Environmental Science & Technology
pubs.acs.org/est
Critical Review

Sedimentary Rocks as Analogues of Coastal Pollution and Sustainable Solutions Building Future Resilience

Liwei Wang, Zhengtao Shen, Michael S. Bank, Satoru Kawasaki, Wei-Min Wu, Daniel S. Alessi, and Kefu Yu*

Cite This: *Environ. Sci. Technol.* 2026, 60, 4470−4486

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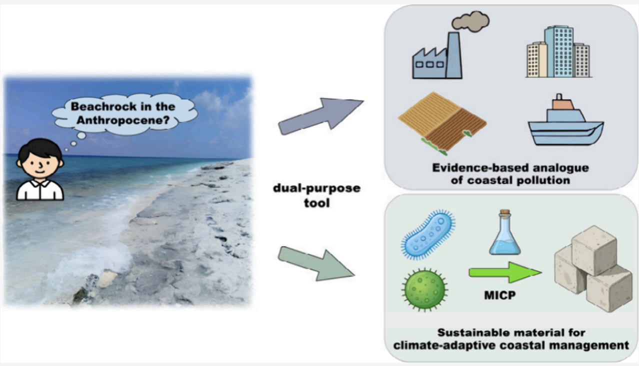
ABSTRACT: Coastal marine ecosystems occur at the land−sea interface and are under severe threat from pollution, species loss, and climate change. Beachrock, a coastal sedimentary rock formed through rapid carbonate cementation, develops in the intertidal zone where land−sea interactions are highly dynamic. In this review, we propose that beachrock not only serves as a potential Anthropocene record of coastal pollution but may also function as a Nature-based Solution (NbS) by building coastal ecosystem resilience. First, elevated concentrations of metal(loid)s in intertidal beachrock were identified, and underlying mechanisms were further assessed. Second, the potential use of beachrock in environmental forensics was examined by analyzing diagnostic compositions of typical organic pollutants. Furthermore, novel plastic forms were discovered when plastic lithifies with beachrock, creating an evidence-based marker of the Anthropocene and signifying the incorporation of synthetic materials into Earth's geological record. Finally, we propose that beachrock formation can be artificially induced through microbially induced carbonate precipitation, offering a restorative alternative to traditional cementitious materials, supporting coastal engineering innovation-based solutions that provide multiple benefits. By integrating perspectives from environmental science, climate science, materials science, earth science, and microbiology, we highlight beachrock's potential regarding innovative applications including coastal pollution monitoring, climate adaptation, and sustainable material development.



KEYWORDS: *Anthropocene, Carbonate precipitation, Coastal pollution, Nature-based Solutions, Climate change*

1. INTRODUCTION

Coastal environments are among the most dynamic and ecologically significant regions on Earth, supporting approximately 40% of the world's population and hosting >1 million marine and terrestrial species.[1] Coastal ecosystems occur at the complex interface between land and sea, sustaining biodiversity, providing key ecosystem services, and supporting major economic activities such as fisheries, tourism, and trade.[2−4] However, rapid socio-economic expansion, globalization, and climate change have significantly degraded coastal ecosystems worldwide.[5−7] Rising sea levels, increasing pollution loads, extreme precipitation events, and habitat loss are major threats that challenge the resilience of coastal environments, necessitating urgent scientific and engineering interventions.[8−11]

In coastal environments, the intertidal zone plays a key role in mediating land−sea interactions.[12,13] This zone, which is periodically submerged and exposed due to tidal fluctuations, serves as a hotspot of physical, chemical, and biological exchange.[14−16] Coastal ecosystems are one of the most vulnerable habitats and are susceptible to anthropogenic stressors such as urbanization, industrial discharge, climate change dynamics, exposure to pollutants, and global environmental change.[17−19] Understanding the processes affecting sediment dynamics, biogeochemical cycling, and natural cementation within the intertidal zone is essential for both environmental monitoring and coastal resilience-building strategies.[20−22]

A notable feature of land−sea interactions in the intertidal zone is the formation of beachrock, a sedimentary rock that develops through rapid carbonate cementation of beach sediments.[23,24] The rapid transformation of sandy beaches into consolidated beachrock due to land−sea interactions is a relatively common phenomenon, particularly in tropical and subtropical coastal areas with relatively high population

Received: November 10, 2025
Revised: December 26, 2025
Accepted: December 30, 2025
Published: January 5, 2026

https://doi.org/10.1021/acs.est.5c16109

Figure 1. Beachrocks in natural coastal environments. (a) Beachrock outcrop on the Weizhou Island, China's youngest volcanic island (Credit: Kefu Yu). (b) Submerged beachrock off northwest coast of the Bahamian island of Bimini, composed of large, oblong, pillow-shape blocks (the Bimini Road). Reproduced with permission from ref 39. Copyright 2009 International Association of Sedimentologists. (c) Partially cemented beachrock buried beneath unconsolidated sand on a South African Beach. Reproduced with permission from ref 34. Copyright 2018 Elsevier. (d) Beachrock affected by a massive oil spill on the Northeastern Brazilian coast. Reproduced with permission from ref 44. Copyright 2021 Elsevier. (e) Beachrock with plastic lithification on Trindade Island. Reproduced with permission from ref 29. Copyright 2022 Elsevier.

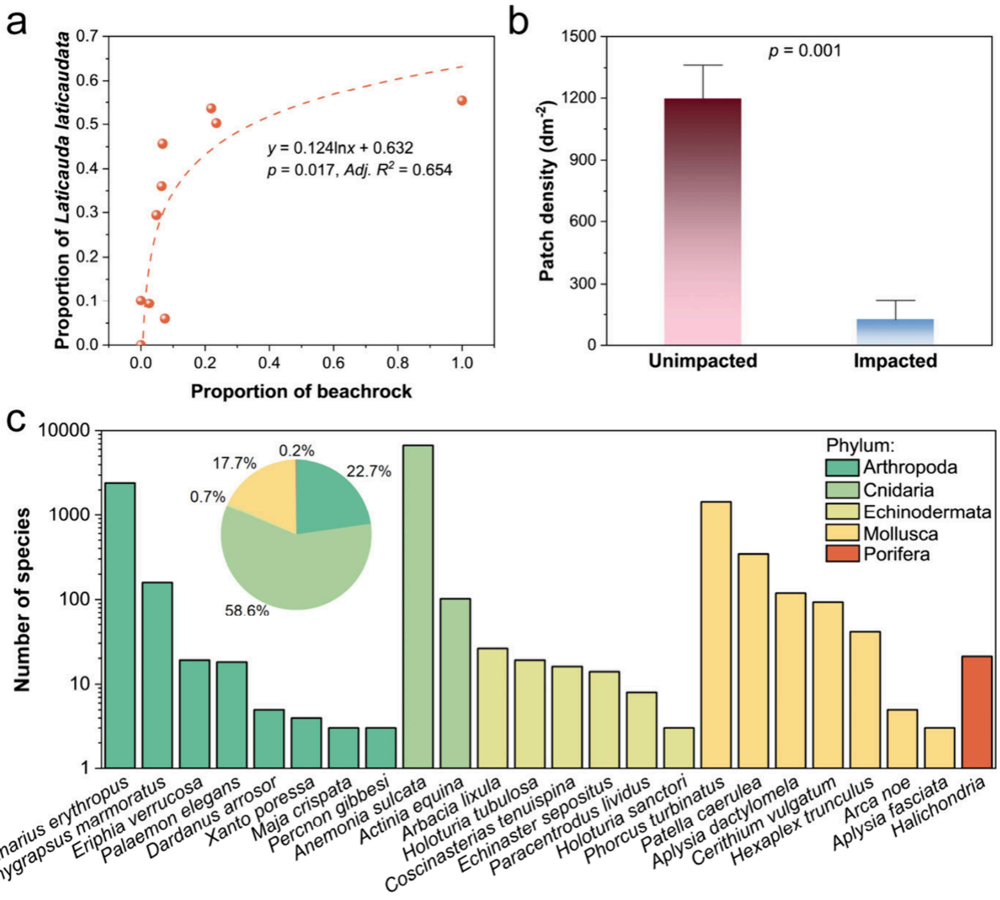


Figure 2. Beachrock as a key habitat for coastal biota. (a) Relationship between proportion of beachrock and proportion of amphibious sea snake *Laticauda laticaudata*. Data retrieved from Bonnet et al.[41] (b) Comparison of patch density of barnacle *Chthamalus bisinuatus* on beachrock, either impacted or unimpacted by a massive oil spill. Data retrieved from Gusmao et al.[44] (c) Beachrock megafauna at Strait of Messina, Italy. Data retrieved from Savoca et al.[42]

densities compared to temperate regions.[25−27] Since its first documentation in the early 19th century, beachrock has attracted interest from several scientific disciplines, and particularly in geology, environmental sciences, and coastal engineering.[22,25,28,29]

