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TENDER: A Conceptual Tethered-Probe System for Localized Remediation of Coastal Acidification Events

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***ABSTRACT*— Ocean acidification is usually framed as a global average, but that is not where it is first felt. In confined coastal waters, local processes like upwelling and organic-load respiration can depress pH faster and further than the atmospheric signal alone, making the confined water body, not the open ocean, the natural unit for detection and response. Existing interventions do not meet that scale: hatchery buffering is fixed to a pipe, cultivated macrophytes are rooted in place and reversed at night, and alkalinity trials broadcast from a ship, where dilution is the goal. None delivers a metered, sensor-triggered dose inside a confined water body and then stays in place to verify whether the chemistry recovers. This paper presents TENDER (Tethered Environmental Neutralization and Dispersal for Ecological Restoration), a system proposed for that gap. A support vessel would carry the operator station and cultivation facility, a carrier vehicle would transport a fleet of tethered probes, and each probe would sense the local chemistry and deliver a metered dose of buffered sodium carbonate or a biological payload under operator authorization, with a monitoring node left behind to report on recovery. Its distinguishing contribution is a cultivation loop, in which organisms native to the treated site are sampled, cultured, and returned rather than shipped in, an approach supported at microcosm and mesocosm scale but not yet at field scale. TENDER is presented as a conceptual design, developed to the point where its architecture, operating logic, and limits can be examined and built upon. If developed as intended, it could correct the chemistry of a localized acidification event while supporting the organisms already capable of clearing the load that drives it.**

Keywords: Coastal Acidification, Marine Robotics, Tethered Underwater Vehicles, Alkalinity Buffering, Bioremediation, Biostimulation, Autochthonous Bioaugmentation, Shellfish Aquaculture

I. INTRODUCTION

The ocean absorbs a large share of the carbon dioxide that human activity releases to the atmosphere. As it dissolves, that carbon dioxide forms carbonic acid, releasing hydrogen ions and lowering pH, the process known as ocean acidification [1]. The average pH of the global surface ocean fell by roughly 0.11 units between 1750 and 2000, an increase in acidity of about 30 percent, and under a high-emissions trajectory it is projected to fall by a further 0.3 to 0.4 units by 2100 [2]. Falling pH also lowers the carbonate ion concentration and the saturation state of surface waters, shoaling the saturation horizon and leaving the mineral that shell-forming organisms depend on harder to build and easier to lose [1], [2].

The biological consequences of this shift are well documented. Elevated seawater carbon dioxide reduces the ability of calcifying organisms, including corals, molluscs, and foraminifera, to build and maintain their calcium carbonate structures, and it disrupts acid-base regulation and related physiological processes more broadly [1]. These effects are not confined to individual organisms: pteropods and foraminifera occur in enormous numbers and feed higher trophic levels, so the impairment of calcifiers can propagate through marine food webs and tilt communities toward non-calcifying species [1].

The global average, however, is not where the damage is first felt. Coastal, estuarine, and enclosed waters swing through far larger pH ranges than the open ocean and can acidify faster, because local processes act on top of the atmospheric signal rather than in place of it [3]. Two of them matter most. Along eastern boundary margins such as the California Current, seasonal upwelling brings deep water naturally rich in carbon dioxide and low in pH onto the shelf, and anthropogenic carbon dioxide has made it more corrosive and shoaled its saturation horizon toward the surface [4]. The second process is respiration. When a large load of degradable organic carbon enters a confined water body, whether from a runoff-driven bloom that later dies back, a sewage input, or a spill, microbial respiration of that material consumes dissolved oxygen and releases carbon dioxide, depressing pH locally and often sharply [5]. At this scale contamination and acidification are genuinely coupled, even though the global signal is driven by atmospheric carbon dioxide uptake alone, which makes the confined water body, not the open ocean, the natural unit at which such events can be detected and addressed.

This is not hypothetical. Beginning in the summer of 2007, the Whiskey Creek Shellfish Hatchery on the Oregon coast suffered repeated, severe failures of its Pacific oyster larvae. After initial suspicion of bacterial disease, the cause was traced to the carbonate chemistry of the seawater drawn into the hatchery, where natural upwelling and the rising anthropogenic carbon dioxide baseline combined to push the aragonite saturation state below the level the larvae require [6]. Oyster larvae are acutely exposed because they precipitate close to 90 percent of their body weight as calcium carbonate shell within roughly the first 48 hours of life, drawing on finite egg reserves before they can feed, which makes the added energetic cost of calcifying in corrosive water decisive [7]. For several seasons the hatchery's production became commercially unviable [6].

The hatchery problem was answered in practice, not in theory. Growers began dosing sodium carbonate, or soda ash, into the intake water to restore its saturation state whenever real-time carbonate monitoring showed the chemistry out of balance, and they rescheduled intake to the times of day and tide when the incoming chemistry was more favorable [6]. The monitoring instrument developed for this purpose, computing the aragonite saturation state in real time, later spread into a wider coastal observing network [6]. Controlled comparisons at the same hatchery found that buffering the intake water improved larval survival across several production cohorts [8]. Metered chemical correction of seawater pH, triggered by live carbonate measurement, is therefore not speculative but current commercial practice. It works, however, precisely because the water is inside a pipe, the very constraint that any broader intervention would have to relax.

A second line of intervention is biological. Photosynthesis by seagrasses, kelps, and cultivated macroalgae draws carbon dioxide out of the water and raises its pH, creating localized refuges from acidification. Measurements inside seaweed farms have recorded pH elevations of about 0.10 units for the kelp Saccharina japonica, with smaller effects for other species [9], and co-culture experiments have shown that seaweeds can raise system pH and improve the growth of juvenile shellfish reared alongside them [10]. Because seaweed farming is scalable and, unlike a natural macrophyte bed, is not confined to sites that happen to offer suitable substrate, it has been proposed as a low-cost way to extend this protective effect to vulnerable areas [9]. Its limits are as important as its promise. The pH gain is a daytime phenomenon that night-time respiration can reverse, and sustaining a net elevation can demand intensive management [11]. It is also effective mainly in sheltered, low-flux settings; where tidal exchange is strong the buffered water is replaced too quickly for the effect to register, so cultivated vegetation is best understood as a tool for creating local refugia rather than for lowering acidity across a region [12].

