Marine Pollution Bulletin 226 (2026) 119329

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Microplastic and biogeochemical releases from plastic, metal, cement, and fiber coastal restoration materials

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ARTICLE INFO

Keywords:
Microplastics
Oyster reef
Galvanized metal gabion
Biopolymer
Carbon
Nitrogen
Phosphorus

ABSTRACT

Coastal areas often include ecologically sensitive habitats and dense human populations, which can contribute to ecosystem degradation and the need for coastal restoration. Typically, coastal restoration requires the placement of a foreign material to serve as a base substrate or shoreline stabilizer, but the potential for these materials to contribute to plastic pollution or impact biogeochemical cycles is not well understood. This research investigated common coastal restoration materials to address two key knowledge gaps, 1) can plastic restoration materials be a source of microplastics?, and 2) can alternative restoration materials release nutrients, metals, or alter microbial respiration? Two polyethylene plastics and five non-plastic alternative materials were studied in experimental laboratory microcosms, including a one-year incubation to quantify microplastic release, a 5-week nutrient and metal release study of fresh and post field-deployed materials, and a one-week respiration (CO_2 production) incubation with site sediment and water. Laboratory results indicated the two plastics studied released microplastics at a rate of 395 ± 100 and 158 ± 56 g^{-1} y^{-1}, for Naltex® and Vexar®, respectively. Jute, made of plant fiber, released 4.7 and 37 times more dissolved inorganic nitrogen and soluble reactive phosphorus, respectively, than the control. The biopolymer, BESE-elements®, released 60 and 32 times more dissolved organic carbon and CO_2-C, respectively, than the control. Fresh galvanized metal gabion wire released iron, manganese, lead, and 28 times more zinc than the control, while cement materials showed minimal effects. Restoration practitioners, resource managers, and permitting organizations should consider microplastic and biogeochemical impacts when choosing materials.

1. Introduction

The coastal zone represents the convergence of some of the most biologically diverse, economically valuable, ecological vulnerable, and densely populated regions on earth (FitzGerald et al., 2008; He and Silliman, 2019). While this unique combination of characteristics contributes to the degradation of many coastal ecosystems, it also affords a strong sense of place that can promote beneficial human intervention in the form of ecosystem restoration (Hawthorne et al., 2022; Kibler et al., 2018; Scyphers et al., 2014). A particularly popular form of coastal restoration targets the reestablishment of oyster reefs along shorelines because these 'ecosystem engineers' can modify the environment to create habitat for other organisms, improve water quality and clarity, and serve as a natural erosion barrier (Barry et al., 2025; Grabowski and Peterson, 2007; Morris et al., 2019; Wallace et al., 2022). Despite oysters' ecological and economic benefits, reef coverage has been on the decline for decades, with over 85% of reefs having been lost globally (Beck et al., 2011).

Oyster reef restoration techniques can vary widely, but a common method focuses on deploying oyster cultch into coastal regions where reefs previously existed to promote new larval recruitment and spat development. Often, this cultch needs to be secured to the sediment using a base-material or weights due to the role excessive wave energy plays in the destruction of many reefs (Herbert et al., 2018; Safak et al., 2020; Stiner and Walters, 2008; Wall et al., 2005). Historically, popular base materials included a plastic mesh made of polyethylene (PE), known commercially as Vexar®, or other synthetic or semi-synthetic materials. These aquaculture-grade extruded plastics are cheap and

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https://doi.org/10.1016/j.marpolbul.2026.119329
Received 20 September 2025; Received in revised form 12 January 2026; Accepted 22 January 2026
Available online 31 January 2026

easy to use to create "oyster mats" by fastening recycled oyster shells to one face and securing it to the sediment using cement weights. Similarly, Naltex® PE mesh bags have also been used to encase loose oyster shells to function as breakwaters and substrates for spat recruitment (Wall et al., 2005; Walters et al., 2022).

While plastic has long been recognized as a source of pollution in marine environments, recent research has highlighted the dangers of microplastics (MPs), which are primary or secondary plastics <5 mm in diameter. Microplastics are classified as hazardous materials (Rochman et al., 2013) because they can act as vectors for parasites and pollutants (Ferreira Carvalho and Lôbo-Hajdu, 2023) and leach toxic chemicals (Li et al., 2024). Negative impacts of MPs on marine organisms, especially filter feeders, have been documented (Mkuye et al., 2022; Shalom et al., 2022). For example, krill-eating blue whales can ingest 10 million MP particles per day (Kahane-Rapport et al., 2022), MPs can delay growth of exposed oyster larvae (Bhatt et al., 2023), and MPs can enter the circulatory system of mussels and accumulate in tissues (Browne et al., 2008). Targeted control of terrestrial sources of marine plastics is critical (e.g., garbage and illegal dumping), but a knowledge gap exists in understanding the potential role direct use and placement of plastic materials in marine environments for aquaculture or restoration efforts could play in marine MP pollution.

