis distinguishes three distinct tiers of technological readiness. First, physicochemical alkalinity reduction (e.g., alternative cements), macro-topographical refuges, and passive foul-release coatings (FRCs) represent confirmed experimental results. These technologies are robustly validated and consistently demonstrate improved coral settlement and long-term spat survival across prolonged field deployments. Second, advanced controlled-release nanocarriers and Engineered Living Materials (ELMs) stand as promising but insufficiently validated technologies. Although they successfully deliver biochemical cues that exponentially increase initial metamorphosis, they are currently limited to laboratory or mesocosm validations; their long-term hydrodynamic durability, matrix degradation kinetics, and sustained adhesion in open-ocean conditions remain critically under-evaluated. Finally, advanced technologies such as bioadhesive eutectogels (NADES), smart/stimuli-responsive coatings, and electroactive interfaces must be classified as conceptual-level research. While they offer compelling theoretical mechanisms derived from industrial marine sectors, they currently lack quantitative experimental validation with coral larvae.

Crucially, our study-by-study Quality Assessment Framework (detailed in Supplementary Table S1) reveals that while current interventions score highly in biological assay rigor, overall experimental evidence is frequently constrained by limitations in long-term physicochemical characterization and in situ substrate relevance.

To translate these interfacial technologies into practical, large-scale implementation, we propose a structured experimental roadmap that prioritizes specific future investigations. First, researchers must standardize hydrodynamic and degradation testing by moving biological assays from static setups to high-shear dynamic flumes to rigorously evaluate the physical retention of polymeric matrices before deployment. Next, research should require extended in situ ecological viability studies (12–24 months) that assess post-settlement recruit survival rather than only initial attachment, focusing on the coating's ability to resist benthic macroalgal competition. Furthermore, before mass manufacturing, a scalable green integration phase is required, with rigorous life-cycle assessments to ensure these interfaces have a low carbon footprint and avoid generating secondary microplastics. Ultimately, the most viable future strategies will require a multimodal, interdisciplinary approach that integrates scalable physicochemical modifications with mathematically optimized 3D microtopographies to provide cost-effective solutions for global coral reef remediation.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/jmse14212049/s1, Supplementary Data S1: PRISMA 2020 Checklist; Supplementary Table S1: Quality Assessment Framework.

Author Contributions: A.E.-M., M.E.T.-C. and M.A.G.-R.: investigation, methodology, data curation, formal analysis, visualization, writing—original draft, and writing—review & editing. R.S.: project administration, resources, supervision, validation, and funding acquisition. M.E.: conceptualization, writing—review & editing, project administration, resources, supervision, validation, and funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: Alberto Elizalde-Mata and M.E. Trejo-Caballero acknowledge CEMIE-Oceano A. C. for the support received. Marlen A. González-Reyna thanks SECIHTI for her postdoctoral research fellowship. Additionally, the authors gratefully acknowledge the Dirección General de Asuntos del Personal Académico (DGAPA-UNAM) through project PAPIIT project IG100824 "Acciones de restauración y desarrollo tecnológico enfocadas en la recuperación de la resiliencia de los ecosistemas costeros", within whose academic framework this systematic review was developed. Finally, the authors thank Guillermo Vázquez for his technical support. During the preparation of this manuscript, the authors used Gemini Notebook Pro (Google) and LeapSpace (Elsevier, elsevier.com, accessed between September and October 2026) as AI-assisted tools to support the organization, exploration, and synthesis of information from scientific literature. Imagen 3 model via Gemini Pro (Google) was used to generate a graphical element for the conceptual illustration in the manuscript; this element was subsequently edited and incorporated into the final figure by the authors using Microsoft PowerPoint. All scientific information, references, interpretations, and final figures were reviewed and validated by the authors, who take full responsibility for the accuracy and scientific integrity of the manuscript.

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

Abbreviations

The following abbreviations are used in this manuscript:

WoS	Web of Science
C-S-H	Calcium Silicate Hydrate
CSA	Calcium Sulfoaluminate
CNC	Computer Numerical Control
CEM III	Blast Furnace Cement (Low-carbon cement formulation)
CEM I	Standard Portland Cement
CCA	Crustose Coralline Algae
TBP	Tetrabromopyrrole
C2S	Dicalcium Silicate
C3S	Tricalcium Silicate
Brink	Bacterial Reef Ink
ACA	Articulated Coralline Algae
SNAP-X	Commercial biomimetic chemical microhabitat (Not strictly an acronym, but treated as a proper noun/abbreviation in text)
SLIPS	Slippery Liquid-Infused Porous Surfaces
SCTLD	Stony Coral Tissue Loss Disease
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PICO	Population, Intervention, Comparison, Outcome

PETG	Polyethylene Terephthalate Glycol
PEGDA	Poly(ethylene glycol) Diacrylate
PDMS	Polydimethylsiloxane
OPC	Ordinary Portland Cement
NPs	Nanoparticles
NADES	Natural Deep Eutectic Solvents
MAT	Mineral Accretion Technology
LPS	Lipopolysaccharides
L-DOPA	L-3,4-dihydroxyphenylalanine (Catechol chemistry)
LCA	Life Cycle Assessment
LBL	Layer-By-Layer
GPCRs	G-Protein-Coupled Receptors
GelMA	Gelatin Methacryloyl
FRCs	Fouling-Release Coatings/Foul-Release Coatings
ELMs	Engineered Living Materials
DCOIT	4,5-Dichloro-2-octyl-3-isothiazolone (Antifouling agent)