A third precedent, microbial remediation, carries a finding that reshapes how such a system should be conceived. Oil-degrading bacteria are ubiquitous in seawater and multiply on their own when hydrocarbons appear; Alcanivorax borkumensis, an alkane specialist, characteristically blooms to dominance in oil-contaminated, nutrient-replete water [13]. Deep-sea sampling of the plume from the 2010 Deepwater Horizon blowout found indigenous oil-degrading bacteria enriched within it, degrading hydrocarbons without anyone having added them [14]. Adding cultured bacteria to a spill, the practice known as bioaugmentation, has not been shown to work under real field conditions and is likely unnecessary, given how widely the relevant organisms already occur [15]. What has repeatedly worked instead is biostimulation: relieving the factor that actually limits the microbes already present, most often nitrogen and phosphorus [15]. The emerging refinement is autochthonous bioaugmentation, in which the organisms are drawn exclusively from the site under treatment, cultured, and returned, since laboratory-grown populations underperform at the low nutrient levels they meet in the field; in microcosm and mesocosm trials it has substantially accelerated hydrocarbon breakdown [16].

At the research frontier, deliberate modification of seawater chemistry has moved from proposal to permitted experiment. In August 2025 the LOC-NESS project ran the first US Environmental Protection Agency permitted field trial of ocean alkalinity enhancement, releasing a dilute alkaline solution with a dye tracer in the Gulf of Maine, with preliminary results reported in February 2026 [17]. Its caveats are as instructive as its progress. Olivine, the mineral most discussed for alkalinity enhancement, dissolves slowly at realistic grain sizes, on the order of one to twenty years for ten-micrometre grains; its dissolution releases nickel and chromium that must be kept within safe limits; and secondary mineral precipitation can roughly halve the alkalinity actually delivered [18], [19]. The activity is also governed. The London Convention and its 1996 Protocol are the principal international framework for marine geoengineering, which the Protocol defines as a deliberate intervention in the marine environment to manipulate natural processes with the potential to cause deleterious effects; ocean alkalinity enhancement is among the techniques it has prioritized for assessment [20]. Legitimate scientific research is expected to proceed transparently and under a precautionary approach [21], and decisions under the Convention on Biological Diversity further advise against geoengineering that may affect biodiversity except in small, controlled scientific study [18].

Set side by side, these precedents reveal a common shape. Hatchery buffering is precise and verified, but it requires the water to be confined inside a pipe [6]. Cultivated macrophytes are gentle and self-sustaining, but immobile, slow to establish, and reversed at night [11], [12]. Alkalinity field trials operate at the scale of a ship and broadcast into open water, where dilution is the goal rather than the obstacle [17]. Remediation practice has learned that relieving what limits the organisms already present beats shipping new ones in, but it has no delivery mechanism finer than a vessel and a hose [15]. None of these approaches delivers a metered, sensor-triggered, spatially resolved dose inside a confined water body and then stays in place to confirm whether the local chemistry actually recovers. That gap is specific, and it is where a different kind of system becomes worth proposing.

This paper presents TENDER, Tethered Environmental Neutralization and Dispersal for Ecological Restoration, a conceptual system proposed to address that gap. In the proposed architecture, a carrier vehicle would transport a fleet of tethered probes to an affected site, where each probe would sense the local water chemistry and deliver a metered dose of a buffering agent, sodium carbonate, together with a biological payload intended to relieve the limitation on the microbial community already present. Its distinguishing feature would be a cultivation loop, in which organisms native to the treated site are sampled, cultured, and returned rather than shipped in from elsewhere, and a monitoring node would be left in place afterward to report whether the local carbonate chemistry recovers. TENDER is proposed deliberately for confined, high-value water bodies, such as hatchery intakes and their source bays, reef lagoons, aquaculture leases, and enclosed harbors, and explicitly not for the open ocean. It is offered here as a conceptual design; no prototype has been built and no performance is claimed. If it could be developed as intended, it would aim to correct the water chemistry of a localized acidification event while supporting the organisms already capable of clearing the load that drives it.

II. METHODOLOGY

This section describes the proposed TENDER architecture: a support layer, a carrier vehicle, a fleet of tethered probes, a chemical and a biological payload line, and a monitoring node left behind after treatment. Because the value of the proposal depends as much on where it is not meant to act as on what it is meant to do, the design constraints and scope are stated first, before any capability is claimed.

A. Design Constraints and Scope

TENDER is a conceptual design proposal. Every statement about what the system would sense, dose, or bring about is therefore conditional, and the section is written in those terms throughout.

The system is deliberately not an open-ocean or planetary-scale intervention. The global acidification signal is driven by the ocean's uptake of atmospheric carbon dioxide, and no localized device could correct it; TENDER does not attempt to. What TENDER is proposed for is the opposite case: a confined, high-value, semi-enclosed water body in which a local acidification event can be detected and addressed as a single unit. The intended settings are hatchery intakes and their source bays, reef lagoons, aquaculture leases, enclosed harbors, and contained spill footprints. These are shallow, sheltered sites, on the order of the upper tens of meters, rather than the deep hydrocarbon zones or exposed open water that would demand a different pressure envelope and a different concept of operations.

The event these sites are subject to has a specific mechanism, and the design follows from it. When a large load of degradable organic carbon enters a confined water body, whether from a runoff-driven bloom that later dies back, a sewage input, or a spill, the microbial community respires that material. Respiration consumes dissolved oxygen and releases carbon dioxide, which depresses the local pH and lowers the carbonate saturation state. Contamination and acidification are in this way coupled at the scale of the event, even though the global signal is atmospheric in origin. The system is designed to read that coupled signature and to act on it locally, not to treat acidification wherever it occurs.

Two further constraints shape every capability claim that follows. First, a human operator authorizes every payload release; the system proposes a dose, and a person approves it before anything enters the water. This human-in-the-loop authorization is a deliberate part of the governance posture, not a limitation to be engineered away. Second, the biological pathway rests on an approach that is promising but not yet proven at field scale, and the section states that limit where the pathway is described rather than claiming more for it than the literature supports.

B. System Architecture and Operational Framework

The architecture has three layers. A support layer, aboard a surface support vessel or ashore, issues mission tasking, receives live telemetry, and authorizes each payload release. A carrier, the Underwater Deployment Vehicle (UDV), transports the working elements to and from the site. A fleet of Tethered Assessment and Remediation Probes (TARPs) performs the sensing and delivery at the treatment point.

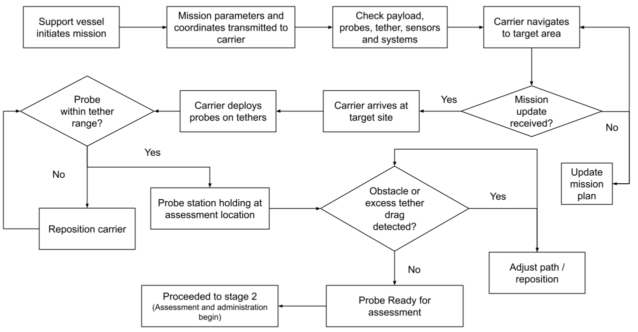

Fig. 1. Stage 1, deployment and positioning.