Although data connecting plastic restoration materials to marine MPs is lacking, scientific awareness, public concern, and new regulations and guidance on best practices have prompted a rapid shift away from the use plastic materials in restoration, and toward diverse non-plastic materials. This shift coincides with similar changes in the aquaculture industry (Baini et al., 2024). Utilized non-plastic alternatives have included metals, biodegradable organic structures, cement, and rock-based products (Walters et al., 2022). Metal alternatives include recycled crab traps that hold loose oyster cultch (Johnson et al., 2019) and cathodically-protected steel mesh oyster mats (Hunsucker et al., 2021). Organic materials include coconut coir, jute, and biopolymers, but research shows these organic materials break down quickly relative to other substrates (Hatchell et al., 2022; Soucy, 2020; Nitsch et al., 2021). To increase the longevity of organic restoration materials, some restoration practitioners coat organic materials in resin or cement (Soucy, 2020; Wellman et al., 2022), while others have tested basalt-rock fibers, limestone blocks, or cement structures, such as "reef balls," "oyster balls," or blocks (Johnson et al., 2019; Uddin et al., 2021; McAfee et al., 2021; Mathews et al., 2023).

The rapidity of the shift to adopt alternative materials, coupled with a lack of scientific data on each material, and the sheer diversity of potential products, has created a second knowledge gap in understanding the implications of alternative materials on the physical, chemical, and biological properties of the ecosystems in which they are deployed. Many products have received little or no scientific testing or evaluation prior to implementation in restoration projects. Rather, past research has focused almost exclusively on the success of non-plastic restoration material for oyster recruitment and reef development, ease of use by stakeholders or volunteers, or life cycle environmental impacts of the products (e.g., Barry et al., 2025; Sakr and Altieri, 2025; Walters et al., 2022). Minimal consideration, if any at all, is typically given to the microbial processes that fuel the breakdown of organic or biodegradable alternative products, or the chemical constituents released into the environment during the degradation process. Furthermore, inherent differences in the physical environments where the products are used (e.g., the unique biotic and abiotic edaphic characteristics), and the variability in 'recipe' or composition of the materials themselves, have further added to the challenges of understanding a product's biogeochemical impact.

One short-term study evaluated the biogeochemical properties and effects of an organic-based biopolymer mat, Biodegradable EcoSystem Engineering Elements, or BESE-elements® (hereafter referred to as "BESE"), in the Indian River Lagoon (IRL), FL (USA). This organic product can be used similarly to Vexar® mats as a base material to attach disarticulated oyster shells. Nitsch et al. (2021) found that oyster recruitment was comparable between BESE and Vexar® PE mats, however, BESE had the potential to impact water chemistry. Under laboratory conditions, BESE released significant dissolved organic carbon (DOC), soluble reactive phosphorus (SRP), and nitrate (NO_3^-) into the surrounding water, and accelerated microbial respiration in the sediments, suggesting potentially adverse impacts on biogeochemical cycling in the environment (Nitsch et al., 2021). Others have documented variable levels of biofilm development on non-plastic restoration materials (O'Reilly and Willerth, 2023), which could also impact nutrient cycling. Considering the growing application of alternative materials, additional studies are needed to evaluate the impacts of plastic alternatives on nutrient and carbon availability and cycling in the coastal environment, and the potential to release metals from certain materials. Moreover, restoration efforts target coastal ecosystems already experiencing habitat degradation, adding to the imperative that novel products be fully vetted to reduce the likelihood of negative unintended consequences to the biogeochemistry of sensitive coastal environments.

The goals of this research were to: 1) quantify MP release during a one-year laboratory incubation of the two historically used plastic restoration materials, and 2) evaluate the biogeochemical and microbial impacts of various plastic and alternative restoration materials under laboratory conditions. Two PE plastics (Naltex®, Vexar®) and five non-plastic materials (BESE, jute, jute covered in cement (jute+cement), cement, and galvanized metal gabions) were studied to quantify the release of nutrients and/or metals into the surrounding water, and the impact on sediment microbial respiration in bottle incubations. All materials were evaluated in their pre-deployment ("fresh") condition, and select materials were also evaluated post-deployment (after being used in a coastal restoration project for up to 4 years). It was hypothesized that, a) Naltex® would produce more MPs than Vexar® due to greater surface area, b) the organic-based materials (BESE and jute) would release nitrogen (N), phosphorus (P), and DOC to the water and accelerate microbial respiration (CO_2-C flux), and c) the gabions would release iron (Fe) and zinc (Zn) into the water. We also hypothesized that the biogeochemical releases and microbial stimulation effects of the organic materials would decline logarithmically with time since deployment.

2. Methods

2.1. General material descriptions

The two traditional plastic materials and five non-plastic alternative restoration materials studied were chosen based on past use, or potential future use, in the local coastal environment (i.e., the IRL estuarine system on east coast of central Florida, USA). First, the plastic materials were both black-colored, extruded PE meshes. The shell bags, commercially known as Naltex®, are thin gauge, stretchable PE with diamond-shaped 1.0 cm openings (Fig. 1a). When deployed for restoration, a 1 m length of circular mesh is tied closed at one end, filled with 5 gal of recycled oyster shells, and tied at the other end. The plastic mats, commercially known as Vexar®, are thick, semi-rigid mesh with square 1.8 × 1.6 cm openings (Fig. 1b). When deployed in the field, 36 recycled oyster shells (collected from local restaurants and quarantined for a minimum of one year), each with a single hole drilled near the umbo, were attached to a 0.25 m^2 mat using nylon cable ties.

BESE are 3-dimentional lattice mats produced from potato starch that is composed of 98.0 ± 0.1% organic material and has a C:N:P ratio of 16,000:5:1 (Nitsch et al., 2021). Oyster restoration mats made from BESE are composed of two 0.25 m^2 squares snapped together, one on top of the other (Fig. 1c). Thirty-six recycled (from local restaurants) adult oyster shells, each with a single hole drilled near the umbo, were attached to the BESE with stainless-steel cable ties.