The diagenesis and global occurrence of beachrock, as well as its use as a paleoclimate indicator of sea-level change, have been well documented and reviewed in the context of sedimentary geology for >20 years.[25,27,30,31] Given that beachrock forms in the intertidal zone, the location of

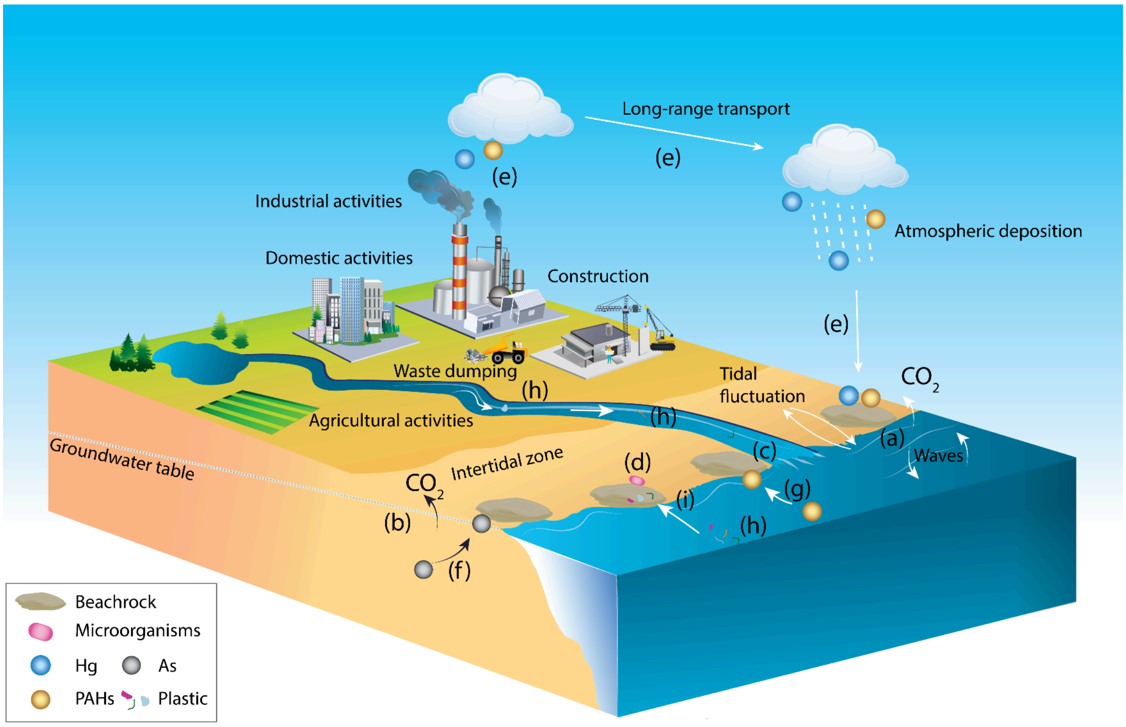


Figure 3. Beachrock diagenesis under land−sea interactions and human impacts. (a) Direct precipitation from marine water under wet−dry cycling events within the intertidal zone on beach sedimentary material. Seawater evaporation, enhanced by tidal fluctuations and waves, further promotes beachrock formation. (b) Direct precipitation from meteoric water. CO_2 degassing from carbonate saturated groundwater induced by tidal oscillation of the groundwater table promotes beachrock formation. (c) Mixing of marine and meteoric waters induces carbonate precipitation and beachrock formation, as the solubility of carbonate decreases with salinity. (d) Biological activities, such as microbially induced carbonate precipitation, also contribute to beachrock formation. (e) Anthropogenic activities lead to the emission of contaminants, such as mercury (Hg) and polycyclic aromatic hydrocarbons (PAHs), which can travel long distances in the atmosphere and eventually deposit with carbonates. (f) Geogenic enrichment can also be a cause of metal(loid) accumulation in beachrock. (g) Beachrock in the intertidal zone also serves as a marker of marine oil spills. (h) Plastic wastes and microplastics (MPs) are generated through various agricultural, industrial, and domestic activities and transported from land to ocean, making the coastal environment a hotspot for plastics and MPs. (i) Plastic waste in the intertidal zone can irreversibly bind with beachrock, serving as an Anthropocene marker of how synthetic products enter the Earth's geological record.

beachrock, combined with appropriate dating techniques, can be used to infer historical sea levels.[31,32] However, several emerging aspects of beachrock research in environmental science and engineering remain largely unexplored, including: (1) its interaction with contaminants, which may provide insights into Anthropocene pollution records, and (2) its potential as a naturally cementing material for environmental engineering applications. In this review, we highlight these emerging research directions and discuss their implications. Focusing on coastal zone pollution monitoring, we explore the potential role of intertidal beachrock as an indicator of various types of pollution and as a possible indicator of the Anthropocene. Additionally, we examine how beachrock may function in pollution remediation, and how its natural carbonate precipitation process could contribute to the development of sustainable materials with enhanced durability, offering a Nature-based Solution (NbS) to build coastal resilience.

2. BEACHROCK AND LAND−SEA INTERACTIONS: AN OVERVIEW

On a global scale, key regions of beachrock formation include the atolls of the Pacific and Indian Oceans, the Mediterranean and Caribbean Seas, and the low-latitude Atlantic coasts.[13,25−27] Beachrocks are widely distributed and occurrences are generally found (>90%) at latitudes <40°, with a few exceptions in temperate coastal regions at much higher latitudes.[27] This distribution can be partly explained by the increase in $CaCO_3$ saturation from polar regions toward the Equator due to increased temperatures.[33] Additionally, microtidal coasts with relatively small tidal ranges are particularly favorable for beachrock formation.[34,35] Beachrock occurrence is often associated with coral reef areas, especially along tropical and subtropical coasts, because these environments provide the necessary combination of carbonate-rich sediments, relatively high temperature, as well as intertidal conditions that promotes cementation.[27,36,37] Most dated beachrocks formed between 1,000 and 5,000 years ago, making them relatively recent and rapidly formed in the context of sedimentary rock diagenesis.[25,38] However, actively developing beachrocks have also been documented in certain coastal environments.[34] Beachrock formations typically occur parallel to the shoreline, dipping seaward at a gentle slope, generally less than 10°.[13,27] Their thickness varies, ranging from a few centimeters to approximately 5 m.[13,27]

Beachrocks often exhibit a layered morphology (Figure 1). Although initially formed in the intertidal zone, beachrock outcrops may either be exposed or submerged due to sea-level changes, and they can appear continuous or fragmented due to weathering. An example of exposed beachrock was observed in our field survey on Weizhou Island, China's youngest volcanic island, where Holocene beachrocks formed during a period of