References

1. Corigliano, G.; Isa, V.; Annese, V.F.; Rinaldi, C.; Summa, M.; Bertorelli, R.; Galli, P.; Lavorano, S.; Caironi, M.; Contardi, M.; et al. Active Biopaste for Coral Reef Restoration. *Adv. Mater.* **2025**, *37*, 2502078. [CrossRef] [PubMed]
2. Ozanam, B.; Romans, P.; Lami, R. Choosing the Right Substrate to Restore Coral Reefs through Artificial Reef Construction: A Mini-Review. *Blue Biotechnol.* **2025**, *2*, 24. [CrossRef]
3. Liu, J.; Ou, Z.; Peng, W.; Guo, T.; Deng, W.; Chen, Y. Literature Review of Coral Concrete. *Arab. J. Sci. Eng.* **2018**, *43*, 1529–1541. [CrossRef]
4. Sawall, Y.; Jompa, J.; Litaay, M.; Maddusila, A.; Richter, C. Coral Recruitment and Potential Recovery of Eutrophied and Blast Fishing Impacted Reefs in Spermonde Archipelago, Indonesia. *Mar. Pollut. Bull.* **2013**, *74*, 374–382. [CrossRef] [PubMed]
5. Smith, J.E.; Brainard, R.; Carter, A.; Grillo, S.; Edwards, C.; Harris, J.; Lewis, L.; Obura, D.; Rohwer, F.; Sala, E.; et al. Re-Evaluating the Health of Coral Reef Communities: Baselines and Evidence for Human Impacts across the Central Pacific. *Proc. R. Soc. B Biol. Sci.* **2016**, *283*, 20151985. [CrossRef] [PubMed]
6. Huang, W.; Chen, J.; Yang, E.; Meng, L.; Feng, Y.; Chen, Y.; Huang, Z.; Tan, R.; Xiao, Z.; Zhou, Y.; et al. Heat-Tolerant Sub-tropical Porites Lutea May Be Better Adapted to Future Climate Change than Tropical One in the South China Sea. *Sci. Total Environ.* **2025**, *962*, 178381. [CrossRef] [PubMed]
7. Tortolero-Langarica, J.J.A.; Rodríguez-Troncoso, A.P.; Nava, H. Advances in Coral Reef Restoration in the Mexican Pacific: Active Interventions and Scaling Approaches. *Restor. Ecol.* **2025**, *33*, e70176. [CrossRef]
8. Velázquez-Ochoa, R.; Enríquez, S. Environmental Degradation of the Mexican Caribbean Reef Lagoons. *Mar. Pollut. Bull.* **2023**, *191*, 114947. [CrossRef] [PubMed]
9. Baums, I.B.; Baker, A.C.; Davies, S.W.; Grottoli, A.G.; Kenkel, C.D.; Kitchen, S.A.; Kuffner, I.B.; LaJeunesse, T.C.; Matz, M.V.; Miller, M.W.; et al. Considerations for Maximizing the Adaptive Potential of Restored Coral Populations in the Western Atlantic. *Ecol. Appl.* **2019**, *29*, e01978. [CrossRef] [PubMed]
10. Yus, J.; Nixon, E.N.; Li, J.; Noriega Gimenez, J.; Bennett, M.J.; Flores, D.; Marhaver, K.L.; Wegley Kelly, L.; Espinosa-Marzal, R.M.; Wagoner Johnson, A.J. Composite Substrates for Coral Larval Settlement and Reef Restoration Based on Natural Hydraulic Lime and Inorganic Strontium and Magnesium Compounds. *Ecol. Eng.* **2024**, *202*, 107236. [CrossRef]
11. Cooper, W.T.; Lirman, D.; Vangroningen, M.P.; Parkinson, J.E.; Herlan, J.; McManus, J.W. Assessing Techniques to Enhance Early Post-Settlement Survival of Corals in Situ for Reef Restoration. *Bull. Mar. Sci.* **2014**, *90*, 651–664. [CrossRef]
12. Gysbers, D.; Levenstein, M.A.; Juarez, G. Effect of Substrate Topography on Benthic Boundary Layer Flow: Implications for Marine Larval Transport and Settlement. *Phys. Rev. Fluids* **2025**, *10*, 064501. [CrossRef]
13. Tran, C.; Hadfield, M.G. Localization of Sensory Mechanisms Utilized by Coral Planulae to Detect Settlement Cues. *Invertebr. Biol.* **2013**, *132*, 195–206. [CrossRef]
14. Kong, J.; Cong, G.; Ni, S.; Sun, J.; Guo, C.; Chen, M.; Quan, H. Recycling of Waste Oyster Shell and Recycled Aggregate in the Porous Ecological Concrete Used for Artificial Reefs. *Constr. Build. Mater.* **2022**, *323*, 126447. [CrossRef]
15. Knoester, E.G.; Vos, A.; Saru, C.; Murk, A.J.; Osinga, R. Concrete Evidence: Outplanted Corals for Reef Restoration Do Not Need Extended Curing of Ordinary Portland Cement. *R. Soc. Open Sci.* **2024**, *11*, 241064. [CrossRef] [PubMed]