The UDV carries the probe fleet, the bulk payload for both payload lines, the tether reels, the pumping and distribution manifold, the onboard processing, and the power supply. It is moved by conventional ducted electric thrusters and navigates with GPS at the surface, an inertial measurement unit, cameras, and SONAR. It holds position close to the treatment zone rather than standing off from it, a choice that keeps the tethers short and lets each probe be positioned by the carrier and its umbilical rather than by any propulsion of its own.

Each TARP is 20 to 30 centimeters in length and is deployed from the UDV on an umbilical of roughly 30 to 60 meters that carries power, data, and payload. At this size and tether length, and with the carrier held close, a probe behaves as a tethered sensing and delivery head: it holds station, senses the local water chemistry, and delivers a metered dose through a nozzle, while its position is set primarily by the UDV and the tether. A short-range camera and SONAR pairing supports station-holding and obstacle avoidance. Probes draw power continuously through their tethers and carry no onboard battery, and they are recovered by being retracted along their tethers; they never surface independently.

The mission runs in three phases. In Deployment and Positioning, the UDV transits to the tasked location and pays out the probe fleet on their tethers to positions within the treatment zone. In Assessment and Administration, each probe characterizes the local water chemistry, the onboard processor proposes a response, the operator authorizes it, and the selected payload is delivered. In Retraction and Monitoring, the probes are drawn back to the UDV and a monitoring node is left in place to report whether the local chemistry recovers. The two payload lines, chemical and biological, are selected conditionally according to what the water chemistry indicates; they are not co-administered by default. Figs. 1 to 3 illustrate the first two phases.

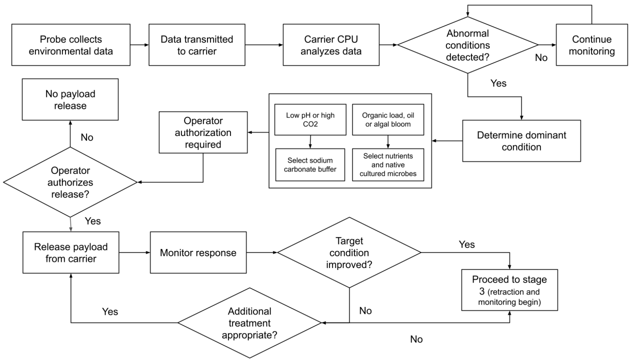

Fig. 2. Stage 2, assessment and administration.

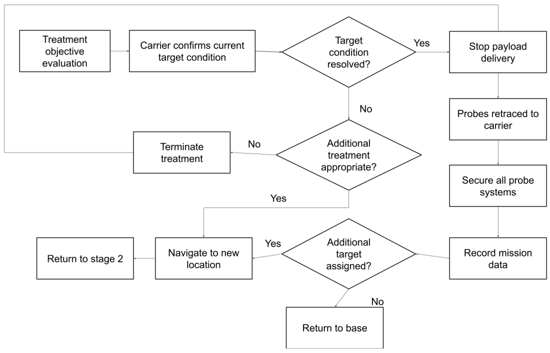

Fig. 3. Stage 3, retraction and monitoring.

C. Systems Applied in TENDER

Table 1 summarizes the functional systems that make up TENDER and the role each plays in a treatment cycle.

Table 1: Systems in TENDER and their functions.

System	Function
Assessment and water-chemistry sensing	The probe fleet would measure pH, dissolved carbon dioxide, dissolved oxygen, conductivity, and temperature, with fluorometry for hydrocarbons, to characterize the local carbonate system and identify a respiration-driven pH depression before any dose is proposed.
Buffered alkalinity dosing	Under operator authorization, the system would deliver a metered dose of buffered sodium carbonate solution into a confined water body to raise a depressed pH and carbonate saturation state toward target.
Biological support and the cultivation loop	The system would relieve the nutrient limiting the microbial community already present and, where used, return consortia that were sampled from the site and cultured aboard the support vessel, rather than introducing organisms from elsewhere.
Tethered delivery and retraction	The UDV would position a fleet of tethered probes close to the treatment zone for spatially resolved delivery through each probe's nozzle, then retract the probes along their tethers rather than allowing them to surface independently.
Post-treatment monitoring	A monitoring node would remain in place after treatment and report whether the local carbonate chemistry recovers.

D. Structural Design

The TARP structure is the compact chassis, 20 to 30 centimeters in length, to which the probe-level subsystems attach. It would be built from corrosion-resistant, non-toxic materials so that a severed tether or lost component poses little environmental risk. A tether termination point at the rear receives the umbilical, through which power, data, control signals, and payload are exchanged with the UDV. The delivery nozzle is mounted next to the termination point so that the dose pumped from the UDV is released at the probe's position. The water-chemistry sensor suite is carried on the upper surface, alongside the short-range camera and SONAR used for station-holding and obstacle avoidance. Internal wiring and a signal-conditioning circuit relay processed readings to the UDV's processor; the probe does not carry independent decision logic, an onboard battery, or a communications radio, because power and data both run through the tether (see Fig. 4).

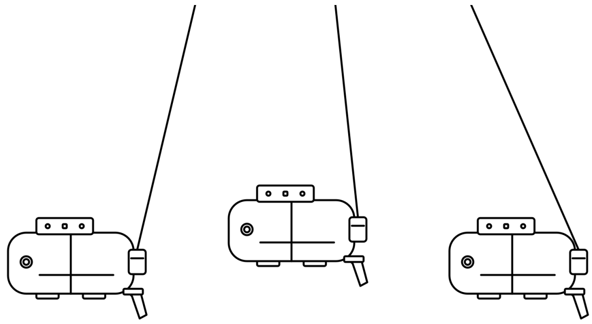

Fig. 4. Tethered assessment and remediation probes (TARPs), side view.

The UDV structure is the carrier and the mobile base for a mission. Its interior storage bays hold the two bulk payload stores, one for the buffered sodium carbonate solution and one for the biological payload, each sized to carry far more than any single probe could. A pumping and distribution manifold connects these stores to the individual tether lines and routes the selected payload to the chosen probe on command. Individual tether reels manage the deployment and retraction of each probe. Ducted electric thrusters provide propulsion, and a central battery bank powers the thrusters, the onboard processor, and the deployed probe fleet through their tethers. The navigation suite of GPS, inertial measurement unit, cameras, and SONAR is arranged along the top and forward sections, and a telemetry link on the hull maintains communication with the operator station (Fig. 5).

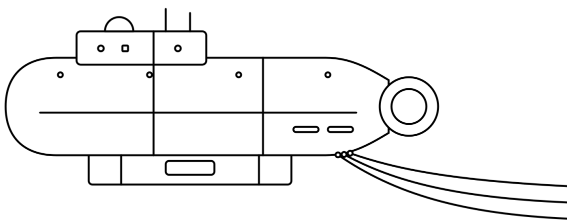

Fig. 5. Underwater deployment vehicle (UDV), side view.