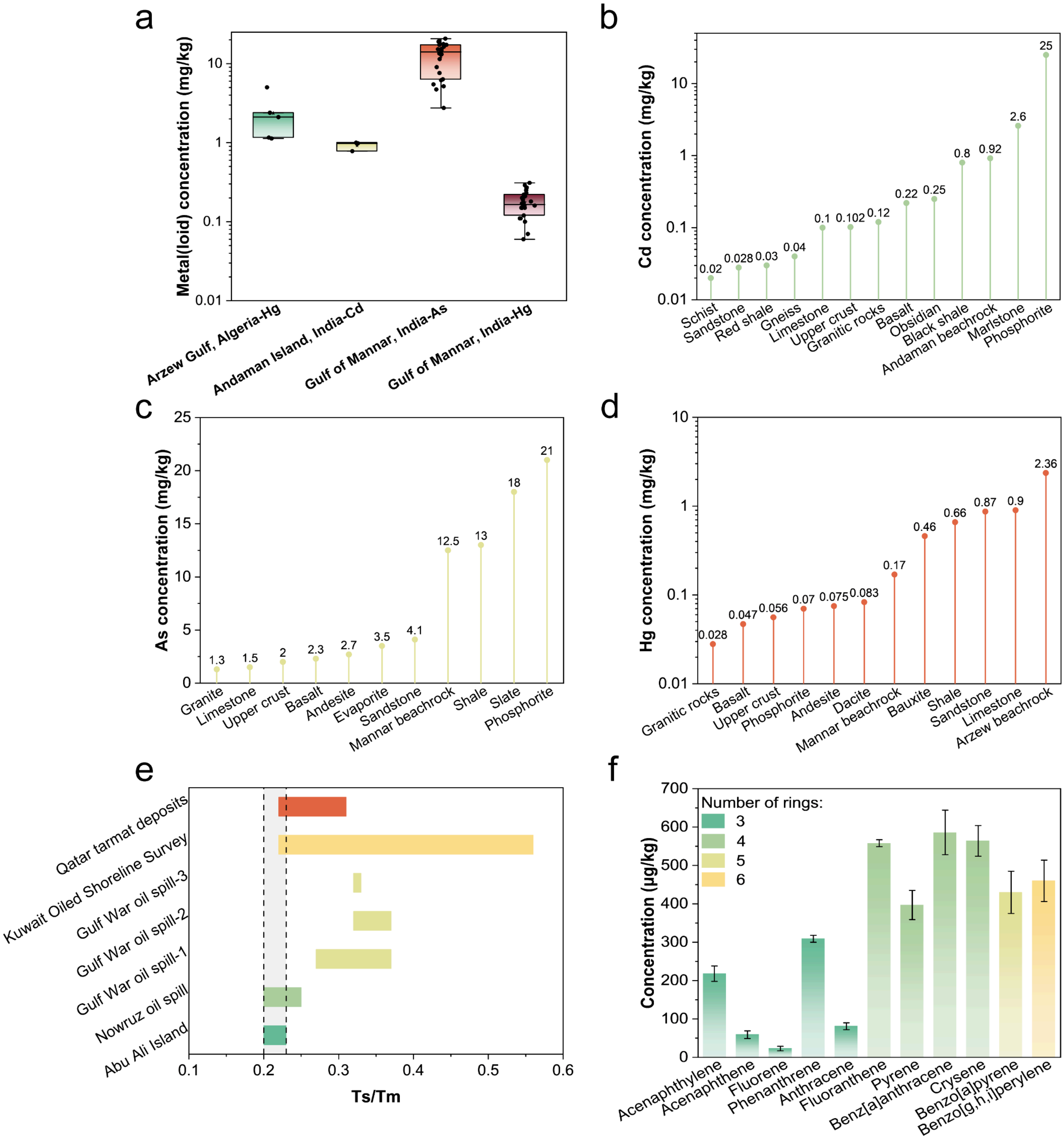


Figure 4. Beachrock metal(loid)s and organic pollution. (a) Boxplot of literature reported ranges of metal(loid) concentrations in beachrocks. Data sources:[43,101,102] (b−d) Comparison of beachrock metal(loid) concentrations with average values of other rock types and the upper continental crust. Average concentration data of Cd in other rock types were retrieved from Kubier et al.;[56] average concentration data of As in other rock types were retrieved from Masuda[103] and Reimann et al.;[104] average concentration data of Hg in other rock types were retrieved from USGS;[105] average Cd, As, and Hg concentration data in the upper continental crust are from Wedepohl.[106] (e) Tracing beachrock oil spill pollution using diagnostic Ts/Tm ratio in Abu Ali Island, Saudi Arabia. Data retrieved from Michel et al.[107] (f) Concentration of typical PAHs in beachrock in Bay of Biscay, Northern Spain. Data retrieved from Blanco-Zubiaguirre et al.[108]. All concentration data are reported on a dry weight basis.

higher sea levels (Figure 1a). In contrast, submerged beachrock formations, such as the "Bimini Road" off Bimini Island in the Bahamas, lie at a depth of 7 m below sea level[39] (Figure 1b). These fragmented, rectangular-shaped beachrocks likely formed during intermittent beach accretion, subsequently cracked due to wet−dry cycling, and were eventually buried by rising sea levels in the early Holocene.[39] Additionally, actively forming beachrock (<5 years) has been observed in the intertidal zone of a microtidal beach in South Africa[34] (Figure 1c). Although rare, beachrocks have also been reported in freshwater environments, such as along the shores of a freshwater lake in Turkey.[40]

Beachrocks play a foundational ecological role in intertidal, coastal ecosystems, serving as a key habitat for various marine organisms (Figure 2).[41,42] For example, the proportion of the amphibious sea snake *Laticauda laticaudata* in a well-preserved reef ecosystem exhibited a logarithmic positive relationship with proportion of beachrock, likely because these rock formations provided good shelter habitats (Figure 2a).[41] In the Strait of Messina, Italy, beachrock habitats have been associated with high megafaunal diversity, which contributes to ecosystem resilience and stability (Figure 2c).[42]

Despite their ecological importance, beachrock intertidal ecosystems are vulnerable to anthropogenic pollution. Beachrock containing elevated metal(loid) concentrations, oil contamination from spills, and lithified plastic debris have all been reported in recent studies. For example, dark-colored beachrock with elevated cadmium (Cd) concentrations has been documented along the coast of Andaman Island, India.[43] Beachrock contaminated with oil following a large spill was reported along the northeastern Brazilian coast, where oil pollution also led to a significant decline in the patch density of the barnacle *Chthamalus bisinuatus*[44] (Figure 1d, Figure 2b). More recently, lithified plastic debris has been observed forming novel plastic-rock complexes on the remote Trindade Island in Brazil[29] (Figure 1e). Investigating the role of beachrock in trapping and interacting with contaminants provides valuable insights into coastal contamination processes, unexplored bioaccumulation regimes and pathways, and potential strategies for pollution mitigation. A more detailed discussion on beachrock interactions with contaminants is provided in the following sections.

Understanding the diagenesis and mineralogical composition of beachrock is essential for evaluating its interactions with contaminants. Lithification occurs in the intertidal zone, where sediments of both clastic and biogenic origin undergo cementation.[25,27] The primary cementing agents in beachrock are carbonate minerals, including high-magnesian calcite (>4% mole percent $MgCO_3$) and aragonite, with occasional occurrences of low-magnesian calcite in cases where carbonate precipitation is influenced by meteoric waters with low Mg/Ca ratios.[25,26] Quantitative analyses by Danjo and Kawasaki[27] indicate that beachrock typically contains > 90% $CaCO_3$. However, in some cases, silica or iron has been found to serve as the main cementing agent.[28,45]

Beachrocks are formed either through chemical or biological processes (or both)[25,26] (Figure 3). First, direct precipitation of carbonate from marine water occurs in the intertidal zone due to the repeated wet−dry cycling of the beach surface and CO_2 degassing (Figure 3a). Notably, marine water is supersaturated with both calcite and aragonite, which is crucial for precipitation to occur.[46] Sediments on beach, including calcareous and siliceous sands, gravels, and bioclasts such as coral and foraminifera fragments, serve as nucleation sites for cementation.[25,26] Daytime warming further enhances precipitation by reducing carbonate solubility.[47] Second, direct precipitation also occurs from meteoric water, such as groundwater in coastal environments (Figure 3b). Tidal oscillations in the groundwater table and the pumping of soil gas in the vadose zone lead to CO_2 degassing from groundwater as it flows toward the sea,[48−50] further facilitating beachrock cementation. In areas with calcium (Ca)-rich groundwater, such as karst regions, this process may play a crucial role in beachrock formation.[51,52] Additionally, frequent mixing of seawater and freshwater in estuarine environments may promote carbonate precipitation due to the decrease in carbonate solubility with increasing salinity (Figure 3c).[26,53] Finally, there is also a possibility that biological activity, in particular, microbially induced carbonate precipitation (MICP), can contribute to beachrock formation[22,37,54] (Figure 3d).

Building on the core concept that beachrock forms in the intertidal zone, beachrocks have been widely used as paleoclimate indicators to decode past climate dynamics. Coupled with dating approaches and mineralogical analyses, beachrock outcrops are located at places where historical sea levels lie.[30,32,55] For instance, in a typical scenario where beachrock mineralogy is characterized by irregularly distributed aragonite needles or fibers and high-magnesium calcite micrite without bedding structures, the location where loose sand becomes locked into place as beachrock serves as an indicator of the mixing zone interface between the mean low water (MLW) and mean high water (MHW) levels.[31] Numerous studies have successfully used beachrock as a sea-level indicator, as detailed in the review by Mauz et al.[31] Despite extensive research in the field of geology, beachrock remains relatively underexplored in environmental science and engineering. The following sections critically examine its interactions with various contaminants and its potential applications as a sustainable material in environmental engineering.