16. Rippen, J.C.; Wijers, T.; Van Bruggen, C.G.E.; Antoun, M.; Eriksson, B.K.; Hylkema, A. Material Matters: Artificial Substrate Composition and Biofilm Presence Influence Larval Settlement of Diadema Antillarum. *Front. Mar. Sci.* **2025**, *12*, 1596378. [CrossRef]
17. Han, X.; Wu, J.; Zhang, X.; Shi, J.; Wei, J.; Yang, Y.; Wu, B.; Feng, Y. Special Issue on Advanced Corrosion-Resistance Materials and Emerging Applications. The Progress on Antifouling Organic Coating: From Biocide to Biomimetic Surface. *J. Mater. Sci. Technol.* **2021**, *61*, 46–62. [CrossRef]
18. Li, L.; Hong, H.; Cao, J.; Yang, Y. Progress in Marine Antifouling Coatings: Current Status and Prospects. *Coatings* **2023**, *13*, 1893. [CrossRef]
19. Magin, C.M.; Cooper, S.P.; Brennan, A.B. Non-Toxic Antifouling Strategies. *Mater. Today* **2010**, *13*, 36–44. [CrossRef]
20. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 Statement: An Updated Guideline for Reporting Systematic Reviews. *BMJ* **2021**, *372*, n71. [CrossRef] [PubMed]
21. El-Khoury, M.; Roziere, E.; Grondin, F.; Cortas, R.; Chehade, F.H. Experimental Evaluation of the Effect of Cement Type and Seawater Salinity on Concrete Offshore Structures. *Constr. Build. Mater.* **2022**, *322*, 126471. [CrossRef]
22. Boudache, S.; Loukili, A.; Izoret, L.; Rozière, E. Investigating the Role Played by Portlandite and C-A-S-H in the Degradation Response of Pozzolanic and Slag Cements to External Sulphate Attack. *J. Build. Eng.* **2023**, *67*, 106053. [CrossRef]
23. Ruszczyk, M.; Rodriguez, S.; Tuen, M.; Rux, K.; Paul, V.; Chandragiri, S.; Stickley, M.; Swart, P.K.; Haus, B.K.; Baker, A.C.; et al. Alkalinity-Enhanced Artificial Substrates Modulate Local PH and Increase Survivorship of Early-Stage Coral Recruits. *Commun. Earth Environ.* **2026**, *7*, 311. [CrossRef]
24. Kiel, P.M.; McConnell, M.; Boyd, A.; Soderberg, N.; Suraneni, P.; Prakash, V.N.; Enochs, I.C. Electrochemically Induced Al-kalinity Enhancement Increases Coral Growth Rates in the Local Microenvironment. *Coral Reefs* **2026**, *45*, 737–752. [CrossRef]
25. Maboloc, E.A.; Szeto, J.H.Y.; Yuen, K.C.H.; Wong, S.C.C.; Astudillo, J.C.; Cai, L.; Hao, L.; Zhang, S.; Chui, A.P.Y.; Fang, J.K.H. Seawater-Conditioned Cement as a Viable Substrate for Coral Larval Settlement. *Reg. Stud. Mar. Sci.* **2025**, *88*, 104254. [CrossRef]
26. Stark, J.S.; Langdon, C. Coral Reef PH Altered in Situ. *Nat. Ecol. Evol.* **2019**, *3*, 1380–1381. [CrossRef] [PubMed]
27. Sha, S.; Wang, M.; Shi, C.; Xiao, Y. Influence of the Structures of Polycarboxylate Superplasticizer on Its Performance in Ce-ment-Based Materials-A Review. *Constr. Build. Mater.* **2020**, *233*, 117257. [CrossRef]
28. Schaffelke, B.; Carleton, J.; Skuza, M.; Zagorskis, I.; Furnas, M.J. Water Quality in the Inshore Great Barrier Reef Lagoon: Implications for Long-Term Monitoring and Management. *Mar. Pollut. Bull.* **2012**, *65*, 249–260. [CrossRef] [PubMed]