Jute is a soft and flexible fiber extracted from members of the

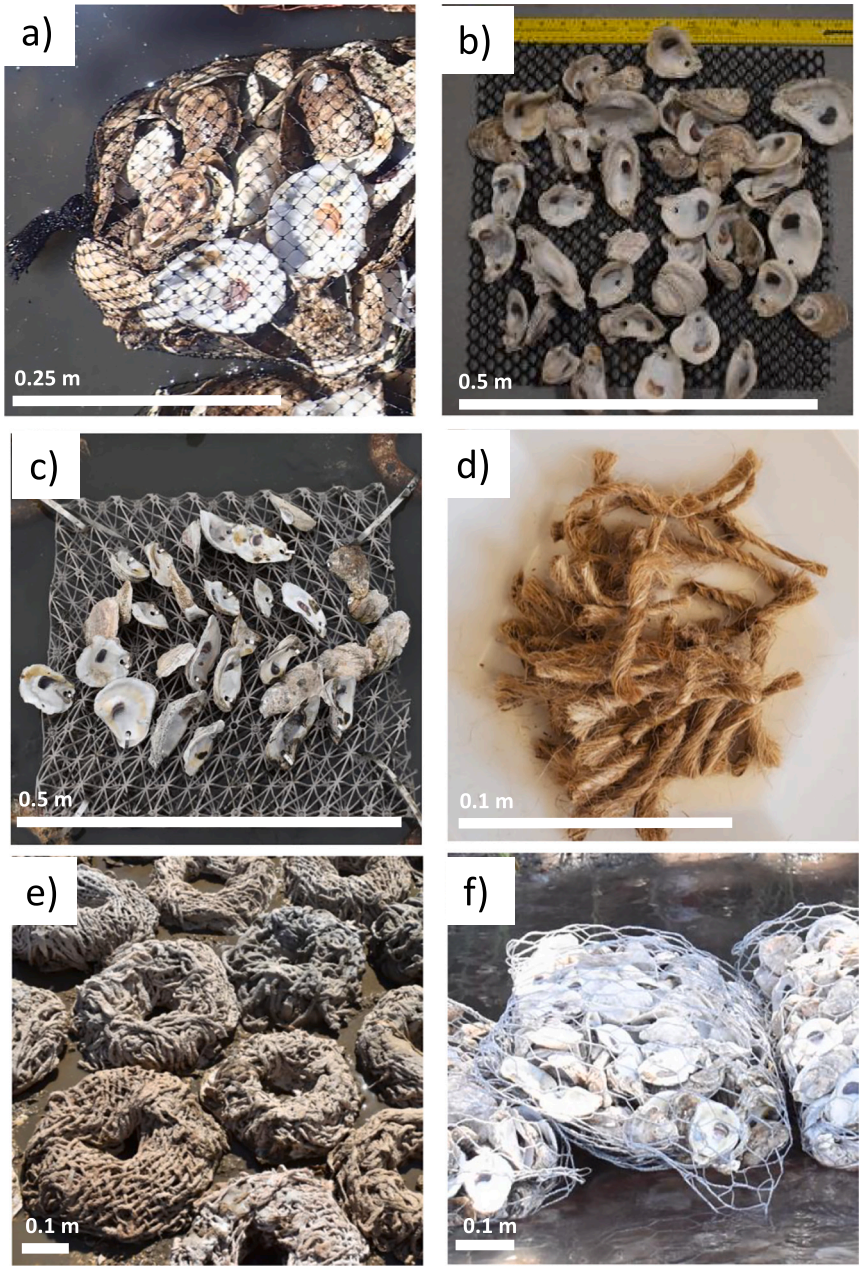

Fig. 1. Photographs of the studied restoration materials: a) Naltex® bags, b) Vexar® mats, c) BESE, d) jute, e) jute+cement patties, d) galvanized metal gabions.

Corchorus genus and consists of ~99% organic matter with structural C molecules including α-cellulose (59–61%), hemicellulose (22–24%), lignin (12–14%), and 1.6–1.9% N compounds (Sanyal, 2017; Fig. 1d). For this study, jute and cement were studied as stand-alone materials, and in combination, to help isolate the impact of each material on the response variables measured. When used in combination to restore the low-profile intertidal reefs, jute+cement rings were approximately 0.3 m in diameter and weighed ~9 kg each (Fig. 1e). The use of cement-jute structures in a range of sizes has become very popular in coastal restoration in recent years (Walters et al., 2022). The cement used was CSA (calcium sulfoaluminate) cement, which, when mixed with jute fibers, could be shaped to form rings for field deployment.

The gabions were produced from flexible 18-gauge, hot-dipped galvanized steel mesh folded into an open mesh cage that measured ~1 m in length and 0.25 m in width. Gabions were filled with enough recycled restaurant shell to fill a 5-gal bucket (weight: ~14 kg) and closed using galvanized steel hog rings (staples; Fig. 1f).