3. LOOKING BACK: BEACHROCK AS ANALOGUES OF COASTAL POLLUTION

As a dynamic interface between land and sea, the intertidal zone is one of the most active regions for material exchange, pollutant accumulation, and mineral precipitation. Beachrock, formed through rapid carbonate cementation of coastal sediments, can incorporate both natural and anthropogenic materials during diagenesis, thus serving as a record of environmental pollution. Recent studies have shown that beachrock can host a range of contaminants including metal(loid)s, hydrocarbons, and plastic debris. The following subsections review current knowledge on the mechanisms and environmental implications of pollutant incorporation in beachrock.

3.1. Record of Metal(loid) Deposition and Intercalation

Metal(loid) concentrations have been reported in several beachrock formations, including those in Arzew Gulf, Andaman Island, and the Gulf of Mannar, all of which have elevated concentrations compared to the upper continental crust, and the most common rock types (Figure 4). For example, the average Cd concentration was 0.92 mg/kg on Andaman Island (Figure 4a, Figure 4b), far exceeding the average value of the upper crust (0.102 mg/kg), and concentrations found in various rock types, including black shale (0.8 mg/kg), basalt (0.22 mg/kg), limestone (0.10 mg/kg), and sandstone (0.028 mg/kg) (Figure 4b). Cd concentration in beachrock was surpassed only by marlstone (2.6 mg/kg) and phosphorite (25 mg/kg) (Figure 4b). Notably, Cd concentrations in beachrock exceeded those found in some rock types known for their geogenic enrichment of this element, such as basalt and black shale.[56,57] Similarly, the average arsenic (As) concentration in beachrock from the Gulf of Mannar was 12.5 mg/kg, exceeding the upper crust average (2.0 mg/kg) and concentrations found in sandstone (4.1 mg/kg), evaporite (3.5 mg/kg), basalt (2.3 mg/kg), and limestone (1.5 mg/kg) (Figure 4c). As concentrations in beachrock were lower than shale (13 mg/kg), slate (18 mg/kg) and phosphorite (21 mg/kg). Elevated mercury (Hg) concentrations have also been reported in Arzew Gulf (2.36 mg/kg) and Gulf of Mannar (0.17 mg/kg), both exceeding the average value of the upper crust (0.056 mg/kg) as well as concentrations found in andesite (0.075 mg/kg), phosphorite (0.07 mg/kg), and basalt (0.047 mg/kg) (Figure 4d). It is noteworthy that beachrock in Arzew Gulf showed the highest reported average Hg concentration among all common rock types, with concentrations exceeding those in limestone (0.9 mg/kg), sandstone (0.87 mg/kg), shale (0.66 mg/kg), and bauxite (0.46 mg/kg) (Figure 4d).

Sedimentary rocks such as phosphorite, black shale, marlstone, and limestone, as well as fine-grained igneous rocks like basalt, are known to exhibit naturally elevated metal(loid) concentrations.[56−60] These rocks are enriched with clay minerals (e.g., black shale, marlstone, and basalt), organic matter (e.g., black shale), pyrite (e.g., black shale), phosphate (e.g., phosphorite), or calcite (e.g., limestone), to which metal(loid)s are preferentially bound.[57,61−64] In addition, sedimentary rocks act as sinks for metals in the environment, where metals accumulate through precipitation and adsorption mechanisms, further contributing to geogenic enrichment.[56−58] In this study, beachrock samples had elevated concentrations of Cd, As, and Hg. Since beachrocks are mainly calcareous, we further investigated the correlation between $CaCO_3$ content and metal(loid) concentrations (Figure S1). A positive correlation was observed, suggesting that higher $CaCO_3$ content may contribute to increased metal(loid) accumulation in beachrock (Figure S1). The substitution of Ca by Cd in carbonate minerals is a well-documented mechanism for geogenic Cd enrichment.[65,66] Similarly, the incorporation of As into the crystal lattice of aragonite and calcite during carbonate precipitation, along with surface adsorption, are key processes leading to As enrichment.[67,68] The irreversible adsorption of Hg onto carbonate surfaces may contribute to the accumulation of this highly mobile element[69,70] that can originate from both atmospheric deposition and runoff.[71,72]

Linking beachrock diagenesis with metal(loid) accumulation, we propose several potential mechanisms that contribute to the enrichment of these elements. First, the coastal environment is a well-known hotspot for metal(loid) deposition,[73,74] meaning that cementing materials in beachrock may already contain elevated metal(loid) concentrations due to the mixing of marine and meteoric water. Given that metal(loid)s have high partitioning coefficients (K_d), they tend to preferentially adsorb onto suspended solid particles rather than dissolve in freshwater during transport from land to sea.[75,76] According to the Derjaguin−Landau−Verwey−Overbeek (DLVO) theory, metal(loid)s are likely to settle with colloids and particles as salinity increases due to the suppression of the electrical double layer.[77] This mechanism explains the observed enrichment of various metal(loid)s in beachrock. Second, geogenic As enrichment in groundwater is a widespread, global phenomenon.[64,78] Consequently, elevated As concentrations in beachrock are expected in areas where cementation occurs due to groundwater degassing. Furthermore, Hg is highly volatile, and elemental Hg undergoes oxidation before being deposited in coastal environments through atmospheric deposition.[72,79] High rates of atmospheric Hg deposition have been reported in coastal regions, where reactive gaseous Hg forms following photochemical oxidation of elemental Hg.[80,81] Additionally, many metal(loid)s, including Cd, As, Hg, copper (Cu), zinc (Zn), antimony (Sb), thallium (Tl), and lead (Pb), are classified as chalcophiles according to Goldschmidt's classification, and show a preference for binding to sulfur (S) in natural environments.[82−84] In this context, we hypothesized that the high sulfur content in biogenic beachrock, particularly in beachrocks formed from sulfate reduction induced MICP, and may contribute to metal(loid) enrichment.[85−87]

It is important to recognize that metal(loid)s exist in different geochemical fractions and speciation within solid matrices, including rock.[57,88,89] Assessing the total concentrations of metal(loid)s is only the first step in evaluating their potential environmental risks. Understanding their geochemical fractions and speciation is crucial for assessing bioavailability and potential impacts on coastal ecosystems. Geochemical fractions can be analyzed using sequential extraction methods such as the Tessier method (for cationic metals), the BCR method (for cationic metals), or the Wenzel method (for oxyanions), which sequentially target fractions with decreasing mobility and bioavailability.[88,90,91] Speciation, on the other hand, can be examined using advanced characterization techniques such as X-ray absorption spectroscopy, which are more precise but also more costly.[92−94]

Since carbonate minerals are the primary constituents of beachrock, and carbonate-bound geochemical fraction of metal(loid)s are generally labile and susceptible to leaching under environmental stressors,[95−97] high mobility and bioavailability of metal(loid)s in beachrock are expected. Additionally, because beachrock forms in the dynamic intertidal zone, where pH and Eh fluctuate frequently, redox-sensitive elements such as As and Hg may undergo mobilization under such variable conditions.[98−100] Moreover, frequent wet−dry cycling on beachrock surfaces may influence mobilization of atmospherically deposited contaminants, Hg methylation and metal speciation dynamics, and induce surface cracking and erosion[25,39] (Figure 1), leading to the dissolution and leaching of metal(loid)s such as Cd, As, and Hg from carbonate minerals.