The support vessel carries the operator station and the cultivation facility. Keeping the sample, culture, and return loop on the surface platform places it where power, working space, and operator attention are available, and it limits what the UDV must carry to bulk payload, the manifold, and the fleet. The trade is that the UDV returns to the vessel between culture cycles rather than treating continuously, which bounds the duration of a single deployment.

The monitoring node is a small, self-contained structure designed to be left on site. It holds a low-power carbonate-chemistry instrument package and a triboelectric generator that harvests the motion of the surrounding water, and it reports its readings to the operator over the mission's communications path.

E. Hardware Design Description

The sensing hardware follows directly from the event mechanism. A pH sensor confirms and quantifies a depression. A dissolved carbon dioxide sensor and a paired conductivity and temperature sensor together allow the local carbonate system to be characterized, since salinity and temperature are needed to compute carbonate parameters. A dissolved oxygen sensor detects the oxygen drawdown that accompanies respiration of an organic load, which is what distinguishes a locally driven event from the background signal. A fluorometer detects hydrocarbons, for the case in which the organic load is a spill. The suite deliberately omits several instruments carried in earlier drafts: it does not use ultrasonic sensing for hydrocarbons, spectroscopy for microplastic concentration, or field-effect-transistor sensing for toxic metals, because those target contaminant classes that fall outside the acidification mechanism this system addresses.

The chemical payload is a metered buffered sodium carbonate, or soda ash, solution. The rationale is practical and is drawn from existing hatchery practice. Finely ground calcium carbonate barely dissolves in seawater that is not already corrosive, so it cannot act on the timescale of an intervention, and the mineral routes studied for broader alkalinity enhancement dissolve on the order of years at realistic grain sizes and can release nickel and chromium that would have to be controlled [18], [19]. Soda ash, by contrast, dissolves readily and is already dosed into shellfish-hatchery intake water under real-time carbonate monitoring to correct a depressed saturation state [6]. TENDER adapts that established chemistry to a confined open-water setting rather than a pipe.

The biological payload has two elements: the limiting nutrients, nitrogen and phosphorus, for biostimulation, and, where used, native microbial consortia collected on site, cultured aboard the support vessel, and returned. No engineered organisms and no shipped-in species are used. The evidentiary basis for this pathway has to be stated plainly, because it sets a hard limit on what the paper may claim. Adding laboratory-cultured strains to a real marine spill, conventional bioaugmentation, has not been shown to work under field conditions and is likely unnecessary given how widely oil-degrading organisms already occur and bloom on their own once hydrocarbons appear [13], [14], [15]. Biostimulation, relieving the nutrient that actually limits the organisms already present, has by contrast been applied successfully many times in the field [15]. The cultivation loop implements autochthonous bioaugmentation, in which organisms are drawn from the site under treatment, cultured, and returned; this approach has produced strong results in microcosm and mesocosm studies but has not yet been demonstrated at field-spill scale [16]. TENDER therefore proposes the cultivation loop as a promising basis for its biological pathway, not as established practice, and every capability attributed to that pathway in this paper is conditional on this limit. The cultivation loop is nonetheless the element that distinguishes TENDER from a simple dosing rig, and it is the design's principal novel contribution: rather than shipping in organisms, the system would culture those already living at the affected site, relieve what limits them, and return them where they are needed.

Propulsion and power are conventional. The UDV's ducted electric thrusters move the carrier and its fleet, and the central battery bank aboard the UDV powers the thrusters, the processor, and every deployed probe through its tether, which is why the probes need no battery of their own. Triboelectric generation is used in exactly one place: the monitoring node. There, a device that harvests the motion of shallow, confined water can supply the low power that a monitoring instrument needs over a long dwell, which is a use its physics genuinely supports; it is not used to propel the carrier or to power the working fleet, both of which draw far more than wave-driven harvesting could provide and operate at depths where that motion is weak.

F. Components of TENDER and Their Functions

Table 2 lists the components of the system by category. It is written to agree with the prose above line by line, and it omits the components that earlier drafts carried but this architecture has removed.

Table 2: Components of TENDER and their functions.

Component	Function
Support and control	
Operator station (aboard the support vessel or ashore)	Issues mission tasking, receives live telemetry, and authorizes every payload release.
Support vessel	Surface platform for the operator station, bulk payload resupply, and the on-board sample, culture, and return facility.
Carrier	
UDV (Underwater Deployment Vehicle)	Transports the probe fleet, bulk payload, tether reels, pumping and distribution manifold, processing, and power supply to and from the treatment site.
Ducted electric thrusters	Provide conventional propulsion for positioning the carrier and its fleet.
UDV battery bank	Powers the UDV and supplies power continuously to each probe through its tether; the probes carry no onboard battery.
Probe	
TARP (Tethered Assessment and Remediation Probe) structure	Corrosion-resistant, non-toxic chassis, 20 to 30 cm, that holds the sensing suite and delivery nozzle and terminates the umbilical.
Umbilical (tether)	Carries power, data, and payload between the UDV and each probe, and is the line along which the probe is deployed and retracted.
Delivery nozzle	Releases the metered dose, buffered alkalinity or biological payload, at the treatment point.
Payload	
Buffered sodium carbonate (soda ash) store	Bulk store aboard the UDV of buffered alkalinity solution for correcting a depressed pH and carbonate saturation state.
Biological payload store	Bulk store aboard the UDV of limiting nutrients and site-native cultured consortia for biostimulation and return.
Pumping and distribution manifold	Routes the selected payload from the UDV's bulk stores to the tether line of the chosen probe on command.
Sensing (water chemistry)	
pH sensor	Measures ambient acidity to confirm a depression and gauge the dose.
Dissolved carbon dioxide sensor	Measures dissolved carbon dioxide as part of characterizing the local carbonate system.
Dissolved oxygen sensor	Detects the oxygen drawdown that accompanies respiration of an organic load, the signature of a locally driven event.

Component	Function
Conductivity and temperature sensor	Provides salinity and temperature for computing carbonate-system parameters.
Fluorometer	Detects hydrocarbons, for identifying a spill-driven organic load.
Sensing (navigation)	
Cameras	Provide visual data for UDV navigation and for probe station-holding and obstacle avoidance.
SONAR	Provides underwater ranging for UDV navigation and short-range probe station-holding.
GPS	Provides surface geolocation for the UDV.
Inertial measurement unit	Provides orientation and motion data for UDV navigation.
Control and communication	
Onboard processor (aboard the UDV)	Fuses sensor data, characterizes the local carbonate state, proposes a dose, and coordinates the fleet; it does not release payload without operator authorization.
Telemetry link (UDV to operator station)	Relays mission status and sensor data to the operator station and receives tasking, updated coordinates, and payload-release authorization.
Verification	
Monitoring node	Left in place after treatment; runs low-power carbonate instrumentation on wave-harvested triboelectric power and reports whether local carbonate chemistry recovers.