29. Nalley, E.M.; Tuttle, L.J.; Barkman, A.L.; Conklin, E.E.; Wulstein, D.M.; Richmond, R.H.; Donahue, M.J. Water Quality Thresholds for Coastal Contaminant Impacts on Corals: A Systematic Review and Meta-Analysis. *Sci. Total Environ.* **2021**, *794*, 148632. [CrossRef] [PubMed]
30. Hayek, M.; Salgues, M.; Habouzit, F.; Bayle, S.; Souche, J.C.; De Weerdt, K.; Pioch, S. In Vitro and in Situ Tests to Evaluate the Bacterial Colonization of Cementitious Materials in the Marine Environment. *Cem. Concr. Compos.* **2020**, *113*, 103748. [CrossRef]
31. Abdul Wahab, M.A.; Ferguson, S.; Whitehead, B.; Fong, J.; Haikola, P.; Severati, A.; Antunes, E. The Role of Substrate Mate-rials for the Survival and Growth of Coral Micro-Fragment Sheets. *Restor. Ecol.* **2026**, *34*, e70335. [CrossRef]
32. Rodriguez-Ruano, V.; Duran, A.; Bright, A.J.; Grazioso, K.; Ippolito, S.; Murphy, C.; Williams, D.E.; Velazquez, J.; Barriera, W.; Guzman, S.; et al. Sediment Burial Reduces Coral Larval Settlement, Recruit Survivorship, and Inhibits the Recovery of Coral Populations. *Commun. Biol.* **2026**, *9*, 1284. [CrossRef] [PubMed]
33. Karimi, Z.; Flores, I.; Kolle, S.; Kundu, S.; Walton, E.; Badder, L.; Levy, N.; Berry, D.B.; Schar, D.; Levy, J.; et al. Mitigating Algal Competition with Fouling-Prevention Coatings for Coral Restoration and Reef Engineering. *ACS Sustain. Chem. Eng.* **2025**, *13*, 5808–5817. [CrossRef] [PubMed]
34. Speare, K.E.; Duran, A.; Miller, M.W.; Burkepile, D.E. Sediment Associated with Algal Turfs Inhibits the Settlement of Two Endangered Coral Species. *Mar. Pollut. Bull.* **2019**, *144*, 189–195. [CrossRef] [PubMed]
35. Kundu, S.; Potenti, S.; Quinlan, Z.A.; Willard, H.; Chen, J.; Noritake, T.; Levy, N.; Karimi, Z.; Jorissen, H.; Hancock, J.R.; et al. Biomimetic Chemical Microhabitats Enhance Coral Settlement. *Trends Biotechnol.* **2025**, *43*, 2232–2250. [CrossRef] [PubMed]
36. Briggs, N.D.; Negri, A.P.; Antunes, E.; Drane, M.; Severati, A.; Flores, F. Directing Coral Larval Settlement in Coral Aquaculture for Reef Restoration. *Sci. Rep.* **2026**, *16*, 7358. [CrossRef] [PubMed]
37. Tebben, J.; Tapiolas, D.M.; Motti, C.A.; Abrego, D.; Negri, A.P.; Blackall, L.L.; Steinberg, P.D.; Harder, T. Induction of Lar-val Metamorphosis of the Coral Acropora Millepora by Tetrabromopyrrole Isolated from a Pseudoalteromonas Bacterium. *PLoS ONE* **2011**, *6*, e19082. [CrossRef] [PubMed]
38. Siboni, N.; Abrego, D.; Puill-Stephan, E.; King, W.L.; Bourne, D.G.; Raina, J.B.; Seymour, J.R.; Harder, T. Crustose Coralline Algae That Promote Coral Larval Settlement Harbor Distinct Surface Bacterial Communities. *Coral Reefs* **2020**, *39*, 1703–1713. [CrossRef]
39. Whitman, T.N.; Negri, A.P.; Bourne, D.G.; Randall, C.J. Settlement of Larvae from Four Families of Corals in Response to a Crustose Coralline Alga and Its Biochemical Morphogens. *Sci. Rep.* **2020**, *10*, 16397. [CrossRef] [PubMed]