2.2. Microplastic quantification experiment

Approximately 1.3 g fresh Naltex® (112 cm^2) and Vexar® (12 cm^2) meshes were added to separate 125 mL Erlenmeyer flasks and filled with 100 mL of filtered (0.45-μm pore size) site water from Mosquito Lagoon at a replication rate of five, plus four control flasks of site water only. The flasks were placed in a translucent shaker at 29 °C, (IRL summer water temperature) at 170 RPM for 1 year. The water level was periodically topped off with nanopure water (ThermoFisher Genpure Pro system with 0.2-μm filter and a UV treatment). After 1 year, each flask was emptied and rinsed with nanopure water; all water was then filtered through a Sartorious 0.4-μm gridded, cellulose nitrate filter where any microplastics >0.45 μm would be retained. Microplastics (0.025–5 mm) on the filters were then visualized and counted (using the 0.1 mm subdivisions of 3 mm scale references on the filters) under a 45× dissecting microscope using published methods for identification, such as checking for uniform color and prodding for breakage (Hidalgo-Ruz et al., 2012).

Microscopy control blanks were placed to the left, right, and behind the microscope to account for aerial contamination on the filter paper during counting.

2.3. Biogeochemical experimental design and site description

All tested materials (plastic, non-plastic) studied were purchased from retailers commonly used to purchase restoration materials. Materials were not washed or sterilized prior to study but were instead handled and prepared similarly to how they would be prior to deployment in a restoration project. For the biogeochemical experiments (i.e., the nutrient/metal release incubations; the microbial respiration incubations), "fresh" material refers to recently purchased material never deployed in the field. In contrast, post-deployment material had been used in real-world restoration projects in the IRL for 1 to 4 years prior to being collected for laboratory experimentation.

Post-deployment materials field use was on intertidal eastern oyster (*Crassostrea virginica*) patch and fringe reef restoration projects in Mosquito Lagoon (28°56′14.10"N; 80°51′41.26"W), the northernmost portion of the IRL. This biologically diverse estuary is wind-driven, shallow (average depth: 1.7 m), microtidal where oyster reef restoration occurred (~ 25 cm tidal range), high salinity (range: 23–45 ppt) with no freshwater inputs other than rainwater (Phlips et al., 2015; Walters et al., 2021). An annual high-water season occurs each fall that coincides with Florida's hurricane season; during this season, the intertidal oyster reefs become subtidal for 3–4 months (Walters et al., 2024).

Although post-deployment materials were desired for each material type, changes in restoration practices over the past four years resulted in only certain ages of post-deployment materials being available (Table 1). All post-deployed material types were consistent items from the same manufacturer over time, but exact chemical formula used by a manufacturer may change with time or production batch without disclosure. All field deployments occurred between early May and late June of the four years preceding collection on April 24 and May 11, 2023; each collection reef was monitored for oyster density in 2023 near the time of collection. For materials aged 1 year, the total mean number of oysters per m^2 were 298.4 for BESE, 222.4 for jute+cement patties, and 204.8 for the gabions. For materials in the field for 2 years, the mean number of oysters per m^2 were 157.6 for BESE and 289.6 for jute+cement patties. The mean number of oysters per m^2 for BESE aged 3 and 4 years was 546.4 and 438.4, respectively. The 4-year-old reefs with Vexar® and Naltex® had a mean value of 902.4 oysters per m^2. For reference, a live (natural) reef aged 4 years in the same vicinity supported a mean of 472.0 oysters per m^2.

All collected post-deployment material was heavily colonized by algal mats, biofilms, and sometimes sponges and ascidians if located in the lower intertidal. To isolate the biogeochemical impacts of the materials themselves, extensive cleaning efforts (e.g., rinsing with deionized (DI) water, hand scrubbing with a soft bristled brush, and mechanically scrubbing with a soft bristled electric toothbrush) were pursued to remove biota. After cleaning, all materials were placed in a drying oven at 70 °C until a constant weight was achieved.

Table 1
Material types and ages for nutrient release and microbial activity experiments. The "X" indicates this treatment category was available and studied.

Material	Pre-deployment	Field-deployed in 2022	Field-deployed in 2021	Field-deployed in 2020	Field-deployed in 2019
Age (years in the field)	*0*	*1*	*2*	*3*	*4*
Naltex®	X				X
Vexar®	X				X
BESE	X	X	X	X	X
Jute only	X				
Jute+cement	X	X	X		
Cement only	X				
Gabion	X	X	X		

2.4. Nutrient and metal release incubation

The potential for biogeochemical release from plastic and non-plastic restoration materials was quantified in laboratory microcosms under non-sterile idealized conditions using the material types and ages listed in Table 1. All materials were tested with a replication rate of five, resulting in 85 total microcosms. The experiment was run in four sets between February and July 2023, with the materials used in each set chosen at random. Each set included controls (water only) and analytical duplicates. Microcosms were 6 oz. (177.4 mL) glass mason jars filled with 100 mL of simulated site water (SSW; chosen over site water to provide consistency between sets) created to mimic the average physical and chemical composition of Mosquito Lagoon water (Chambers et al., 2018; Locher et al., 2021). Simulated site water was created by dissolving sea salt (Lake Products Company LLC, Florissant, MO) in deionized (DI) water to a salinity of 33 ppt and adding 1 mg NH4+ L-1 (as NH4Cl) and 0.05 mg SRP L-1 (as HNa2O4P·7H2O). Experimental groups also received 5 g of one material, except for fresh (pre-deployment) cement and jute+cement, which were mixed in mason jars and weighed 15–50 g. Controls consisted of only SSW. Microcosm jars were incubated for 5 weeks in the dark at a temperature of 30 °C while oscillating at a rate of 150 rpm, following Nitsch et al. (2021). After incubation, water was filtered (0.45-μm membrane filter, Pall Corporation, Port Washington, NY, USA), acidified (pH < 2 with double distilled H2SO4), stored (4 °C), and analyzed within 28 days. Concentrations of nitrite + nitrate (NO3-), soluble reactive P (SRP), and ammonium (NH4+) were determined colorimetrically on a Seal AQ2 Automated Discrete Analyzer (Seal Analytical, Mequon, WI, USA) using EPA methods 353.2 Rev. 2.0, 350.1 Rev. 2.0, and 365.1 Rev. 2.0, respectively (USEPA, 1993). Nitrate and NH4+ data were pooled and presented as dissolved inorganic N (DIN). The DOC concentration was quantified on a Shimadzu TOC-L (Shimadzu Instruments, Kyoto, Japan).