3.2. Record of Oil Spills and Implications for Organic Pollution Tracing

Coastal ecosystems are highly vulnerable to oil spills, and interactions between beachrock and organic pollutants following oil spill incidents have been documented. For example, beachrocks along the Brazilian eastern coast were found to be covered with oil stains following a massive oil spill that spread >3,000 km since August 2019 (Figure 1d).[44] As a result, beachrock biodiversity declined significantly, and the barnacle *Chthamalus bisinuatus* was the only surviving, sessile invertebrate in the affected habitat. The patch density of *Chthamalus bisinuatus* dramatically decreased from 1197 to 34 individuals/dm^2.[44]

Even in areas unaffected by oil spills, beachrock has been found to accumulate typical organic contaminants, such as polycyclic aromatic hydrocarbons (PAHs). For instance, Blanco-Zubiaguirre et al.[108] developed a focused ultrasound solid−liquid extraction method to accurately determine PAH concentrations in beachrock. Their findings showed that the concentration of typical United States Environmental Protection Agency (USEPA) priority PAHs ranged from 23 to 586 μg/kg (Figure 4f). Moreover, a trend of increasing PAH

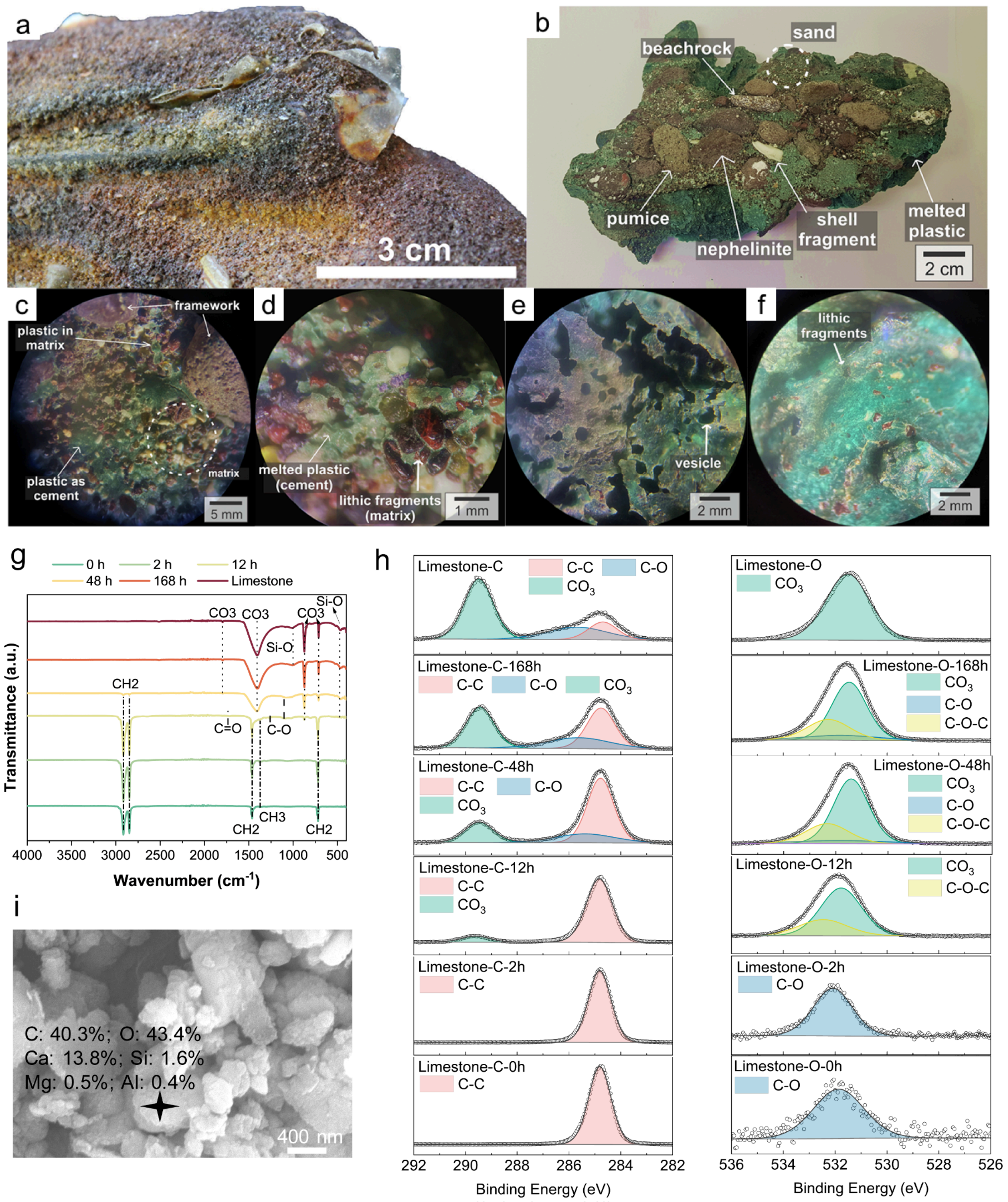


Figure 5. Plastic waste and beachrock lithification. (a–f) Plastic waste cemented with beachrock in the coastal environment: (a) Plastic film cemented with an iron-rich beachrock in Rio Grande do Sul, Brazil. Reproduced with permission from ref 120. Copyright 2020 Elsevier. (b) Melted plastic cemented with beachrock in Trindade Island, Brazil. (c–f) Microscopic view of interactions between plastic and rock matrix. Panels (b–f) were reproduced with permission from ref 29. Copyright 2022 Elsevier. (g–i) Organo-mineral lithification between LDPE and standard limestone material under UV irradiation, including (g) FTIR spectra of the lithified region under 0 to 168 h irradiation. (h) XPS C 1s and O 1s spectra of the lithified region under 0 to 168 h irradiation. (i) Morphology of the lithified region following 48 h irradiation. Data from panel (g) were retrieved from Wang et al.[127] Panels (h and i) were reproduced with permission from ref 127. Copyright 2024 Elsevier.

concentration was observed with an increasing number of aromatic rings (Figure 4f).

By analyzing the diagnostic compositions of organic pollutants in beachrock, it is possible to trace their potential sources. For instance, relative concentration ratios of PAHs in different samples can indicate whether their origins are pyrolytic or petrogenic.[18,109] Pyrolytic PAHs, which form at high temperatures, are primarily associated with combustion emissions and atmospheric deposition. These PAHs are characterized by high molecular weights (i.e., more aromatic rings), a lower degree of alkylation, and a predominance of fused-ring structures.[109−111] In contrast, petrogenic PAHs, which originate from petroleum spills or leaks, contain a higher proportion of alkylated homologues and show a relative depletion of high molecular weight PAHs.[109−111] One example of environmental forensic analysis using PAH ratios comes from the study of beachrock in the Bay of Biscay, Northern Spain.[108] Multiple diagnostic PAH ratios provided strong evidence that the detected PAHs had a pyrolytic rather than petrogenic origin. Key indicators included a Phenanthrene/Anthracene ratio of <10, a Chrysene/Benz[a]anthracene ratio of <1, a Fluoranthene/Pyrene ratio of >1, and a Fluoranthene/(Fluoranthene + Pyrene) ratio of >0.5.[108,112]

Additionally, other compounds have also been used to trace the sources of organic contaminants in beachrock. For instance, terpane biomarkers, specifically the diagnostic ratio of 18α-22,29,30-trisnorneohopane (Ts) to 17α-22,29,30-trisnorhopane (Tm), are frequently applied in oil spill environmental forensics.[113−115] This Ts/Tm ratio has been successfully used to trace the origins of oil contamination in beachrock on Abu Ali Island, Saudi Arabia (Figure 4e).[107] The Ts/Tm ratio in beachrock closely matched that of oil from the Nowruz oil spill, which occurred between 1983 and 1985 during the Iran-Iraq War (Figure 4e). The overlap in diagnostic ratios strongly suggests that the Nowruz spill was the primary source of oil contamination in Abu Ali Island's beachrock.[107]

It is notable that organo-mineral binding mechanisms between these contaminants and rock matrices are still poorly understood. Existing evidence has shown that van der Waals interactions play a vital role in hydrocarbon interactions with carbonate minerals, with Ca sites, rather than Mg or CO_3 sites, serving as the most energetically favorable for hydrocarbon adsorption.[116] In addition, hydrogen bonding also contributes to the adsorption of organic contaminants, with molecules containing phenolic and pyrrolic functional groups being preferentially adsorbed.[117] Finally, preferential attachment of organic acids over bases has been reported, primarily due to electrostatic interactions.[118]

3.3. Potential Anthropocene Indicators of Plastic Pollution

Beachrock matrices can be cemented by a mixture of natural sediments and anthropogenic debris, including plastic waste. Recent studies have shown that plastic debris can become incorporated into or attached to beachrock matrices, forming novel plastic-rock complexes that may serve as potential geological markers of the Anthropocene.[29,119,120] For instance, plastic film has been found cemented within an iron (Fe)-rich beachrock in Rio Grande do Sul, Brazil[120] (Figure 5a). As another example, melted plastic was observed within beachrock on Trindade Island, Brazil[29] (Figure 5b). Microscopic analysis further revealed how plastic debris interacts with the rock matrix, showing that melted plastic can serve as a cementing material in plastic-rock complexes (Figure 5c−f).[29] Beyond these cases where plastic lithifies with beachrock, similar plastic-rock complexes have been reported across five continents in 11 countries,[119] not only in other types of coastal environments with rocky shores[121,122] but also in inland environments, such as along a creek.[123] These findings suggest that such novel plastic forms may serve as reliable, Anthropocene indicators of plastic pollution, providing direct evidence that human activities have affected Earth's geological record.[119,124−126]