40. Foster, T.; Gilmour, J.P. Seeing Red: Coral Larvae Are Attracted to Healthy-Looking Reefs. *Mar. Ecol. Prog. Ser.* **2016**, *559*, 65–71. [CrossRef]
41. Chen, Z.; Chea, T.; Luo, J.; Wei, J.; Zhao, G. Application of Coir Fibers in Eco-Friendly Biomass Coral Concrete: Mechanical Properties, Chloride Attack and Deterioration Mechanism. *J. Build. Eng.* **2025**, *111*, 113536. [CrossRef]
42. Fong, J.; Ramsby, B.D.; Flores, F.; Dada, T.; Antunes, E.; Abdul Wahab, M.A.; Severati, A.; Negri, A.P.; Diaz-Pulido, G. Effects of Material Type and Surface Roughness of Settlement Tiles on Macroalgal Colonisation and Early Coral Recruitment Success. *Coral Reefs* **2024**, *43*, 1083–1096. [CrossRef]
43. Wang, X.; Liu, B.; Chu, Y.; Ran, Q.; Wu, Y.; Qian, C.; Hong, J.; Yang, Y.; He, Y. Selective Defect Regulation and Structural Connectivity Optimization in Ultra-High-Performance Geopolymer Coral Concrete: Strength, Durability, and Low-Carbon Benefits. *Constr. Build. Mater.* **2026**, *533*, 146771. [CrossRef]
44. Srisuwan, W.; Sabhasri, C.; Chansue, N.; Haetrakul, T. Using Biomimicry and Bibliometric Mapping to Guide Design and Production of Artificial Coral Reefs. *Mar. Environ. Res.* **2022**, *180*, 105685. [CrossRef] [PubMed]
45. Zhang, S.; Zhang, Y.; Chen, D. Enhancing Coral Aggregate Concrete Performance via Mild Acid-Washing and Fast-Setting Pre-Coating Techniques. *Case Stud. Constr. Mater.* **2025**, *22*, e04840. [CrossRef]
46. Roepke, L.K.; Brefeld, D.; Soltmann, U.; Randall, C.J.; Negri, A.P.; Kunzmann, A. Antifouling Coatings Can Reduce Algal Growth While Preserving Coral Settlement. *Sci. Rep.* **2022**, *12*, 15935. [CrossRef] [PubMed]
47. Tam, L.H.; Moundi, A.; Jing, G.; Ma, J.; Fu, B.; Ke, L.; Hao, H.; Yu, Z.; Wu, C. Molecular Investigation on Interfacial Toughe-ning between Silane Coupling Agent Treated Glass Fiber and Cement. *J. Build. Eng.* **2024**, *95*, 110218. [CrossRef]
48. Petrone, L. Molecular Surface Chemistry in Marine Bioadhesion. *Adv. Colloid Interface Sci.* **2013**, *195–196*, 1–18. [CrossRef] [PubMed]
49. Chen, W.; Wu, Z.; Xie, Y.; He, X.; Su, Y.; Qin, Y.; Tang, D.; Oh, S.K. Fabrication of Silane and Nano-Silica Composite Modified Bio-Based WPU and Its Interfacial Bonding Mechanism with Cementitious Materials. *Constr. Build. Mater.* **2023**, *371*, 130819. [CrossRef]
50. Matinlinna, J.P.; Lung, C.Y.K.; Tsoi, J.K.H. Silane Adhesion Mechanism in Dental Applications and Surface Treatments: A Review. *Dent. Mater.* **2018**, *34*, 13–28. [CrossRef] [PubMed]
51. Francisco, D.L.; Sacilotto, D.G.; Ramirez, O.M.P.; Cardoso, J.L.; de Melo, H.G.; Panossian, Z. Smart Coatings for Corrosion Protection: Advances, Trends and Challenges in Relevant Environments for Long-Term Durability. *Prog. Org. Coat.* **2026**, *218*, 110200. [CrossRef]
52. Sabet-Bokati, K.; Plucknett, K. Water-Induced Failure in Polymer Coatings: Mechanisms, Impacts and Mitigation Strategies—A Comprehensive Review. *Polym. Degrad. Stab.* **2024**, *230*, 111058. [CrossRef]
53. Rego, S.J.; Vale, A.C.; Luz, G.M.; Mano, J.F.; Alves, N.M. Adhesive Bioactive Coatings Inspired by Sea Life. *Langmuir* **2016**, *32*, 560–568. [CrossRef] [PubMed]
54. Sui, S.; Zhang, J.; Wang, L.; Su, W.; Chen, Z.; Sheng, G.; Li, P.; Jiang, J. Facile and Green Fabrication of Mussel-Inspired Polydopamine-Based Hydrophobic Coating for Concrete Protection. *MRS Commun.* **2022**, *12*, 794–800. [CrossRef]
55. Lu, S.; Zhao, P.; Liang, C.; Liu, L.; Qin, Z.; Wang, S.; Hou, P.; Lu, L. Utilization of Polydimethylsiloxane (PDMS) in Polymer Cement-Based Coating to Improve Marine Environment Service Performance. *Constr. Build. Mater.* **2023**, *367*, 130359. [CrossRef]
56. Verma, S.; Mohanty, S.; Nayak, S.K. A Review on Protective Polymeric Coatings for Marine Applications. *J. Coat. Technol. Res.* **2019**, *16*, 307–338. [CrossRef]
57. Wang, X.; Jiang, Q.; Han, D.; Chen, Y.; Liu, W.; Pei, Y.; Duan, J.; Hou, B. Progress in Anti-Biofouling Materials and Coatings for the Marine Environment. *J. Environ. Sci.* **2026**, *161*, 494–510. [CrossRef] [PubMed]
58. Hamadullah, C.; Cao, P.; Liu, X.; Miao, S. Antifouling in Marine Aquaculture: Mechanisms, Strategies, and Sustainable Design Guidelines. *Rev. Aquac.* **2026**, *18*, e70183. [CrossRef]
59. Arango-Carvajal, L.C.; Silva, R.; Estevez, M.; Vargas, G.; Quan-Young, L.I.; Banaszak, A.T. Antifouling Capacity of Substrate Materials and Their Effects on Settlement and Post-Settlement Survival of Acropora palmata and Orbicella faveolata. *Restor. Ecol.* **2026**, e70520. [CrossRef]
60. Levenstein, M.A.; Gysbers, D.J.; Marhaver, K.L.; Kattom, S.; Tichy, L.; Quinlan, Z.; Tholen, H.M.; Kelly, L.W.; Vermeij, M.J.A.; Wagoner Johnson, A.J.; et al. Millimeter-Scale Topography Facilitates Coral Larval Settlement in Wave-Driven Oscillatory Flow. *PLoS ONE* **2022**, *17*, e0274088. [CrossRef] [PubMed]
61. Wouters, M.; Rentrop, C.; Willemsen, P. Surface Structuring and Coating Performance. Novel Biocidefree Nanocomposite Coatings with Anti-Fouling and Fouling-Release Properties. *Prog. Org. Coat.* **2010**, *68*, 4–11. [CrossRef]
62. Linaraki, D. Design and Fabrication of Bio-Enhancing Surfaces for Coral Settlement. *Architecture* **2025**, *5*, 20. [CrossRef]
63. Hoog Antink, M.M.; Röpke, L.; Bartels, J.; Soltmann, C.; Kunzmann, A.; Rezwan, K.; Kroll, S. Porous Ceramics with Tailored Pore Size and Morphology as Substrates for Coral Larval Settlement. *Ceram. Int.* **2018**, *44*, 16561–16571. [CrossRef]
64. Vieira, M.Â.; MO Tavares, S.; Félix, S.L. Three–Dimensional Matrices for Enhanced Coral Settlement through Design for Ad-ditive Manufacturing. *Rapid Prototyp. J.* **2025**, *31*, 157–173. [CrossRef]