Metal analysis included Fe, Zn, aluminum (Al), vanadium (V), chromium (Cr), manganese (Mn), cobalt (Co), nickel (Ni), copper (Cu), arsenic (As), cadmium (Cd), barium (Ba), and lead (Pb) in the water. Samples from the control and gabion wire nutrient release incubations were quantified by inductively coupled plasma mass spectrometry (ICP-MS) on a Thermo Fisher Scientific iCap QC with QCell technology (Thermo Scientific, Waltham, MA) and operated in kinetic energy discrimination (KED) mode of analysis with He as the collision gas using a subsample of water acidified with 2% nitric acid (trace metal grade) with rhodium as the internal standard (McCormac and Beazley, 2020). All nutrient and metal data were output as concentrations (e.g., mg L-1 for nutrients and μg L-1 for metals), then normalized to the mass of the material added to the incubation and presented as both a concentration and mg kg-1. The nutrient or metal content of the control group was subtracted from that of the treatment (material) group when presenting release data, unless otherwise noted.

2.5. Microbial respiration incubation

The impact of the plastic and non-plastic materials on microbial activity was also assessed by quantifying the rate of CO_2 production in microcosms that incorporated site sediment (the microbial source) in 120 mL gas-tight serum bottles that were incubated for 7 days (Hurst et al., 2022; Nitsch et al., 2021). The sediment (homogenized triplicate sediment cores from 0 to 5 cm) was collected from Mosquito Lagoon within 2 weeks of experimentation. Microcosm construction focused on producing a consistent mass ratio of 0.5 material: 1.0 sediment: 3.0 SSW, regardless of the density of the material; controls contained only sediment and SSW the material. Respiration incubations were performed in four sets, each with their own controls and analytical duplicate. The

atmosphere in the bottles was maintained as anerobic (evacuated to −75 mmHg and purged with 99% O_2-free N2 gas at creation), as was the SSW (purged with O2-free N2 gas, then added to create a slight over-pressure). All bottles were placed on an orbital shaker (New Brunswick Excella E25, Eppendorf AG, Hamburg, Germany), at 100 rpm and incubated in the dark at 33 °C. Gas headspace samples were extracted at approximately 1, 3, 5 and 7 days and analyzed on a GC-2014 gas chromatograph (Shimadzu Instruments, Kyoto, Japan) to determine potential CO2 production over time. To accurately calculate dissolved inorganic C in the bottles, pH was determined by creating a 1:5 slurry of soil: DI water with the sediment and measured with an Accumet XL200 benchtop pH probe (ThermoFisher Scientific, Waltham, MA, USA). The Ideal Gas Law was used to account for the effect of temperature and pressure within the microcosms, while Henry's Law was used to estimate the amount of dissolved CO2 in the liquid phase. Respiration data was presented as a rate over time (mg CO_2-C kg soil^{-1} h^{-1}).

2.6. Data analysis

All data was square-root transformed to improve normality and heterogeneity of variances prior to statistical analyses. For the nutrient release study, the mean concentration of DOC, DIN, and SRP found in the controls of each set was subtracted from the concentration for the experimental groups, then divided by the mass of material added to each microcosm. All fresh (pre-deployment) material types were then compared using a one-way ANOVA with material as main effect, given that all assumptions of the test were met. A Tukey HSD was used for pair-wise comparisons of materials. The amount of DOC, DIN, and SRP released from each material was compared over time if deployed in field over multiple years (Naltex® and Vexar® = 0, 4 years in field; BESE = 0, 1, 2, 3, 4 years in field; jute/cement and gabion = 0, 1, 2 years in field) using separate one-way ANOVAs with time as main effect. Tukey HSD tests were applied to all significantly different main effects. Microbial respiration of fresh material (time 0) was compared between different materials using a one-way ANOVA with material as main effect. Microbial respiration of each material was compared over time if deployed in field over multiple years (Naltex® and Vexar® = 0, 4 years in field; BESE = 0, 1, 2, 3, 4 years in field; jute/cement and gabion = 0, 1, 2 years in field) using separate one-way ANOVAs with time as main effect. Metal concentrations of gabion treatments (control, fresh, 1, 2 years in field) were compared to controls with one-way ANOVAs with treatment as main effect. Metal release of gabion treatments (fresh, 1, 2, years in field) were compared with one-way ANOVAs. All data analysis was performed in IBM SPSS statistical software and an $\alpha = 0.05$ was used to determine significant differences.