G. Assembly of Innovation

Assembly would begin with the UDV. Its corrosion-resistant, non-toxic chassis would be built with interior bays for the buffered sodium carbonate store, the biological payload store, and the probe fleet with their spooled tethers. The pumping and distribution manifold would be installed to connect the two stores to each tether reel assembly, so that any deployed probe can be served on command. The ducted electric thrusters and the central battery bank would be fitted and wired, and the navigation suite of GPS, inertial measurement unit, cameras, and SONAR would be mounted along the top and forward sections. The onboard processor would be installed and wired to the navigation suite, the manifold, the propulsion and power systems, and each tether reel, and programmed with the sensor-fusion and dose-proposing logic. The telemetry link would then be fitted to maintain communication with the operator station.

Each TARP would be assembled separately, starting from its compact corrosion-resistant, non-toxic chassis sized to 20 to 30 centimeters. A tether termination point would be built into the rear, carrying the delivery nozzle and internal feed line together with the conductors and data paths that supply power and relay readings. The water-chemistry sensor suite and the short-range camera and SONAR pairing would be mounted on the upper surface and wired into a signal-conditioning circuit that relays processed readings to the UDV rather than acting on its own. Once integrated, each probe would be sealed against water intrusion, its tether connected to the matching reel in the UDV, and the finished probe stowed in its bay.

The support vessel would be outfitted with the operator station and the cultivation facility for sampling, culturing, and returning site-native consortia. The monitoring node would be built as a sealed low-power instrument package with its triboelectric generator. As a conceptual proposal, none of this has been fabricated; any build would require calibration and testing in controlled conditions to confirm sensor accuracy, tether integrity, payload-flow reliability, and safe handling of the biological payload before any field use.

H. Mechanism of Components

A mission would begin when the operator station tasks the UDV with a location, identified from prior monitoring, sampling, or a reported event. The UDV would transit to the site under its own navigation and hold position close to the treatment zone. It would then pay out the probe fleet on their tethers, each probe taking a position within the zone with its station held by the carrier and the umbilical and refined by its short-range camera and SONAR.

Each probe's sensor suite would stream water chemistry back to the UDV's processor through the tether. The processor would characterize the local carbonate state from the combined pH, dissolved carbon dioxide, dissolved oxygen, conductivity, and temperature readings, using the oxygen drawdown and, where present, the fluorometric hydrocarbon signal to confirm that the depression is respiration-driven rather than part of the background. On that basis the processor would propose a response and relay it to the operator station. Nothing enters the water until the operator authorizes the release.

The response is selected conditionally. Where the reading indicates a depressed pH and saturation state, the proposal would be a metered dose of buffered sodium carbonate delivered through the probe's nozzle. Where it indicates that the microbial community clearing the organic load is nutrient-limited, the proposal would be biostimulation, and where the site's own consortia have been cultured aboard the vessel, their return. The chemical and biological lines are proposed independently according to what the chemistry shows; they are not delivered together as a matter of course. After a dose, the probe would continue to sense the treated water, and the processor would propose further action, again subject to authorization, until the readings recover or the onboard payload is spent.

At the close of a treatment cycle, each probe would be retracted along its tether to the UDV rather than surfacing on its own, its data having already been relayed through the tether during the mission. The UDV would then either move to a further position within the same deployment or return to the support vessel for payload resupply, data review, and a further culture cycle. A monitoring node would be left on the treated site, drawing the small power it needs from the motion of the surrounding shallow water, to report over the following period whether the local carbonate chemistry actually recovers. That returning record, rather than any claim made at the moment of dosing, is what would tell an operator whether a treatment worked.

I. Applications of TENDER

The system is intended for the confined, high-value settings named in the scope: hatchery intakes and their source bays, reef lagoons, aquaculture leases, enclosed harbors, and contained spill footprints. In each, an operator would task the UDV to a site, the probe fleet would characterize the water and propose a response, the operator would authorize dosing, and a monitoring node would be left behind to report on recovery. The design's endurance is bounded by the return trips to the support vessel that resupply payload and run the culture cycle, which suits episodic, site-scale events rather than continuous regional treatment.

Because the architecture is built around modular sensing, operator-authorized conditional release, and tethered, spatially resolved delivery, the same platform could in principle be adapted to other tasks that call for precise delivery of a metered agent in a confined, hard-to-reach body of water, by changing the stored payload and the sensing thresholds rather than redesigning the probes. Any such extension would be a separate line of work; the contaminant classes that fall outside the acidification mechanism, such as microplastics and toxic metals, are noted here only as possible future adaptations of the platform and are not treated as drivers of acidification or as targets of the system described in this paper.

III. ANTICIPATED OUTCOMES AND LIMITATIONS

TENDER is a conceptual design proposal, worked out far enough that its architecture, its operating logic, and the conditions it would depend on can all be examined and argued with. This section sets out the outcomes the proposed system is intended to produce, each stated conditionally, and then the constraints that would bound them. Subsections A through C describe the anticipated outcomes; D through H describe the limitations. Both are given full weight, because a design at this stage is most useful when the boundaries of what it could do are drawn as carefully as the capabilities themselves, and it is that pairing which makes a proposal testable by whoever builds on it.

A. Correction of a Confined Acidification Event

The best supported of the proposed outcomes would be the chemical one. Where the probe fleet reads a respiration-driven depression of pH and carbonate saturation state, the system would deliver a metered dose of buffered sodium carbonate at the affected point, with the aim of raising the local saturation state toward the level that calcifying organisms require. This pathway rests on established hatchery practice, in which soda ash is dosed into intake water under real-time carbonate monitoring to counter a depressed saturation state [6], and on controlled comparisons at one such hatchery in which buffering the intake water was associated with improved survival of oyster larvae across several production cohorts [8]. Those comparisons are the closest reference point in the present literature for the chemical pathway, and they are informative precisely because oyster larvae precipitate most of their body weight as shell within the first days of life and are therefore acutely sensitive to the saturation state of the water around them [7]. If the buffering pathway could be realized as proposed, its intended effect would be a local correction of carbonate chemistry within the treated zone, offered for the duration of an event rather than as a permanent alteration of the water body.

B. Support for the Site's Resident Microbial Community

The distinguishing outcome, and the design's principal novel contribution, would be biological. Rather than introducing organisms from elsewhere, the system would relieve the nutrient that limits the microbial community already present at the affected site and, where the cultivation loop is used, return consortia that were sampled on site and cultured aboard the support vessel. The intent is that the organisms best suited to clearing the organic load driving a local event are those the site already holds, and that supporting them in place would be more appropriate than shipping in cultured strains. This outcome is stated with more caution than the chemical one, because the approach it depends on has been established at smaller scales rather than at the scale of a real field event. That evidentiary boundary is the central constraint of the paper and is set out first among the limitations below, in Section III-D. Every capability attributed to the biological pathway here is conditional on it.