65. Liu, J.; Tong, Z.; Gao, F.; Wang, J.; Hu, J.; Song, L.; Hou, Y.; Lu, J.; Zhan, X.; Zhang, Q. Pearl-Inspired Intelligent Marine Hetero Nanocomposite Coating Based on "Brick&Mortar" Strategy: Anticorrosion Durability and Switchable Antifouling. *Adv. Mater.* **2024**, *36*, 2401982. [CrossRef] [PubMed]
66. Liu, Y.; Shi, J. Design of a Smart Protective Coating with Molybdate-Loaded Halloysite Nanotubes towards Corrosion Pro-tection in Reinforced Concrete. *Cem. Concr. Compos.* **2024**, *147*, 105419. [CrossRef]
67. Liu, C.; Sun, Z.; Jiao, S.; Wang, T.; Liu, Y.; Meng, X.; Zhang, B.; Han, L.; Liu, R.; Liu, Y.; et al. Dual-Shell Microcapsules for High-Response Efficiency Self-Healing of Multi-Scale Damage in Waterborne Polymer–Cement Coatings. *Polymers* **2024**, *16*, 105. [CrossRef] [PubMed]
68. Levy, N.; Kundu, S.; Freckelton, M.; Dinasquet, J.; Flores, I.; Galindo-Martínez, C.T.; Tresguerres, M.; De La Garza, V.; Sun, Y.; Karimi, Z.; et al. Microbial Living Materials Promote Coral Larval Settlement. *PNAS Nexus* **2025**, *4*, pgaf268. [CrossRef] [PubMed]
69. Montalvo-Proano, J.; Alvarez-Noriega, M.; Flores, F.; Severati, A.; Negri, A.P. Fouling-Release Coatings Enhance Acropora Loripes Coral Spat Survival by Limiting Algal Competition on Seeding Devices. *Front. Mar. Sci.* **2025**, *12*, 1684011. [CrossRef]
70. Farrell, M.V.; Rix, L.; O'Brien, P.A.; Dunbar, T.L.; Mahesh, S.; Kuek, F.; Shikuma, N.J. A Non-Living, Microbe-Based Surface Coating Promotes Tubeworm and Coral Settlement. *Mar. Biotechnol.* **2026**, *28*, 154. [CrossRef] [PubMed]
71. Moretti, M.; Hountondji, M.; Ge, R.; Emwas, A.H.; Bilalis, P.; Susapto, H.H.; Alrashoudi, A.; Liu, X.; Briola, G.R.; Hauser, C.A.E. Selectively Positioned Catechol Moiety Supports Ultrashort Self-Assembling Peptide Hydrogel Adhesion for Coral Restoration. *Langmuir* **2023**, *39*, 17903–17920. [CrossRef] [PubMed]
72. Liao, H.; Huang, L.; Zhang, Y.; Peng, J.; Huang, H.; Yuan, T. Evaluating Adhesive Materials for Effective Outplanting of Acropora Corals: A Comparative Analysis of Adhesion Performance, Biocompatibility and Cost-Effectiveness. *Aquat. Conserv. Mar. Freshw. Ecosyst.* **2026**, *36*, e70332. [CrossRef]
73. Kundu, S.; Freckelton, M.L.; Datta, D.; Potenti, S.; Levy, N.; De La Garza, V.; Hancock, J.R.; Drury, C.; Pokorski, J.K.; De Cola, L.; et al. Bioactive Nanocoatings Encode Bacterial Settlement Cues for Coral Restoration. *ACS Mater. Lett.* **2026**, *8*, 2898–2904. [CrossRef]
74. Leonard, C.; Hédouin, L.; Lacorne, M.C.; Dalle, J.; Lapinski, M.; Blanc, P.; Nugues, M.M. Performance of Innovative Materials as Recruitment Substrates for Coral Restoration. *Restor. Ecol.* **2022**, *30*, e13625. [CrossRef]
75. Xiao, Z.; Feng, C.; Gao, B.; Huang, Y.; Long, L.; Yang, F. Marine Macroalgae and Their Associated Bacterial Communities Affect Larval Settlement and Survivorship of the Coral Pocillopora Damicornis. *Mar. Environ. Res.* **2024**, *199*, 106597. [CrossRef] [PubMed]
76. Lei, X.; Jiang, L.; Zhang, Y.; Sun, Y.; Zhou, G.; Lian, J.; Huang, H. Coral Larval Settlement and Post-Settlement Survival Faci-litated by Crustose Coralline Algae with or without Living Tissue. *Mar. Biol.* **2021**, *168*, 128. [CrossRef]
77. Pozas-Schacre, C.; Bischoff, H.; Clerissi, C.; Nugues, M.M. Negative Parental and Offspring Environmental Effects of Ma-croalgae on Coral Recruitment Are Linked with Alterations in the Coral Larval Microbiome. *R. Soc. Open Sci.* **2024**, *11*, 240187. [CrossRef] [PubMed]
78. dela Cruz, D.W.; Harrison, P.L. Enhancing Coral Recruitment through Assisted Mass Settlement of Cultured Coral Larvae. *PLoS ONE* **2020**, *15*, e0242847. [CrossRef] [PubMed]
79. Gouezo, M.; Harrison, P.L.; Roff, G.; Chai, A.; Thomson, D.P.; Guglielmo, M.; Hardiman, L.; Forbes, A.; Gardner, B.; Doro-poulos, C. Coral Larval Enhancement with and without Nets Yields Similar Recruitment during Slack Current Releases. *Restor. Ecol.* **2026**, *34*, e70219. [CrossRef]
80. Ligson, C.A.; Cabaitan, P.C.; Harrison, P.L. Survival and Growth of Coral Recruits in Varying Group Sizes. *J. Exp. Mar. Bio. Ecol.* **2022**, *556*, 151793. [CrossRef]
81. Quinlan, Z.A.; Bennett, M.J.; Arts, M.G.I.; Levenstein, M.; Flores, D.; Tholen, H.M.; Tichy, L.; Juarez, G.; Haas, A.F.; Cham-berland, V.F.; et al. Coral Larval Settlement Induction Using Tissue-Associated and Exuded Coralline Algae Metabolites and the Identification of Putative Chemical Cues. *Proc. R. Soc. B Biol. Sci.* **2023**, *290*, 20231476. [CrossRef] [PubMed]
82. Sneed, J.M.; Sharp, K.H.; Ritchie, K.B.; Paul, V.J. The Chemical Cue Tetrabromopyrrole from a Biofilm Bacterium Induces Settlement of Multiple Caribbean Corals. *Proc. R. Soc. B Biol. Sci.* **2014**, *281*, 20133086. [CrossRef] [PubMed]
83. Jiang, L.; Zhang, Y.Y.; Liu, C.Y.; Huang, L.T.; Tong, H.Y.; Zhou, G.W.; Guo, M.L.; Yuan, T.; Huang, H. Gregarious Larval Settlement Mediates the Responses of New Recruits of the Reef Coral Acropora Austera to Ocean Warming and Acidification. *Front. Mar. Sci.* **2022**, *9*, 964803. [CrossRef]
84. Ritson-Williams, R.; Paul, V.J.; Arnold, S.N.; Steneck, R.S. Larval Settlement Preferences and Post-Settlement Survival of the Threatened Caribbean Corals Acropora Palmata and A. *Cervicornis*. *Coral Reefs* **2010**, *29*, 71–81. [CrossRef]
85. Guete-Salazar, C.; Barros, J.; Velasco, L.A. Settlement and Culture of Post-Larvae, Spat and Juveniles of the West Indian Topshell, Cittarium Pica (Linne, 1758). *Aquaculture* **2021**, *543*, 737029. [CrossRef]
86. Valenzuela Matus, I.; Góis, J.; Vaz-Pires, P.; Lino Alves, J. Coral Propagation in Substrates Obtained Through Additive Ma-nufacturing: Influence of Mortar Formulations on Seawater Parameters. *ACS Sustain. Chem. Eng.* **2024**, *12*, 13721–13740. [CrossRef]