The process by which plastic debris becomes cemented within beachrock is still under debate, and here we propose three plausible mechanisms. First, melting and subsequent resolidification of plastic may be a key process in its incorporation into beachrock.[29] Various factors may contribute to plastic melting in coastal environments, including campfire burning, waste incineration, and long-term exposure to solar radiation, especially on dark-colored rock surfaces where temperatures rise significantly.[124,128,129] Once melted, plastic debris can fuse with the rock matrix in a glue-like morphology, forming plastic-rock complexes.[29]

Second, plastics incorporation may also occur simultaneously with beachrock cementation, particularly in microtidal coastal environments where beachrocks are actively forming. In this process, inorganic minerals such as calcite and Fe oxides serve as cementing agents, binding plastic debris within the rock structure. The plastic-rock complex reported by Fernandino et al.[120] likely formed through this mechanism, as the plastic film retained its original morphology with no visible signs of melting or resolidification. Elemental analysis further suggested that Fe and Ca acted as cementing agents in this case.[120]

Finally, plastic debris may also undergo chemical interactions with carbonate minerals on rock surfaces, particularly under ultraviolet (UV) irradiation. Recent experiments using low-density polyethylene (LDPE) and limestone ($CaCO_3$ as the main mineral component) showed that UV exposure can lead to irreversible mineral attachment and the formation of C−O−C chemical groups (Figure 5g−i).[127] After 12 h of accelerated UV irradiation (equivalent to 8.8 days of sunlight exposure on Earth's surface), chemical binding between plastic and $CaCO_3$ was observed.[127] Notably, LDPE-limestone binding occurred more rapidly than with sandstone, shale, or ironstone, with the latter requiring 48 h (approximately 35 days of natural exposure) to achieve chemical binding.[127] Morphological analysis of lithified regions further confirmed that $CaCO_3$ particles adhered to the polymer matrix (Figure 5i). Theoretical calculations suggested that surface oxidation is a prerequisite for chemical binding, with monodentate complexes being the most energetically favorable configuration.[127] This mechanism likely explains cases where plastics debris are found attached to rock surfaces rather than incorporated within the matrix.[121−123]

Apart from interactions with macroplastics debris, studies have shown that beachrock habitats also accumulate high concentrations of microplastics (MPs, <5 mm). It was reported that MP abundance was significantly higher in areas with beachrock than in adjacent environments without beachrock. MP concentrations were significantly elevated in beachrock-protected areas of Boa Viagem Beach, Brazil.[130] Similarly, beaches along the eastern Gulf of Thailand, where beachrock provided protection from wave action, had extremely high MP concentrations (>200,000 items/kg),[131] far exceeding the reported MP abundance in most coastal environments, which typically ranged from 20 to 7,900 items/kg.[132] These findings highlight the role of beachrock in fate and transport, and source-sink dynamics of MPs in coastal marine environments. Given the overlap between high MP abundance and high biodiversity in coastal beachrock habitats (Figure 2), further research is needed to assess the potential ecological impacts of MPs on coastal marine biota. In addition, while no data are currently available on nanoplastics (NPs, <1 μm) in beachrock habitats, it has been hypothesized that frequent wet−dry cycling in the intertidal zone may accelerate the fragmentation of MPs into NPs.[133,134] This process could be accompanied by the release of plastic-derived dissolved organic matter (<0.45 μm), which contains oligomers and various plastic addi-

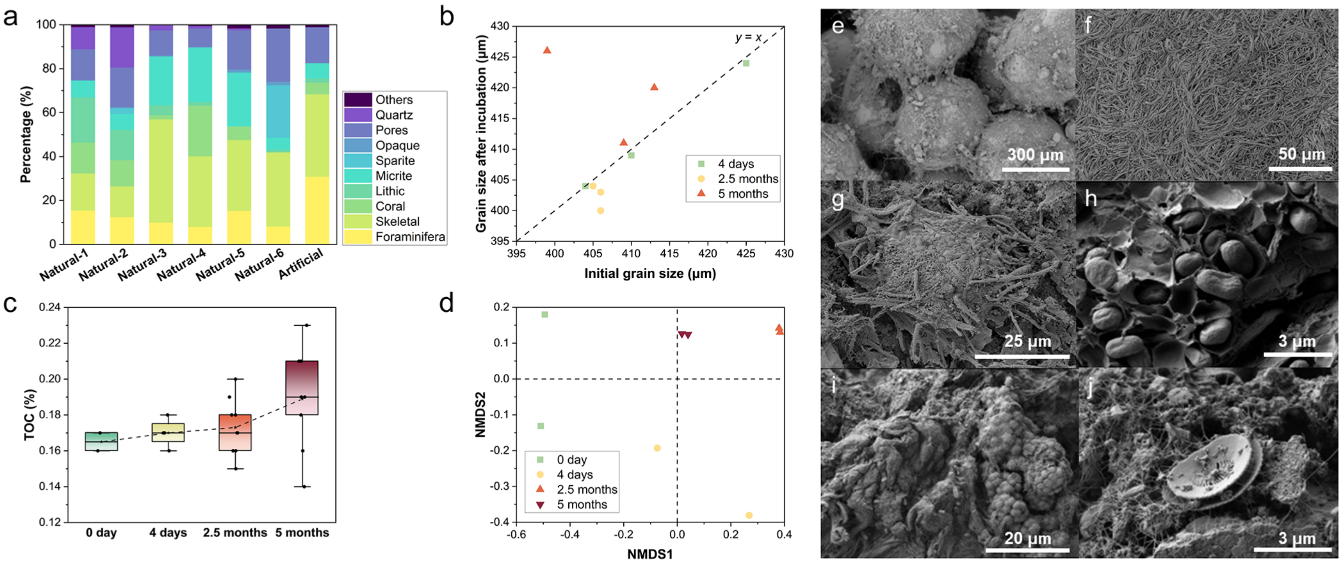


Figure 6. Properties of artificially synthesized beachrocks and morphologies of beachrocks with microbial colonization suggesting carbonate precipitation mechanisms. (a) Composition of natural beachrocks and an artificially synthesized beachrock. Data retrieved from Daryono et al.[141] (b) Comparison of median grain size before and after 5 months of incubation. Data retrieved from Hibner et al.[22] (c) Changes in TOC content during 5 months of incubation. Data retrieved from Hibner et al.[22] (d) Variance in microbial community during 5 months of incubation. Data retrieved from Hibner et al.[22] (e) Network of microbial filaments forming bridges between mineral grains. Reproduced with permission from ref 22. Copyright 2025 John Wiley and Sons. (f, g) Biofilm on beachrock surface with filamentous cyanobacteria producing abundant EPS. Panels (f and g) were reproduced with permission from ref 140. Copyright 2017 Elsevier. (h) A microcolony of coccoid cells producing casts of calcium carbonate. (i) Coccoid cells with associated EPS. (j) A coccolith among EPS. Panels (h−j) were reproduced with permission from ref 142. Copyright 2016 Elsevier.

tives.[135−137] These smaller particles and dissolved compounds are of particular concern due to their increased bioavailability and potential toxicity to aquatic organisms.[138,139] For instance, preliminary evidence has shown that dissolved organic matter leached from biodegradable polymers can cause acute toxicity to *Daphnia magna*, and the underlying mechanisms warrant further investigation.[138]

4. LOOKING FORWARD: HARNESSING THE POTENTIAL OF BEACHROCK FOR COASTAL MANAGEMENT

The previous section discussed beachrock's role as a sedimentary record of Anthropocene pollution, which has attracted increasing research interest in recent years in environmental science. In this section, we focus on beachrock's potential for coastal protection and development from an environmental engineering perspective. We first examine how beachrock formation could potentially be scaled up through artificially induced MICP. Next, we discuss potential applications of beachrock for pollution control. Finally, we propose the broader use of beachrock as a NbS for strengthening coastal resilience.

