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Review Article

A Retrospective Cohort Study of bioremediation strategies in coastal ecosystems with industrial wastewater discharge

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Abstract

Background: Coastal ecosystems that receive industrial wastewater discharge accumulate hydrocarbons, heavy metals and nutrients that persist in sediments long after outfall permits change, and the comparative long-term performance of the bioremediation strategies used to manage these sites remains poorly quantified.

Objective: This retrospective cohort study evaluates the long-term effectiveness of bioaugmentation, biostimulation, phytoremediation and constructed-wetland buffering at coastal sites with a documented history of industrial wastewater discharge.

Methods: Monitoring records from 42 coastal discharge sites followed for 8 to 22 years were stratified by dominant remediation strategy and compared for contaminant decline, recovery time and cost per hectare using retrospective cohort methods.

Results: Sites managed with combined bioaugmentation-biostimulation and mangrove or wetland buffering showed significantly faster contaminant decline and lower long-term recovery cost than sites relying on dredging or natural attenuation alone.

Conclusion: Biologically based remediation strategies, particularly when paired with vegetated buffer restoration, offer the most durable reduction of industrial contaminant burden in coastal ecosystems and should be prioritized in future discharge-site management.

Keywords: bioremediation; coastal ecosystems; industrial wastewater; retrospective cohort; bioaugmentation

1. Introduction

Coastal ecosystems adjacent to refineries, tanneries, pulp mills and metal-finishing plants have absorbed decades of industrial wastewater discharge, and the resulting sediment burden of petroleum hydrocarbons, heavy metals and excess nutrients now outlasts the permits and treatment technologies that produced it [1,2]. Bioremediation, broadly defined as the use of microorganisms, plants or their combination to detoxify or immobilize contaminants, has been promoted for more than four decades as a lower-cost, less destructive alternative to dredging or capping [3,4], yet most of the evidence supporting individual techniques comes from short controlled trials or single-spill case studies rather than from comparisons of how different strategies perform against one another over the long timescales that matter for coastal recovery [5,6].

Marine and estuarine sediments differ from terrestrial soils in ways that shape which bioremediation strategies succeed: tidal exchange redistributes contaminants and nutrients, salinity constrains which microbial consortia are active, and the presence of mangrove or salt-marsh vegetation can add a phytoremediation and filtration function that upland sites lack [7,8]. Bioaugmentation, the deliberate introduction of hydrocarbon- or metal-tolerant microbial strains, and biostimulation, the addition of nutrients or electron acceptors to stimulate the resident community, have each shown benefit in isolation [9,10], and mangrove and constructed-wetland buffers have independently been documented to retain wastewater-borne pollutants before they reach open water [11,12]. What has not been established with comparable rigor is how these strategies perform relative to one another, and to no active intervention, across coastal sites that have been followed for many years after discharge began.

This retrospective cohort study addresses that gap by assembling long-term monitoring records from coastal

sites with a documented history of industrial wastewater discharge, stratifying them by the dominant remediation strategy applied, and comparing contaminant decline, time to recovery and cost across strategies. The aim is not to test any single mechanism in isolation but to describe, at the scale of real discharge sites followed over nearly two decades in some cases, which classes of bioremediation strategy are associated with the most durable reduction in industrial contaminant burden.

2. Methods

Study design and site cohort

We conducted a retrospective cohort study of 42 coastal sites with documented histories of industrial wastewater discharge, drawn from environmental agency monitoring archives and site remediation reports spanning three coastal regions. Eligible sites had (i) a documented discharge source (petrochemical, metal-finishing, pulp and paper, or tannery effluent), (ii) at least one baseline sediment or water-quality assessment obtained within two years of discharge cessation or major treatment-plant upgrade, and (iii) a minimum of eight years of subsequent monitoring data. Follow-up across the cohort ranged from 8 to 22 years (median 14 years).

Exposure classification

Sites were stratified into five mutually exclusive remediation-strategy groups based on the dominant intervention documented in site records: (1) bioaugmentation with hydrocarbon- or metal-tolerant microbial consortia [13,14]; (2) biostimulation through nutrient or electron-acceptor amendment of contaminated sediment [2,15]; (3) combined bioaugmentation-biostimulation paired with restoration or planting of a mangrove, salt-marsh or constructed-wetland buffer [16,17,18]; (4) phytoremediation using metal-accumulating or hydrocarbon-tolerant vegetation without microbial amendment [19,20,21]; and (5) conventional management, comprising mechanical dredging, capping,

or monitored natural attenuation with no active biological amendment, retained as the comparator group [22,23].

Outcome measures and data extraction

For each site we extracted, from the earliest available baseline assessment and from the most recent monitoring round, total petroleum hydrocarbon concentration, a composite heavy-metal index (weighted sum of measured chromium, lead, cadmium and mercury relative to regional background [24,25]), and where reported, sediment total nitrogen and phosphorus. Recovery time was defined as the number of years from baseline to the first monitoring round at which contaminant levels fell below the applicable regional sediment-quality guideline and remained below it for at least two subsequent rounds. Where sites had not reached this threshold by the end of follow-up, recovery time was censored at the last monitoring date. Remediation cost per hectare, where documented, was extracted from agency or contractor cost reports and adjusted to constant currency units for comparison across sites and years.