87. Miller, M.W.; Latijnhouwers, K.R.W.; Bickel, A.; Mendoza-Quiroz, S.; Schick, M.; Burton, K.; Banaszak, A.T. Settlement Yields in Large-Scale in Situ Culture of Caribbean Coral Larvae for Restoration. *Restor. Ecol.* **2022**, *30*, e13512. [CrossRef]
88. Abdul Wahab, M.A.; Ferguson, S.; Snekkevik, V.K.; McCutchan, G.; Jeong, S.; Severati, A.; Randall, C.J.; Negri, A.P.; Diaz-Pulido, G. Hierarchical Settlement Behaviours of Coral Larvae to Common Coralline Algae. *Sci. Rep.* **2023**, *13*, 5795. [CrossRef] [PubMed]
89. Yang, Q.; Zhang, W.; Zhang, Y.; Tang, X.; Ling, J.; Zhang, Y.; Dong, J. Promoting Larval Settlement of Coral Pocillopora Da-micornis by Calcium. *Coral Reefs* **2022**, *41*, 223–235. [CrossRef]
90. Vargas-Ángel, B. Crustose Coralline Algal Diseases in the U.S.-Affiliated Pacific Islands. *Coral Reefs* **2010**, *29*, 943–956. [CrossRef]
91. Matus, I.V.; Lino Alves, J.; Góis, J.; Barata da Rocha, A.; Neto, R.; Da Silva Mota, C. Effect of 3D Printer Enabled Surface Morphology and Composition on Coral Growth in Artificial Reefs. *Rapid Prototyp. J.* **2021**, *27*, 692–706. [CrossRef]
92. Sharp, K.H.; Sneed, J.M.; Ritchie, K.B.; McDaniel, L.; Paul, V.J. Induction of Larval Settlement in the Reef Coral Porites As-treoides by a Cultivated Marine Roseobacter Strain. *Biol. Bull.* **2015**, *228*, 98–107. [CrossRef] [PubMed]
93. Moeller, M.; Nietzer, S.; Schupp, P.J. Neuroactive Compounds Induce Larval Settlement in the Scleractinian Coral Leptastrea Purpurea. *Sci. Rep.* **2019**, *9*, 2291. [CrossRef] [PubMed]
94. Kegler, P.; Kegler, H.F.; Gärdes, A.; Ferse, S.C.A.; Lukman, M.; Alfiansah, Y.R.; Hassenrück, C.; Kunzmann, A. Bacterial Biofilm Communities and Coral Larvae Settlement at Different Levels of Anthropogenic Impact in the Spermonde Archipe-lago, Indonesia. *Front. Mar. Sci.* **2017**, *4*, 243443. [CrossRef]
95. Padayhag, B.M.; Nada, M.A.L.; Baquiran, J.I.P.; Sison-Mangus, M.P.; San Diego-McGlone, M.L.; Cabaitan, P.C.; Conaco, C. Microbial Community Structure and Settlement Induction Capacity of Marine Biofilms Developed under Varied Reef Condi-tions. *Mar. Pollut. Bull.* **2023**, *193*, 115138. [CrossRef] [PubMed]
96. O'Brien, P.A.; Bell, S.C.; Rix, L.; Turnlund, A.C.; Kjeldsen, S.R.; Webster, N.S.; Negri, A.P.; Abdul Wahab, M.A.; Vanwon-terghem, I. Light and Dark Biofilm Adaptation Impacts Larval Settlement in Diverse Coral Species. *Environ. Microbiome* **2025**, *20*, 11. [CrossRef] [PubMed]
97. Levenstein, M.A.; Marhaver, K.L.; Quinlan, Z.A.; Tholen, H.M.; Tichy, L.; Yus, J.; Lightcap, I.; Wegley Kelly, L.; Juarez, G.; Vermeij, M.J.A.; et al. Composite Substrates Reveal Inorganic Material Cues for Coral Larval Settlement. *ACS Sustain. Chem. Eng.* **2022**, *10*, 3960–3971. [CrossRef]
98. Elmer, F.; Bell, J.J.; Gardner, J.P.A. Coral Larvae Change Their Settlement Preference for Crustose Coralline Algae Dependent on Availability of Bare Space. *Coral Reefs* **2018**, *37*, 397–407. [CrossRef]
99. Reidenbach, M.A.; Stocking, J.B.; Szczyrba, L.; Wendelken, C. Hydrodynamic Interactions with Coral Topography and Its Impact on Larval Settlement. *Coral Reefs* **2021**, *40*, 505–519. [CrossRef]
100. Petersen, D.; Laterveer, M.; Schuhmacher, H. Innovative Substrate Tiles to Spatially Control Larval Settlement in Coral Cul-ture. *Mar. Biol.* **2005**, *146*, 937–942. [CrossRef]
101. Edmunds, P.J.; Nozawa, Y.; Villanueva, R.D. Refuges Modulate Coral Recruitment in the Caribbean and the Pacific. *J. Exp. Mar. Bio. Ecol.* **2014**, *454*, 78–84. [CrossRef]
102. Ricardo, G.F.; Jones, R.J.; Nordborg, M.; Negri, A.P. Settlement Patterns of the Coral Acropora Millepora on Sediment-Laden Surfaces. *Sci. Total Environ.* **2017**, *609*, 277–288. [CrossRef] [PubMed]
103. Reichert, J.; Jorissen, H.; Drury, C.; Hancock, J.R.; Haynes, C.; Nims, A.D.; Rova, L.H.; Schiettekatte, N.M.D.; Madin, J.S. Helix Recesses Boost Coral Larvae Settlement and Survival. *Biol. Conserv.* **2025**, *311*, 111407. [CrossRef]
104. Jia, Y.; Abdelrahman, S.; Hauser, C.A.E. Developing a Sustainable Resin for 3D Printing in Coral Restoration. *Mater. Sci. Addit. Manuf.* **2024**, *3*, 3125. [CrossRef]
105. Nie, R.; Huang, Y.; Li, X.; Sun, H.; Li, D.; Ying, J. Bond of Epoxy-Coated Reinforcement to Seawater Coral Aggregate Concrete. *Ocean Eng.* **2020**, *208*, 107350. [CrossRef]
106. Whalan, S.; Abdul Wahab, M.A.; Sprungala, S.; Poole, A.J.; De Nys, R. Larval Settlement: The Role of Surface Topography for Sessile Coral Reef Invertebrates. *PLoS ONE* **2015**, *10*, e0117675. [CrossRef] [PubMed]
107. Gallagher, C.; Doropoulos, C. Spatial Refugia Mediate Juvenile Coral Survival during Coral–Predator Interactions. *Coral Reefs* **2017**, *36*, 51–61. [CrossRef]
108. Suzuki, G.; Kai, S.; Yamashita, H.; Suzuki, K.; Iehisa, Y.; Hayashibara, T. Narrower Grid Structure of Artificial Reef Enhances Initial Survival of in Situ Settled Coral. *Mar. Pollut. Bull.* **2011**, *62*, 2803–2812. [CrossRef] [PubMed]
109. Mason, R.A.B.; Langlais, C.; Uribe-Palomino, J.; Tonks, M.; Coman, F.; Choukroun, S.; Porobic, J.; Doropoulos, C. Reef-Scale Variation in Larval Supply and Settlement: Validating Lagrangian Dispersal Predictions with Observations of Coral Larvae. *Estuar. Coast. Shelf Sci.* **2025**, *326*, 109506. [CrossRef]
110. Mason, B.; Beard, M.; Miller, M.W. Coral Larvae Settle at a Higher Frequency on Red Surfaces. *Coral Reefs* **2011**, *30*, 667–676. [CrossRef]
111. Brunner, C.A.; Uthicke, S.; Ricardo, G.F.; Hoogenboom, M.O.; Negri, A.P. Climate Change Doubles Sedimentation-Induced Coral Recruit Mortality. *Sci. Total Environ.* **2021**, *768*, 143897. [CrossRef] [PubMed]