4.1. Scaling up Beachrock Formation through Artificially Induced MICP

Scaling up beachrock formation is a prerequisite for environmental engineering applications, as it enables beachrock production for pilot- and full-scale demonstrations. Given that natural beachrock is rapidly cemented in the intertidal zone, several laboratory-scale studies and in situ field trials have explored carbonate precipitation mechanisms in beachrock and the potential for artificially synthesizing beachrock for environmental engineering applications (Figure 6). One key finding is that beachrocks can form rapidly via artificially induced MICP within several months, achieving similar physicochemical properties to naturally precipitated beachrocks.[22,54,140,141]

Based on the natural diagenetic mechanisms of beachrock, artificially induced MICP has been successfully applied to generate beachrock for engineering applications, with cyanobacteria and urease-producing bacteria playing vital roles in this process. For instance, the mechanisms of beachrock diagenesis on Heron Island, Great Barrier Reef, Australia, were first explored using electron and X-ray fluorescence microscopy.[142] It was found that cementation initially occurred in biofilms, forming meniscus-shaped attachments, followed by the growth of aragonite needles containing bacterial extracellular polymeric substances (EPS).[142] The metabolism of cyanobacteria and associated heterotrophic bacteria played a key role in creating supersaturated conditions that initiated carbonate precipitation. As a result, the precipitated beachrock contained coccoid cyanobacteria cells and EPS (Figure 6h−j).[142] Inspired by these natural diagenetic mechanisms, beachrock was successfully synthesized within 8 weeks under controlled laboratory conditions that simulated the natural environment of Heron Island, using a microbial inoculum derived from natural beachrock.[140] Biofilms were observed on the surface of the synthetic beachrock, with filamentous cyanobacteria producing abundant EPS (Figure 6f,g).[140] Another successful attempt used urease-producing bacteria to induce MICP and synthesize beachrock. The mineralogical composition of the artificially synthesized beachrock was found to be similar to that of natural beachrock, with a slightly higher proportion of foraminifera (Figure 6a).[141]

In addition, an in situ field study was conducted by Hibner et al.[22] on Little Ambergris Cay, Turks and Caicos Islands. It was found that initial cementation occurred within just 4 days, followed by substantial cyanobacteria biofilm attachment within 2.5 months, and final formation of beachrock within 5 months. Networks of microbial filaments were observed forming bridges between mineral grains (Figure 6g). The grain size following cementation first decreased at 2.5 months and then increased at 5 months (Figure 6b), while total organic carbon (TOC) content steadily increased over the 5-month period (Figure 6c). Besides, microbial community composition evolved throughout the incubation period (Figure 6d). Additionally, artificial cement precipitation in Fe-rich environments and the synthesis of Fe-rich beachrock have also been reported through the stimulation of native microbial communities.[54] Although still at a very early stage, these findings are encouraging and have significant implications for future engineering applications, particularly in the development of nature-based materials for pollution remediation and coastal infrastructure support (Sections 4.2 and 4.3).

4.2. Potential Applications for Coastal Pollution Control and Remediation

Here we propose that beachrock, whether naturally formed or artificially produced, may be used in several ways to mitigate pollution in coastal zones. The major remediation mechanisms include the immobilization of contaminants such as metals and (micro)plastics, and the natural attenuation of organic pollutants through microbial activities. These mechanisms can be translated into practical engineering applications for surface runoff management, soil remediation, and oil-spill treatment.

The immobilization capability of beachrock arises from both its carbonate mineralogy and its artificial formation via MICP. Evidence is mounting that calcite and aragonite are promising sorbents for toxic metals and metalloids, including Cd, Pb, Cu, and As, primarily through isomorphous substitution and inner-sphere surface complexation reactions, thereby reducing the mobility and bioavailability of metal(loid)s.[57,66,143] Coprecipitation of MPs with calcite has also been reported in both freshwater and marine environments, where cyanobacteria (i.e., a key microbe in MICP) play vital roles in mediating these reactions.[144,145] The microbial biofilms associated with MICP further enhance sorption capacity, allowing pollutants to be retained or transformed within the carbonate matrix.[146,147]

This property can be applied in surface runoff control systems in coastal zones to intercept land−sea pollutant transport, including metal(loid)s and MPs. In this context, artificially synthesized beachrock or calcite-precipitating microbe-treated sand could be used as reactive filter media. Installed in drainage channels or bioretention ponds in coastal cities dominated by impervious surfaces,[148−150] such materials could capture a variety of contaminants from urban runoff before they enter the marine environment. Furthermore, beachrock structures may assist in the retention of plastics and MPs along coastlines. The reactive carbonate matrix and associated biofilms provide abundant surface sites for plastic debris attachment, limiting their dispersion by wave and tidal action.[119,126] Engineered artificial beachrock barriers placed near river mouths or tidal flats could serve as passive traps for plastic debris and MPs, thus reducing their input into the open sea.

Another potential application of the immobilization mechanism involves coastal sediment and soil remediation through beachrock amendment. Carbonate minerals are effective for immobilizing cationic metals in soils and sediments via a "liming effect", which elevates soil or sediment pore water pH, enhancing precipitation and electrostatic interactions between metals and soil/sediment particles.[151,152] Direct interactions through surface complexation and precipitation reactions between amendments and metals may also contribute to metal immobilization.[152,153] The application of crushed beachrock powder in areas affected by cationic metal contamination (such as estuarine sediments, coastal contaminated sites, and metal-impacted arable lands), either in situ or ex-situ, could provide a cost-effective means of metal immobilization. Furthermore, inoculation of calcite-precipitating microbes, such as cyanobacteria and urease-producing bacteria, into beachrock-amended soils can promote MICP-induced Solidification/Stabilization (S/S), enabling encapsulation and physical entrapment of contaminated soils and sediments.[154,155] Previous studies on metal(loid) immobilization with MICP suggested that this technology are capable of reducing bioavailable fractions of metals in soil by >90% for various elements such as Cd, As, Ni, Cr, and Pb.[156,157] However, the long-term stability of MICP-based immobilization in real coastal environments deserves further investigation.

In addition to immobilization, beachrock formation may also support the natural attenuation of hydrocarbons through its associated microbial communities. Cyanobacteria, sulfate-reducing bacteria, and heterotrophic bacteria commonly found in beachrock are known to degrade petroleum hydrocarbons and other organic compounds.[158−161] When stimulated under controlled conditions (Section 4.1), these communities can promote the self-purification of oil-contaminated shorelines. For instance, MICP can be encouraged in beach sediments following oil spills, facilitating both microbial degradation of hydrocarbons and their physical encapsulation within newly precipitated beachrock layers. This dual process, namely, biodegradation and mineral sealing, can reduce the persistence and mobility of oil residues in the intertidal zone, functioning similarly to natural attenuation methods widely used in groundwater remediation.[162] In addition, the beachrock matrix also provides nutrients such as Ca, Mg, K, and Fe,[27,163] thus stimulating microbial growth and the biodegradation of organic pollutants.

4.3. Beachrock-Inspired Nature-Based Solutions for Resilient Coastal Infrastructure

Natural beachrocks have been reported to have a positive impact on beach geomorphology, aiding in the prevention of coastal erosion and maintaining sand cay stability.[25−27] The ability of beachrock to undergo rapid cementation despite continuous exposure to wet−dry cycling, wave action, and mechanical stress in the intertidal zone highlights its potential as a cementitious material for sustainable coastal infrastructure.