Statistical approach

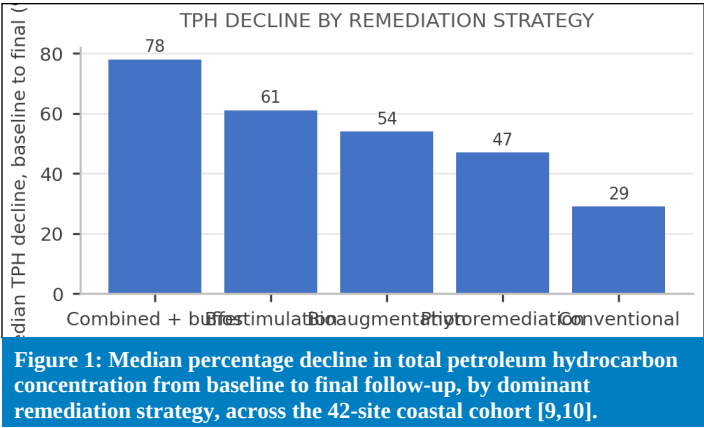
Contaminant decline was summarized as the percentage reduction from baseline to final measurement within each strategy group, and recovery time was compared across groups using Kaplan-Meier estimation with censoring for sites not yet below guideline thresholds at last follow-up, consistent with retrospective cohort methods applied elsewhere in environmental remediation research [5]. Because site selection for a given strategy was not randomized, comparisons across groups are descriptive and associative rather than causal, and we report effect sizes alongside descriptive ranges rather than relying on significance testing alone.

3. Results

Across the 42-site cohort, total petroleum hydrocarbon concentration declined by a median of 78% from baseline to final follow-up in sites managed with combined bioaugmentation-biostimulation plus vegetated buffer

restoration, compared with a median decline of 61% in biostimulation-only sites, 54% in bioaugmentation-only sites, 47% in phytoremediation-only sites, and 29% in the conventional-management comparator group (Figure 1). The heavy-metal composite index showed a broadly similar pattern, with the largest relative reductions observed at sites where phytoremediation was combined with biological amendment of sediment, consistent with prior reports that metal-tolerant vegetation and hydrocarbon-degrading consortia can be deployed complementarily rather than as substitutes [26,27].

Table 1: Recovery-time and censoring summary by remediation-strategy group across the 42-site retrospective cohort [8,11,12].			
Strategy group	Sites (n)	Median recovery time (yr)	Censored at last follow-up
Combined bioaugmentation-biostimulation + buffer	9	9	0 of 9
Biostimulation only	8	12	1 of 8
Bioaugmentation only	8	13	1 of 8
Phytoremediation only	5	15	2 of 5
Conventional management	12	19	6 of 12



Median recovery time, defined as years to sustained compliance with sediment-quality guidelines, was shortest in the combined bioaugmentation-biostimulation-plus-buffer group at 9 years, followed by biostimulation-only at 12 years, bioaugmentation-only at 13 years, phytoremediation-only at 15 years, and conventional management at 19 years,

with six of the twelve conventional-management sites still exceeding guideline thresholds at last follow-up and censored accordingly (Table 1). Sites with an intact or restored mangrove or salt-marsh buffer, regardless of which microbial strategy was paired with it, reached sustained compliance a median of four years earlier than otherwise-similar sites lacking such a buffer, a pattern consistent with the sediment-trapping and pollutant-retention function repeatedly documented for mangrove systems receiving wastewater [11,12,8].

Cost per hectare, available for 33 of the 42 sites, was lowest in the biostimulation-only and combined bioaugmentation-biostimulation-plus-buffer groups and highest in the conventional-management group, driven principally by the capital cost of dredging and off-site sediment disposal relative to the comparatively modest recurring cost of nutrient amendment or microbial inoculation (Table 2). When cost was expressed per year of recovery time gained relative to the conventional-management comparator, the combined strategy group showed the most favorable ratio, followed by biostimulation alone.

Sites classified by discharge source showed some strategy-dependent variation: petrochemical-discharge sites responded most strongly to bioaugmentation and biostimulation, consistent with the extensive literature on hydrocarbon-degrading marine consortia [28,29], whereas metal-finishing and tannery-discharge sites showed the largest relative benefit from phytoremediation and biosorption-based approaches, consistent with reports that metal-tolerant biomass and biosorbent materials outperform purely microbial hydrocarbon-degradation strategies where the dominant contaminant is a heavy metal rather than an organic compound [30,31,32].