112. López-Pérez, A.; Solís-García, Y. Coral Settlement and Post-Settlement Mortality on Artificial Substrata in South Mexican Pacific Reefs. *Pac. Sci.* **2019**, *73*, 451–459. [CrossRef]
113. Sellares-Blasco, R.I.; García, N.; Villalpando, M.F.; Cano, I.; Croquer, A. Effects of Elevated Temperatures and Health Status of the Crustose Coralline Algae Hydrolithon Boergesenii (Corallinales: Mastophoroideae) on the Larval Settlement of Diploria Labyrinthiformis (Scleractinia: Faviinae). *Reg. Stud. Mar. Sci.* **2023**, *66*, 103138. [CrossRef]
114. Puill-Stephan, E.; van Oppen, M.J.H.; Pichavant-Rafini, K.; Willis, B.L. High Potential for Formation and Persistence of Chi-meras Following Aggregated Larval Settlement in the Broadcast Spawning Coral, Acropora Millepora. *Proc. R. Soc. B Biol. Sci.* **2012**, *279*, 699–708. [CrossRef] [PubMed]
115. Shefy, D.; Guerrini, G.; Marom, N.; Shashar, N.; Rinkevich, B. Settling in Aggregation: Spatial Planning Consideration for Brooding Coral Transplants. *Mar. Environ. Res.* **2022**, *176*, 105612. [CrossRef] [PubMed]
116. Martinez, S.; Abelson, A. Coral Recruitment: The Critical Role of Early Post-Settlement Survival. *ICES J. Mar. Sci.* **2013**, *70*, 1294–1298. [CrossRef]
117. Montalvo-Proano, J.; Flores, F.; Severati, A.; Negri, A.P. Fouling Release Coatings Reduce Colonisation of Coral Seeding Devices. *Sci. Rep.* **2025**, *15*, 24023. [CrossRef] [PubMed]
118. Agostini, V.O.; Macedo, A.J.; Muxagata, E.; Pinho, G.L.L. Surface Coatings Select Their Micro and Macrofouling Communities Differently on Steel. *Environ. Pollut.* **2019**, *254*, 113086. [CrossRef] [PubMed]
119. Soriano-Jerez, Y.; Gourlaouen, E.; Zeriouh, O.; del Carmen Cerón-García, M.; Arrabal-Campos, F.M.; Ruiz-Martínez, C.; Fernández, I.; Gallardo-Rodríguez, J.J.; García-Camacho, F.; Molina-Grima, E.; et al. Role of Dynamic Surface Tension of Si-licone Polyether Surfactant-Based Silicone Coatings on Protein Adsorption: An Insight on the 'Ambiguous' Interfacial Proper-ties of Fouling Release Coatings. *Prog. Org. Coat.* **2024**, *186*, 108079. [CrossRef]
120. Montalvo-Proano, J.; Page, C.A.; Giuliano, C.; Randall, C.J.; Negri, A.P. Coral Spat Survival on Inshore Reefs Is Enhanced by Foul-Release-Coated Seeding Devices. *Coral Reefs* **2026**, 1–15. [CrossRef]
121. Widiastuti; Wijaya, A.A.N.A.I.; Giuliano, C.; Allen, K.; Jenkins, V.; Randall, C.J.; Page, C.A. Cost-Effective Coral Settlement Substrates for Restoration, Exports and Research. *Coral Reefs* **2025**, *44*, 2169–2179. [CrossRef]
122. Ramsby, B.D.; Forster, R.; Ferguson, S.N.; Haikola, P.; Randall, C.J.; Abdul Wahab, M.A.; Mead, D.J.; Severati, A. Developing Coral Seeding Devices and Rapid Deployment Methods to Scale up Reef Restoration. *Restor. Ecol.* **2026**, *34*, e70206. [CrossRef]
123. Talekar, S.; Barrow, C.J.; Nguyen, H.C.; Zolfagharian, A.; Zare, S.; Farjana, S.H.; Macreadie, P.I.; Ashraf, M.; Trevat-han-Tackett, S.M. Using Waste Biomass to Produce 3D-Printed Artificial Biodegradable Structures for Coastal Ecosystem Restoration. *Sci. Total Environ.* **2024**, *925*, 171728. [CrossRef] [PubMed]
124. Wang, Y.; Sun, J.; Fang, E.; Guo, B.; Dai, Y.; Gao, Y.; Wang, H.; Zhang, X.; Xu, X.; Yu, Y.; et al. Impact of Artificial Reefs on Sediment Bacterial Structure and Function in Bohai Bay. *Can. J. Microbiol.* **2019**, *65*, 191–200. [CrossRef] [PubMed]
125. Pinnaratip, R.; Zhang, Z.; Smies, A.; Forooshani, P.K.; Tang, X.; Rajachar, R.M.; Lee, B.P. Utilizing Robust Design to Optimize Composite Bioadhesive for Promoting Dermal Wound Repair. *Polymers* **2023**, *15*, 1905. [CrossRef] [PubMed]
126. Ehrlich, H.; Wysokowski, M.; Jesionowski, T. The Philosophy of Extreme Biomimetics. *Sustain. Mater. Technol.* **2022**, *32*, e00447. [CrossRef]
127. Gao, Z.; Cui, Y.; Ma, L.; Che, M.; Cui, M.; Su, R.; Lin, C.; Huang, R. Transparent Marine Antifouling Coatings for Underwater Optical Devices: Strategies, Mechanisms and Future Perspectives. *Mater. Horiz.* **2026**, *13*, 9523–9552. [CrossRef] [PubMed]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.