3. Results

3.1. Microplastic release

The mean number of total MPs per 100 mL were 6 ± 1 (mean ± SE), 526 ± 132, and 203 ± 72 for the water-only control, Naltex®, and Vexar®, respectively, in one year. This equated to 395 ± 100 MPs g Naltex®$^{-1}$ and 158 ± 56 g Vexar®$^{-1}$ released into the water within one year (Fig. 2a). The mean number of MPs per cm^2 of material were 4.7 ± 1.2 for Naltex® and 16.9 ± 6 for Vexar® (Fig. 2b). Black fragments comprised 98.2 ± 0.7% of MPs observed in Naltex® samples, while the remaining fraction were fibers. Likewise, black fragments also comprised 97.5 ± 0.6% of MPs observed in Vexar® samples, while the remaining fraction were fibers. However, controls were dominated (73.0 ± 8.8%) by fibers of various colors. Aerial contamination of the filters during processing was quantified at 0.05 ± 0.01 MPs per minute and were 82.4 ± 8.6% fibers of assorted colors.

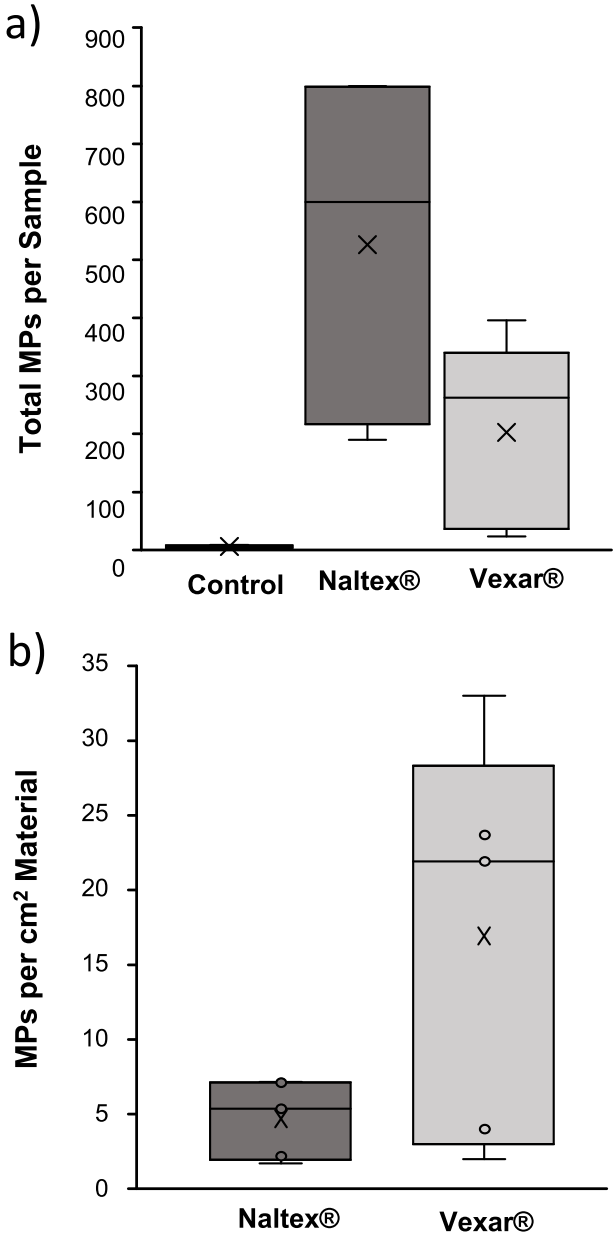

Fig. 2. The a) total numbers observed microplastics (MPs) in 100 mL of site water incubated with ~1.3 g of control (water only), Naltex®, and Vexar®, in a laboratory setting for one year, and b) how those numbers related to the area covered (per cm^2) by each material when used in the field for restoration projects. The x represents the mean, central bar is the median, and box represents the 1st and 3rd quartile (n = 5 for Naltex® and Vexar®; $n = 4$ for control).

3.2. Nutrient and metal releases

In general, the organic materials (jute and BESE) showed higher N, P, and C releases than all other treatments. For N, all fresh materials showed similar release of DIN (6.31 ± 0.90 mg kg^{-1}), except for jute, which was greater (per mass of material) than all other treatments (42.93 ± 11.17 mg kg^{-1}; $p < 0.0001$; Fig. 3a). By concentration, fresh jute released 2.49 ± 0.73 mg DIN L^{-1} (Table 2). Greater SRP release was observed for jute and BESE compared to all other materials ($p < 0.0001$), which were below detection (BD). Specifically, jute released on average ~ 4× more SRP (2.14 ± 0.69 mg L^{-1}, or 36.75 ± 9.9 mg kg^{-1}) than BESE (0.53 ± 0.04 mg L^{-1}, or 8.59 ± 0.63 mg kg^{-1}) (Fig. 3b). In contrast, the BESE released ≥3.5 times greater DOC (per mass of material) than all other treatments (8940 ± 321 mg kg^{-1}), which was