C. Spatially Resolved Delivery, Operator Oversight, and Verification

Beyond the two payload lines, the architecture is intended to yield three procedural outcomes. First, because the probes are positioned individually on their tethers and dose through their own nozzles, delivery would be spatially resolved within the treatment zone rather than broadcast across it, which in a confined body of water is the setting where a metered dose could be placed where it is needed. Second, because a human operator authorizes every release, the system would keep a person in control of what enters the water, a governance posture adopted deliberately rather than as a temporary safeguard. Third, because a monitoring node would be left in place after treatment to report on the local carbonate chemistry over the following period, the concept builds in a means of checking whether a treated site recovers, so that any judgment of success would rest on the returning record rather than on the act of dosing.

D. The Field-Scale Gap in Autochthonous Bioaugmentation

The most important limitation concerns the biological pathway on which the novelty of the design rests. Conventional bioaugmentation, the addition of laboratory-cultured strains to a real marine spill, has not been shown to work under field conditions and is in most settings unnecessary, since the organisms that degrade a given load are already widespread in seawater and multiply on their own once that load appears [13], [14], [15]. Biostimulation, relieving the nutrient that limits the organisms already present, has by contrast been applied successfully in the field many times [15]. The cultivation loop implements a third approach, autochthonous bioaugmentation, in which organisms are drawn only from the site under treatment, cultured, and returned. In microcosm and mesocosm studies this approach has accelerated breakdown of an organic load, but it has not yet been demonstrated at the scale of a field event [16]. The design therefore proposes the cultivation loop as a promising basis for its biological pathway rather than as established practice, and the paper claims no more for it than the literature supports. Until autochthonous bioaugmentation is validated at field scale, the biological outcome described in Section III-B remains an expectation grounded in smaller-scale evidence rather than a capability that can be assumed.

E. Dilution in Open Water

The chemical pathway carries a limitation of a different kind. The hatchery evidence that supports it comes from water held inside an intake pipe, where a dose can be mixed into a bounded volume and monitored as it passes [6]. A confined but open water body, a lagoon, an enclosed harbor, or a source bay behind a hatchery intake, is not a pipe. A dose delivered into open water would be diluted and carried away by exchange with the surrounding volume, so holding a corrected saturation state across a treatment zone would be harder than holding it in a pipe, and would likely call for repeated or sustained dosing rather than a single application. This is one reason the design is restricted to confined, sheltered settings on the order of the upper tens of meters and is not proposed for open or well-flushed water, where a delivered dose would be lost before it could act. The reference point noted in Section III-A should be read with this difference in mind.

F. Endurance Bounded by the Culture Cycle

The endurance of a single deployment would be bounded by the logic of the design itself. The sample, culture, and return facility is kept aboard the support vessel rather than on the carrier, which places it where power, working space, and operator attention are available but requires the carrier to return to the vessel between culture cycles rather than treating continuously. The buffered payload is likewise finite and would be spent in the course of dosing. A deployment would therefore treat an episodic, site-scale event and then pause for resupply and a further culture cycle, a pattern suited to discrete events in high-value waters rather than to continuous or regional treatment. This bound follows from the architecture rather than from any incidental shortcoming, and it would set the practical ceiling on how much water a single deployment could address.

G. Tether Drag and Operating Radius

The tethered arrangement that supplies the probes with power, data, and payload also constrains their reach. Each probe is served by an umbilical of roughly 30 to 60 meters, and the carrier is intended to hold position close to the treatment zone so that the tethers stay short and each probe can be placed by the carrier and its umbilical rather than by any propulsion of its own. That choice keeps the probes simple, but it ties the treatment radius to where the carrier can sit, and it means that tether drag and the risk of entanglement would grow with tether length and with water movement. The area reachable around a single carrier position would be limited accordingly, and treating a larger zone would require the carrier to reposition and redeploy rather than to extend its tethers further. How drag, station-holding, and entanglement would behave in practice is left open here, and is among the first characteristics a prototype would need to establish.

H. What Remains to Be Tested

Every outcome above is inferred from the architecture set out in Section II and from the prior work cited in Section I rather than measured, and the one external reference point available, the hatchery survival comparison [8], describes intake buffering in a pipe rather than any operation of the proposed system. Establishing whether TENDER would perform as intended would require a staged program: calibration of the sensing suite against reference carbonate measurements; tank testing of tether handling, station-holding, and metered delivery; a controlled trial of the cultivation loop at mesocosm scale; and, only after those, a supervised deployment at a confined site with the monitoring node reporting on recovery. That sequence is the natural continuation of the work presented here, and each stage would test a specific claim made in this section rather than the concept as a whole.

IV. ENVIRONMENTAL SAFETY AND GOVERNANCE

A system that would place matter into coastal water, and return cultured organisms to the site they were drawn from, operates inside an existing body of international law and guidance. That body is not a constraint applied to the concept after the fact; it shaped several of the choices described in Section II, most directly the decision to work with organisms native to the treated site. This section states what the relevant instruments do and do not cover, and then the posture the design adopts in response.

A. Why Engineered Organisms Were Ruled Out

A system intended to support the breakdown of an organic load could in principle carry organisms engineered for that purpose. TENDER does not, for regulatory as much as biological reasons.

The Cartagena Protocol on Biosafety, adopted in 2000 under the Convention on Biological Diversity, is the principal international instrument addressing organisms that carry a novel combination of genetic material obtained through modern biotechnology, which it terms living modified organisms [22]. Its reach is specific. It governs the transboundary movement, transit, handling, and use of such organisms, establishes an advance informed agreement procedure before a first movement intended for introduction into the environment of an importing party, and frames its objective in accordance with the precautionary approach set out in Principle 15 of the Rio Declaration on Environment and Development [22]. It is a procedural framework rather than a prohibition, and it leaves purely domestic development and use to national law [22].

What the Protocol establishes is therefore a precautionary norm, and that norm, together with the domestic biosafety regulation through which states govern release into the open environment, is what made the engineered route unattractive here. A system of this kind would release its biological payload into water it does not enclose, at a site it does not own, and could not recover what it released. Meeting a precautionary standard for such a release would require characterizing the behavior of a built organism in a receiving environment that is open, variable, and shared, which is a research program in itself rather than a design detail. The design avoids the question instead of arguing it: the biological payload consists of the limiting nutrients and, where the cultivation loop is used, consortia sampled from the treated site, cultured aboard the support vessel, and returned to that same site. Nothing is engineered and nothing is brought in from elsewhere, which keeps whatever enters the water within the genetic complement the site already holds.