In recent years, nature-based concrete has garnered significant attention in material sciences (Figure S2), with MICP being widely explored as a restorative measure to seal cracks in construction and building materials through carbonate precipitation.[164−167] These studies suggested that MICP can be achieved through various microbial processes, including oxygenic photosynthesis by cyanobacteria or algae, anoxygenic photosynthesis by green sulfur bacteria, acidobacteria and purple bacteria, sulfate reduction by sulfate-reducing bacteria, and urea or uric acid degradation by urease-producing bacteria.[87,168,169] These self-healing concretes have been successfully applied in infrastructure development, offering improved durability and resistance to environmental stressors.[164,165] Given that cyanobacteria and urease-producing bacteria, key organisms associated with MICP-based cement self-healing, are also major contributors to beachrock diagenesis, artificially synthesized beachrock holds strong potential as a novel cementitious material for coastal infrastructure.[22,140,141]

Given the increasing threats posed by climate change, including sea level rise and intensified storm activity, making use of the natural carbonate precipitation mechanisms of beachrock could offer sustainable solutions for long-term coastal adaptation and mitigation strategies. Inspired by the natural cementation process of beachrock, artificially synthesized beachrock could similarly be used as a novel construction material and as a NbS, potentially revolutionizing coastal engineering with multiple benefits:[170]

First, harnessing the nature-based potential of beachrock could lead to the development of bioengineered coastal protection structures, such as breakwaters, seawalls, and revetments, that can naturally regenerate and maintain their structural stability over time. Additionally, incorporating artificially synthesized beachrock as an additive in conventional cementitious materials, such as Portland cement, could enhance the durability and environmental resilience of concrete used in marine infrastructure, coastal buildings, and erosion control measures. Second, coastal resilience is strongly influenced by an ecosystem's ability to retain sediments.[22,171,172] Sandy coastlines are particularly vulnerable to intensified erosion due to climate change.[173,174] Given its rapid cementation capabilities, beachrock acts as a natural sediment sink and help stabilize coastal zones while reducing sediment loss. Besides, beachrock also serves as a key habitat for organisms in the coastal environment. Increasing the density of beachrock geomorphologies in intertidal zones could further enhance microbial and faunal biodiversity, thereby strengthening ecosystem resilience to global environmental change factors.[5,175] Finally, the cement industry is among the largest energy consumers and CO_2 emitters, contributing approximately 5% to 8% of global anthropogenic CO_2 emissions annually.[176] As an alternative to traditional cement materials, biologically synthesized beachrock using natural sediments has the potential to reduce carbon footprints and environmental impacts of coastal development practices.

In conclusion, by integrating knowledge from sedimentary geology, environmental science and engineering, microbiology, and materials science, we propose that beachrock is a promising NbS that can support sustainable pollution remediation and coastal infrastructure. Its ability to self-cement, immobilize/degrade pollutants, and to resist environmental stressors makes it a potential candidate for future innovations in developing climate-resilient remedies and infrastructures.

5. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Intertidal beachrock, a rapidly cemented sedimentary rock, has attracted much attention from a wide array of scientific disciplines including environmental science and engineering, earth sciences, climate sciences, material sciences, and microbiology. In this review, we assessed the potential of beachrock as an analogue and indicator of coastal pollution by metal(loid)s, typical organic contaminants, and plastics, as well as for interactions between beachrock and these pollutants. Additionally, we evaluated the potential of beachrock as a nature-based material for coastal pollution control and engineering, potentially offering an adaptive management strategy for climate change resilience. Research in this field is still in its infancy, and several important questions and knowledge gaps remain and still need to be properly addressed.

First, the current understanding of beachrock contamination is limited, and data in this field is severely lacking. While many studies have focused on beachrock diagenesis and its use as a sea-level indicator, relatively few have examined beachrock contaminant concentrations. Current studies typically report only the total concentration of metal(loid)s, without assessing their mobility, speciation, or bioavailability. However, understanding these factors is essential for evaluating the ecotoxicological risks in coastal ecosystems. In this context, chemical extraction could serve as a cost-effective means of distinguishing metal(loid)s into different geochemical fractions, providing insights into sources, fate, and transport dynamics, and flux rates. Besides, our knowledge of the interactions between beachrock and other types of organic pollutants in coastal environments, such as pesticides, chlorinated solvents, benzene, and per- and polyfluoroalkyl substances, remains very limited. The mechanisms by which organic pollutants adhere to carbonate minerals and biofilms within beachrock are still poorly understood and require further investigation. To better understand plastics pollution, polymer type-specific investigations are necessary, as polymers originate from different sources and have varying physicochemical properties. Further research should also explore plastic weathering processes and the abundance of NPs, since smaller, weathered plastic particles typically exhibit greater bioavailability. Additionally, it is important to examine the potential role of contaminants in beachrock formation, specifically, whether they contribute to, inhibit, or have no effect on the cementation processes.

Second, long-term interactions between beachrock and contaminants under the highly dynamic conditions of the intertidal zone warrant further exploration. Environmental stressors including fluctuating pH, Eh, and wet−dry cycling in intertidal environments may significantly influence contaminant cycling and trophic transfer in beachrock ecosystems. Artificial accelerated aging experiments or in situ field trials could provide valuable insights into these processes. The mechanisms governing metal(loid) accumulation, mobility, and potential release under environmental stressors also require further investigation, particularly for redox-sensitive elements such as As and Hg. Moreover, it remains uncertain whether native microbial communities within beachrock contribute to hydrocarbon degradation and to what extent natural attenuation of organic contaminants occurs. The isolation and identification of hydrocarbon-degrading bacteria from oil-contaminated beachrock could offer new insights for bioremediation applications. Additionally, the reversibility and stability of plastic-rock interactions require further investigation. A mechanistic understanding of polymer degradation and stability should be developed to determine whether plastic interactions with beachrock preserves plastic debris or accelerates its degradation.

In addition, the feasibility of using artificially synthesized beachrock for coastal engineering remains largely theoretical. Pilot-scale, in situ field studies are needed to evaluate long-term performance under real-world coastal conditions. Further research should focus on optimizing the synthesis and scaling up of artificial beachrock for practical applications, ensuring that its mechanical properties, longevity, and environmental compatibility meet environmental engineering standards and sustainability goals. Investigating the influence of different microbial strains, precipitation conditions, and substrate compositions will be crucial for optimizing MICP-based processes. Additionally, future studies should assess whether and how beachrock-derived materials, when incorporated into traditional concrete formulations, affect its mechanical stability, properties, and long-term durability.

Finally, another emerging but underexplored aspect of beachrock research is its potential role as a coastal carbon sink. The formation of beachrock represents a natural pathway for the conversion of dissolved inorganic carbon into solid-phase carbonates, thus effectively immobilizing carbon within the sedimentary rock matrix. Although beachrock formation is often associated with local degassing and emissions of CO_2, the long-term preservation of carbonate minerals in coastal deposits can act as a semipermanent carbon reservoir. This dual role both as a transient CO_2 source during precipitation and as a long-term sink through mineral sequestration remains poorly quantified in intertidal environments. Given the widespread occurrence of beachrock in tropical and subtropical regions, even modest rates of carbonate accumulation could contribute meaningfully to coastal blue carbon budgets if properly quantified. Future studies should focus on carbon flux measurements, isotopic characterization, and modeling of carbon residence times within beachrock matrices to determine whether these formations act as net carbon sinks or sources over geological time scales. Moreover, integrating beachrock formation into broader NbS frameworks could open new pathways for biomediated carbon capture and storage, complementing vegetated blue carbon ecosystems such as mangroves and seagrasses. Understanding this potential will be essential to fully evaluate the biogeochemical and climate regulation roles of beachrock in the Anthropocene coastal system.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.5c16109.

> Correlation between calcium carbonate content and beachrock metal(loid) concentrations and representative photos of cementitious materials generated from microbially induced carbonate precipitation (PDF)

■ AUTHOR INFORMATION

Corresponding Author

Kefu Yu − *Guangxi Laboratory on the Study of Coral Reefs in the South China Sea, Coral Reef Research Center of China, School of Marine Sciences, Guangxi University, Nanning 530004, China;* orcid.org/0000-0003-3409-9945; Phone: +86-0771-3227855; Email: kefuyu@scsio.ac.cn

Authors

Liuwei Wang − *Guangxi Laboratory on the Study of Coral Reefs in the South China Sea, Coral Reef Research Center of China, School of Marine Sciences, Guangxi University, Nanning 530004, China;* orcid.org/0000-0002-6176-6056

Zhengtao Shen − *School of Earth Sciences and Engineering, Nanjing University, Nanjing 210023, China*

Michael S. Bank − *Institute of Marine Research, 5817 Bergen, Norway; University of Massachusetts Amherst, Amherst, Massachusetts 01003, United States;* orcid.org/0000-0001-5194-7171

Satoru Kawasaki − *Division of Sustainable Resources Engineering, Faculty of Engineering, Hokkaido University, Sapporo 060-8628, Japan*

Wei-Min Wu − *Department of Civil and Environmental Engineering, Stanford University, Stanford, California 94305-4020, United States*

Daniel S. Alessi − *Department of Earth and Planetary Sciences, Jackson School of Geosciences, The University of Texas at Austin, Austin, Texas 78712-1692, United States;* orcid.org/0000-0002-8360-8251

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.est.5c16109

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was supported by Guangxi Science and Technology Program (No. AD25069075) and the National Natural Science Foundation of China (Nos. 42030502 and 42090041).

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