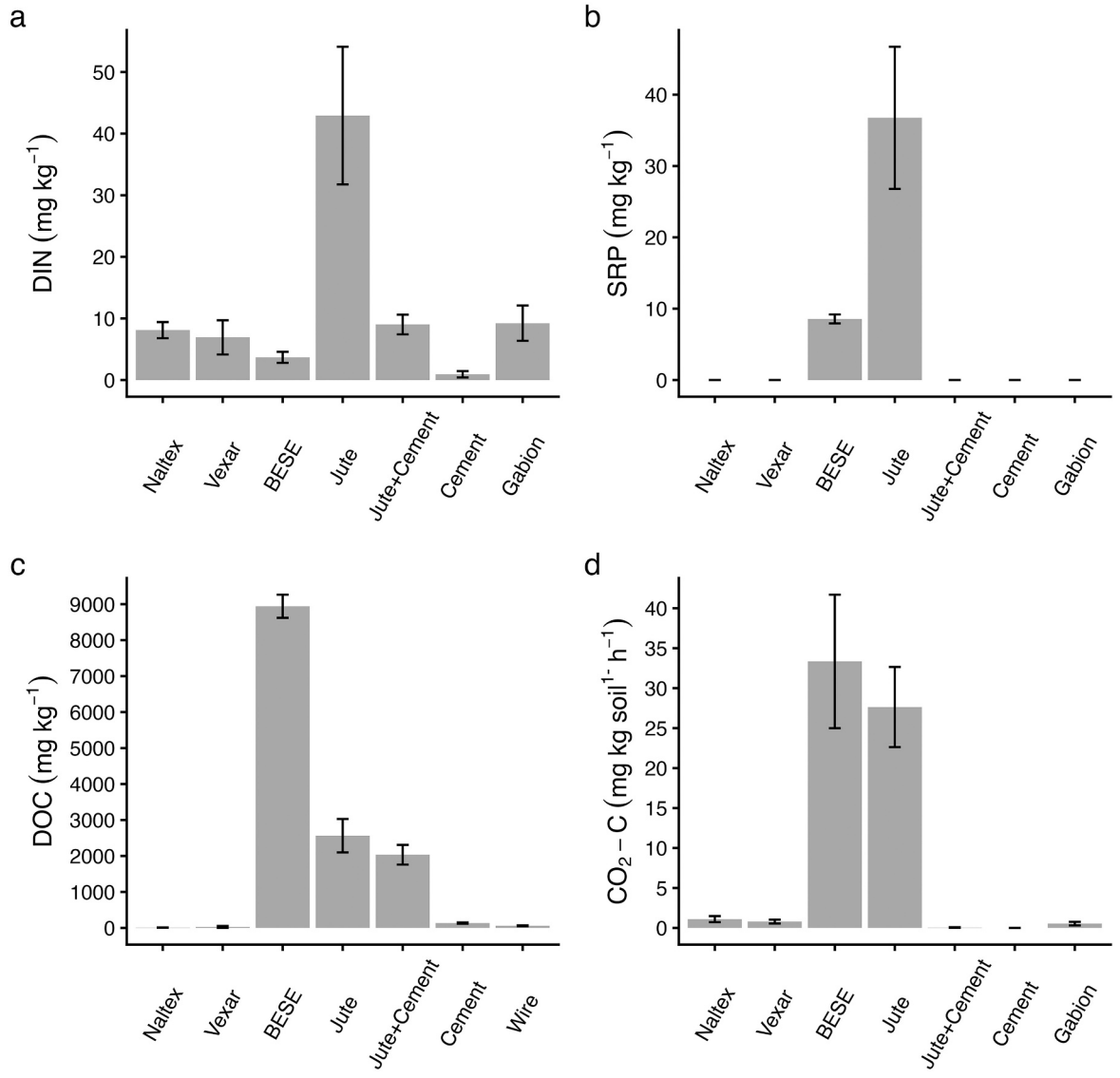

Fig. 3. Mass release of a) dissolved inorganic nitrogen (DIN), b) soluble reactive phosphorus (SRP), c) dissolved organic carbon (DOC), and d) microbial respiration rate (per kg of material) after correcting for the concentration in the simulated site water. Bars represent means (n = 5) and error bars represent standard error.

greater than jute and jute+cement (2299 ± 269 mg kg^{-1}) and all other treatments (59.4 ± 13.2 mg kg^{-1}; p < 0.0001; Fig. 3c). By concentration, the BESE released 554 ± 18.0 mg DOC L^{-1} (Table 2).

For the metal analysis, the concentration of Zn averaged ~28 times higher in bottles containing fresh galvanized steel gabion compared to the SSW control, and Fe was ~5 times higher with gabion (Table 3), but these differences were not significant due to high within treatment variability (p = 0.1 and 1.0 for Zn and Fe, respectively). Per mass of material, fresh gabion released 0.33 ± 0.23 mg kg^{-1} of Fe and 23.9 ± 6.1 μg L^{-1} of Zn. No other metal concentrations were elevated due to the fresh gabion.

Over time, BESE nutrient release declined in a roughly linear manner between 0 and 3 years of deployment for DIN and SRP, but both nutrients increased in year 4. Specifically, after 4 years of deployment, BESE released ~50% as much SRP was when fresh, and year 4 DIN release exceeded that of fresh material by ~23% (Fig. 4a). In tracking success of this material in the field, significant breakage of mats into smaller pieces occurs at year 4, while all were intact at year 3 (Walters, pers. obs.). In contrast, the release of DOC from BESE was much higher (8942 ± 321 mg kg^{-1} or 33.35 ± 8.35 mg L^{-1}) when fresh, then declined steeply following deployment in the field to a steady 490 ± 64.2 mg kg^{-1}, or 26.9 ± 3.6 mg L^{-1}, for years 1–4 (Table 2). Other noteworthy nutrient release on post-deployed material included very high concentrations of DIN (20.99 ± 7.33 mg L^{-1}) and SRP (0.68 ± 0.21 mg L^{-1}) on 4-year-old Naltex® and higher than expected DIN on some samples of post-deployed jute+cement and gabion (Table 2).