B. The London Convention and the 1996 Protocol

Deliberate placement of matter into the sea is governed by the London Convention and its 1996 Protocol, which together form the principal international framework addressing marine geoengineering [20]. The Protocol defines marine geoengineering as deliberate intervention in the marine environment to manipulate natural processes, including intervention directed at counteracting anthropogenic climate change or its impacts, where that intervention has the potential to produce deleterious effects [20].

One point of detail matters for a proposal that would dose alkalinity. An amendment adopted in 2013 provides for marine geoengineering activities to be listed in Annex 4 to the Protocol, and Annex 4 currently lists ocean fertilization alone [20]. Alkalinity enhancement is among the techniques prioritized for evaluation under this framework rather than one already listed within it [20], [21]. The proposal does not treat that gap as permission. The field trial of alkalinity enhancement discussed in Section I proceeded under a national permit [17], which indicates the route such work follows at present: an international framework still being settled, applied through domestic permitting. Legitimate scientific research in this area is expected to proceed transparently and under a precautionary approach [21], and that expectation, rather than the absence of a listing, is the standard this proposal takes as binding on itself.

C. Guidance Under the Convention on Biological Diversity

Decisions taken under the Convention on Biological Diversity advise against geoengineering activities that may affect biodiversity, with the exception of small-scale scientific studies conducted under controlled conditions and assessed before they begin [18]. This is advice to parties rather than a treaty obligation, but it states plainly the scale at which such work is regarded as acceptable while the evidence supporting it remains thin. It points in the same direction as the evidentiary limit described in Section III-D. Where a pathway has been established in microcosm and mesocosm studies but not at the scale of a field event [16], the appropriate first use is small, controlled, assessed beforehand, and observed afterward. The staged program outlined in Section III-H was set out for scientific reasons and describes the same sequence.

D. The Design's Governance Posture

Four features of the design follow from the instruments above, and each carries a cost that is accepted deliberately.

Operation would be confined to jurisdictional coastal waters and to the confined, semi-enclosed settings named in Section II-A rather than the high seas. Beyond the technical reasons for that scope, it places any deployment inside a single state's regulatory reach, where permitting authority, monitoring obligations, and liability are attributable. The cost is that the system would be unavailable for the larger and less governed waters where acidification is also felt.

A human operator would authorize every payload release. Its governance value is that it produces an identifiable decision, made by an identifiable person, before anything enters the water, and the proposed dose, the reading that prompted it, and the authorization together would form a record that a permitting authority could examine afterward. The cost is a system that cannot act faster than its operator.

Only organisms native to the treated site would be released, cultured from that site and returned to it, for the reasons set out in Section IV-A.

The monitoring node would remain on site after treatment and report on the local carbonate chemistry over the following period. Its scientific purpose is verification, as Section II-H describes, but it also functions as an accountability mechanism, since it records what followed a treatment rather than what was intended by it.

None of this substitutes for the regulatory review that an actual deployment would require, and the posture is not offered as evidence that such review would be satisfied. It is intended to make the proposal legible to that review: to state in advance where the system would operate, who would decide what enters the water, what may be released, and how anyone would later know what happened.

V. CONCLUSION

TENDER is a conceptual design for a tethered-probe system intended to address localized acidification events in confined coastal waters. A support vessel would carry the operator station and the cultivation facility, an underwater deployment vehicle would carry the bulk payload and the probe fleet to the affected site, and each tethered probe would sense the local water chemistry and deliver a metered dose where it is needed. The two payload lines would be selected conditionally: buffered sodium carbonate where the pH and carbonate saturation state are depressed, and the limiting nutrients with, where the cultivation loop is used, site-native cultured consortia where the microbial community clearing the organic load needs support. A monitoring node would remain in place afterward to report whether the local chemistry recovers.

The scope is narrow by choice, and the narrowness is a commitment rather than an omission. TENDER is proposed for confined, high-value, semi-enclosed water bodies inside jurisdictional coastal waters, not for the open ocean and not for the global acidification signal, which no localized device could correct. Within that scope, a human operator would authorize every release, only organisms native to the treated site would be returned to it, and the monitoring node would report what followed a treatment rather than what was intended by it. Those choices bound what the system could do and would make it answerable for what it did.

What the paper does not offer should be equally clear. Nothing has been built or tested, and no performance is claimed. Section III names the limits rather than leaving them for a reader to find: the field-scale gap beneath the biological pathway, the dilution that distinguishes open water from a hatchery pipe, the endurance bounded by the culture cycle, and the operating radius set by the tethers.

What distinguishes the proposal is the cultivation loop. Rather than bringing organisms to a damaged site, the system would culture those already living there, relieve what limits them, and return them where they are needed, while correcting the water chemistry that holds them back. That inversion, from delivering a remedy to a place toward supporting what the place already contains, is this paper's contribution. Whether it would hold at the scale of a real event is the question the next stage of the work must answer.

VI. FUTURE WORK

The staged program described in Section III-H sets the order of the work that follows. Each item below is deferred rather than claimed.

The first and most consequential is field-scale validation of the cultivation loop. Autochthonous bioaugmentation has accelerated the breakdown of an organic load in microcosm and mesocosm studies but has not been demonstrated at the scale of a field event [16], and until that gap closes it remains the least supported element of the design. Within the staged program, the controlled mesocosm trial and then the supervised deployment at a confined site are the stages where the question would be addressed, in that order and not before the earlier stages are complete. Two qualifications belong with it. A single supervised deployment would produce a first field-scale observation rather than a general validation, and establishing whether the approach holds would require repetition across sites, seasons, and load types. The question is also a scientific one that does not depend on this hardware, so progress may come from work unconnected to TENDER, which would serve the design rather than threaten it.

The platform could also be adapted to contaminant classes outside the mechanism treated here. Microplastics and toxic metals do not drive acidification and are not targets of the system described in this paper, but they occur in the same confined, high-value waters, and an architecture built around modular sensing and metered delivery could in principle serve them. Such an adaptation would be a matter of changing the stored payload and the sensing thresholds rather than redesigning the probes, and it would mean restoring sensing modalities this design deliberately omits, as Section II-E describes. That work would require its own literature and justification.

The depth and pressure envelope is a further line. The design targets shallow, sheltered settings on the order of the upper tens of meters, and the chassis, tether, and pressure housings follow from that choice. Extending the system deeper would change those components and the concept of operations with them.

The monitoring node's endurance deserves attention this paper has not given it. The node would sit on site and report over a long dwell, and biofouling of its sensing surfaces and drift in its readings are what would decide whether its record can be trusted. Since a drifting node would weaken the verification the design depends on, characterizing that drift and the servicing intervals it implies belongs in any build.