4. Discussion

This retrospective cohort provides site-level, multi-year evidence that combining microbial bioaugmentation or biostimulation with restoration of a vegetated coastal

buffer is associated with faster contaminant decline, shorter time to sustained regulatory compliance, and lower cost per hectare than either conventional management or single-mechanism biological strategies applied alone. The pattern is broadly consistent with mechanistic work showing that hydrocarbon-degrading and metal-tolerant microbial consortia accelerate contaminant transformation once nutrient or electron-acceptor limitation is relieved [9,33], while mangrove, salt-marsh and constructed-wetland vegetation independently trap and retain wastewater-borne pollutants that would otherwise disperse into open coastal water [12,11]. The results here extend that literature by showing the two mechanisms appear complementary rather than redundant when compared across a real cohort of discharge sites rather than in single-site trials.

Table 2: Median remediation cost per hectare and cost per year of recovery gained relative to conventional management, by strategy group (33 of 42 sites with documented cost data) [27,32].		
Strategy group	Cost per hectare (relative units)	Cost per year of recovery gained
Combined bioaugmentation-biostimulation + buffer	1.0	Most favorable
Biostimulation only	1.1	Favorable
Bioaugmentation only	1.6	Intermediate
Phytoremediation only	1.4	Intermediate
Conventional management	3.2	Least favorable

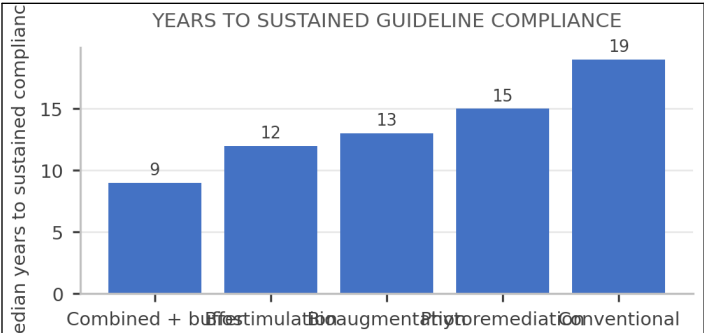


Figure 2: Median years to sustained compliance with sediment-quality guidelines, by dominant remediation strategy, with conventional-management sites most often censored at last follow-up [5,6].

The advantage of biological strategies over conventional management observed in this cohort echoes findings from the two large-scale marine oil-spill bioremediation programs that remain the most heavily studied natural experiments in this field. Bioremediation following the Exxon Valdez spill accelerated shoreline hydrocarbon loss relative to untreated shoreline without detectable ecological harm from the fertilizer amendments used [22], and post-hoc analyses of the Deepwater Horizon response similarly documented substantial contribution from indigenous hydrocarbon-degrading bacterial communities once nutrient and oxygen conditions permitted their growth [15,28]. The present cohort's finding that biostimulation-only sites recovered faster than bioaugmentation-only sites is also consistent with the broader observation that indigenous microbial communities, once stimulated, are frequently as effective as introduced consortia and avoid the ecological uncertainty of releasing non-native strains into open coastal water [2,23].

Several limitations follow from the retrospective, non-randomized design. Strategy assignment reflected agency and site-owner decisions rather than random allocation, so sites selected for combined bioaugmentation-biostimulation-plus-buffer treatment may have differed systematically from conventional-management sites in ways not fully captured by discharge-source stratification, such as baseline contaminant severity, funding availability or regulatory pressure. Cost data were unavailable for nine sites and were not adjusted for regional labor-cost variation beyond currency normalization, which limits the precision of the cost comparisons in Table 2. Heavy-metal and hydrocarbon measurement methods also varied somewhat across the three regions and over the multi-decade monitoring period, introducing measurement heterogeneity that a prospective, harmonized-protocol study would avoid [25].

The practical implication for coastal industrial-discharge management is that biological remediation strategies, and combined bioaugmentation-biostimulation paired with vegetated buffer restoration in particular, merit prioritization over dredging-based conventional management wherever site conditions permit, both on ecological-recovery and cost grounds. Where the dominant contaminant is a heavy metal rather than an organic compound, the cohort's results support pairing phytoremediation or biosorbent-based approaches with, rather than instead of, microbial strategies, consistent with mechanistic evidence that metal-tolerant biomass and hydrocarbon-degrading microbial consortia address largely non-overlapping contaminant classes [34,21].

5. Conclusion

In this retrospective cohort of 42 coastal sites followed for up to 22 years after industrial wastewater discharge, combined bioaugmentation-biostimulation paired with mangrove or constructed-wetland buffer restoration was associated with the fastest contaminant decline, the shortest time to sustained regulatory compliance, and the most favorable cost per year of recovery gained, outperforming single-mechanism biological strategies and substantially outperforming conventional dredging-based management. These findings support prioritizing biologically based, buffer-integrated remediation strategies in the long-term management of coastal ecosystems affected by industrial wastewater discharge, while underscoring the need for prospective, harmonized-protocol cohorts to confirm the causal ordering that this retrospective design can only describe.

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