A final note closes the list. This paper offers no basis for assessing cost or economic feasibility, and none should be inferred from it. A formal cost analysis, resting on hardware that has been built and a deployment pattern that has been observed, would be required before the concept could be weighed as a practical proposition rather than a design.

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References

[1] V. J. Fabry, B. A. Seibel, R. A. Feely, and J. C. Orr, "Impacts of ocean acidification on marine fauna and ecosystem processes," *ICES Journal of Marine Science*, vol. 65, no. 3, pp. 414–432, 2008, doi: 10.1093/icesjms/fsn048.

[2] L.-Q. Jiang et al., "Global surface ocean acidification indicators from 1750 to 2100," *Journal of Advances in Modeling Earth Systems*, vol. 15, no. 3, Art. no. e2022MS003563, 2023, doi: 10.1029/2022MS003563.

[3] C. M. Duarte et al., "Is ocean acidification an open-ocean syndrome? Understanding anthropogenic impacts on seawater pH," *Estuaries and Coasts*, vol. 36, no. 2, pp. 221–236, 2013, doi: 10.1007/s12237-013-9594-3.

[4] R. A. Feely, C. L. Sabine, J. M. Hernandez-Ayon, D. Ianson, and B. Hales, "Evidence for upwelling of corrosive 'acidified' water onto the continental shelf," *Science*, vol. 320, no. 5882, pp. 1490–1492, 2008, doi: 10.1126/science.1155676.

[5] W.-J. Cai et al., "Acidification of subsurface coastal waters enhanced by eutrophication," *Nature Geoscience*, vol. 4, no. 11, pp. 766–770, 2011, doi: 10.1038/ngeo1297.

[6] A. Barton et al., "Impacts of coastal acidification on the Pacific Northwest shellfish industry and adaptation strategies implemented in response," *Oceanography*, vol. 28, no. 2, pp. 146–159, 2015, doi: 10.5670/oceanog.2015.38.

[7] G. G. Waldbusser, E. L. Brunner, B. A. Haley, B. Hales, C. J. Langdon, and F. G. Prahl, "A developmental and energetic basis linking larval oyster shell formation to acidification sensitivity," *Geophysical Research Letters*, vol. 40, no. 10, pp. 2171–2176, 2013, doi: 10.1002/grl.50449.

[8] I. Gimenez, G. G. Waldbusser, and B. Hales, "Ocean acidification stress index for shellfish (OASIS): Linking Pacific oyster larval survival and exposure to variable carbonate chemistry regimes," *Elementa: Science of the Anthropocene*, vol. 6, Art. no. 51, 2018, doi: 10.1525/elementa.306.

[9] X. Xiao et al., "Seaweed farms provide refugia from ocean acidification," *Science of the Total Environment*, vol. 776, Art. no. 145192, 2021, doi: 10.1016/j.scitotenv.2021.145192.

[10] S. L. Hamilton, M. S. Elliott, M. S. deVries, J. Adelaars, M. D. Rintoul, and M. H. Graham, "Integrated multi-trophic aquaculture mitigates the effects of ocean acidification: Seaweeds raise system pH and improve growth of juvenile abalone," *Aquaculture*, vol. 560, Art. no. 738571, 2022, doi: 10.1016/j.aquaculture.2022.738571.

[11] L. Kapsenberg and T. Cyronak, "Ocean acidification refugia in variable environments," *Global Change Biology*, vol. 25, no. 10, pp. 3201–3214, 2019, doi: 10.1111/gcb.14730.

[12] Alaska Ocean Acidification Network, "Q&A: Kelp, climate and ocean acidification," Alaska Ocean Observing System. Accessed: Jul. 23, 2026. [Online]. Available: https://aoan.aoos.org/qa-kelp-climate-and-ocean-acidification/

[13] I. M. Head, D. M. Jones, and W. F. M. Röling, "Marine microorganisms make a meal of oil," *Nature Reviews Microbiology*, vol. 4, no. 3, pp. 173–182, 2006, doi: 10.1038/nrmicro1348.

[14] T. C. Hazen et al., "Deep-sea oil plume enriches indigenous oil-degrading bacteria," *Science*, vol. 330, no. 6001, pp. 204–208, 2010, doi: 10.1126/science.1195979.

[15] R. C. Prince and R. M. Atlas, "Bioremediation of marine oil spills," in *Consequences of Microbial Interactions with Hydrocarbons, Oils, and Lipids: Biodegradation and Bioremediation*, R. Steffan, Ed. Cham, Switzerland: Springer, 2018, pp. 1–25, doi: 10.1007/978-3-319-44535-9_13-1.

[16] M. Nikolopoulou, N. Pasadakis, and N. Kalogerakis, "Evaluation of autochthonous bioaugmentation and biostimulation during microcosm-simulated oil spills," *Marine Pollution Bulletin*, vol. 72, no. 1, pp. 165–173, 2013, doi: 10.1016/j.marpolbul.2013.04.007.

[17] Woods Hole Oceanographic Institution, "Preliminary results from the first EPA-permitted ocean alkalinity enhancement (OAE) field trial," Feb. 2026. Accessed: Jul. 23, 2026. [Online]. Available: https://www.whoi.edu/press-room/news-release/oae-prelim

[18] National Academies of Sciences, Engineering, and Medicine, "Ocean alkalinity enhancement," in *A Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration*. Washington, DC, USA: The National Academies Press, 2021, doi: 10.17226/26278.

[19] T. Zhu, L. Zheng, F. Li, J. Liu, and W. Zhuang, "Sustainable carbon sequestration via olivine based ocean alkalinity enhancement in the east and South China Sea: Adhering to environmental norms for nickel and chromium," *Science of the Total Environment*, vol. 930, Art. no. 172853, 2024, doi: 10.1016/j.scitotenv.2024.172853.

[20] National Oceanic and Atmospheric Administration, "Geoengineering as a response to climate change: The London Convention and London Protocol." Accessed: Jul. 23, 2026. [Online]. Available: https://www.noaa.gov/geoengineering-as-response-to-climate-change-london-convention-and-london-protocol

[21] Y. L. B. L. Lyons, D. Santillo, and F. Catonini, "Legitimate scientific research: Objective scientific assessment of marine geoengineering activities under the London Convention and London Protocol," *The International Journal of Marine and Coastal Law*, vol. 39, no. 3, pp. 528–540, 2024, doi: 10.1163/15718085-bja10196.

[22] Secretariat of the Convention on Biological Diversity, Cartagena Protocol on Biosafety to the Convention on Biological Diversity: Text and Annexes. Montreal, QC, Canada: Secretariat of the Convention on Biological Diversity, 2000. Accessed: Jul. 23, 2026. [Online]. Available: https://www.cbd.int/doc/legal/cartagena-protocol-en.pdf