For metals over time, gabion released the greatest Fe, Mn, and Pb after 1-year deployed, then declined in year 2 (Fig. 5). Specifically, Fe was higher after 1-year deployed (321 ± 71.9 mg kg^{-1}) than when fresh (0.33 ± 0.23 mg kg^{-1}) and 2-years deployed (7.5 ± 12.7 mg kg^{-1}; both p < 0.001). All time points differed for Mn, with 1-year deployed material having the highest Mn release (7.5 ± 12.7 mg kg^{-1}), followed by 2-years deployed (1.29 ± 0.31 mg kg^{-1}), and fresh material (below detection; all p < 0.001). Lead release was greater after 1-year deployed (0.38 ± 0.14 mg kg^{-1}) than when fresh (0.01 ± 0.01 mg kg^{-1}; p = 0.01), which was not different from 2-years deployed (0.19 ± 0.12 mg kg^{-1}). In contrast, the oldest material (2-years deployed) released the most Zn (44.3 ± 18.2 mg kg^{-1}), but this release was not significantly different from fresh (23.9 ± 6.13 mg kg^{-1}) or 1-year deployed (13.9 ± 3.2 mg kg^{-1}; p > 0.05; Fig. 5) material.

Table 2
Material weight and concentrations (mean ± standard error; n = 5) of dissolved inorganic nitrogen (DIN), soluble reactive phosphorus (SRP) and dissolved organic carbon (DOC) measured in each 100 mL microcosm incubation after 5 weeks. Pre-deployed ("fresh") materials are highlighted in gray. SSW = simulated site water; BD = below detection.

	Time De-ployed	Material wt.	Water Vol.	DIN*	SRP*	DOC*	CO_2-C
	years	*g*	*mL*	*mg L^{-1}*	*mg L^{-1}*	*mg L^{-1}*	*mg kg $soil^{-1}$ h^{-1}*
Control (SSW)	–	–	100	0.83 ± 0.10	0.12 ± 0.03	6.92 ± 1.12	1.02 ± 0.13
Naltex®	0	6.73 ± 0.17	100	0.54 ± 0.09	BD	0.66 ± 0.24	1.10 ± 0.38
	4	5.51 ± 0.30	100	20.99 ± 7.33	0.68 ± 0.21	11.1 ± 2.90	5.00 ± 1.06
Vexar®	0	6.14 ± 0.04	100	0.42 ± 0.17	BD	2.22 ± 1.38	0.80 ± 0.24
	4	5.98 ± 0.02	100	0.47 ± 0.18	0.12 ± 0.03	2.38 ± 0.94	0.57 ± 0.49
BESE	0	6.26 ± 0.41	100	0.24 ± 0.07	0.53 ± 0.04	554 ± 18.0	33.35 ± 8.35
	1	5.43 ± 0.11	100	0.04 ± 0.04	0.36 ± 0.04	26.82 ± 6.98	7.17 ± 1.98
	2	5.34 ± 0.11	100	BD	0.14 ± 0.05	21.2 ± 7.54	6.51 ± 2.09
	3	5.62 ± 0.13	100	BD	0.09 ± 0.04	30.1 ± 6.06	5.64 ± 1.59
	4	5.29 ± 0.05	100	0.24 ± 0.18	0.23 ± 0.08	29.41 ± 9.37	6.24 ± 1.37
Jute	0	5.60 ± 0.52	100	2.49 ± 0.73	2.14 ± 0.69	147.0 ± 34.9	27.64 ± 5.01
Jute+Cement	0	33.8 ± 5.95^	100	2.68 ± 0.15^	BD	625.5 ± 53.7^	0.05 ± 0.22
	1	5.32 ± 0.09	100	0.08 ± 0.08	0.02 ± 0.02	4.21 ± 1.53	0.53 ± 0.13
	2	5.96 ± 0.28	100	1.47 ± 0.63	BD	0.30 ± 0.30	0.60 ± 0.13
Cement	0	28.3 ± 4.03^	100	0.24 ± 0.13^	BD	36.0 ± 1.14^	0.003 ± 0.002
Gabion	0	5.97 ± 0.06	100	0.55 ± 0.17	BD	3.55 ± 0.72	0.54 ± 0.22
	1	5.40 ± 0.14	100	2.10 ± 0.32	BD	8.18 ± 0.94	0.34 ± 0.11
	2	5.31 ± 0.13	100	0.05 ± 0.03	BD	0.90 ± 0.25	0.41 ± 0.09

* Note: all material nutrient concentrations are already corrected for the SSW control by subtracting the concentration in the respective control.
^ Note: fresh Jute+Cement and Cement were made in the incubation bottles and have a much greater mass than other treatments.

Table 3
Material weight and concentrations (mean ± standard error; *n* = 5) of manganese (Mn), iron (Fe), zinc (Zn), and lead (Pb) in each 100 mL microcosm incubation after 5 weeks. SSW = simulated site water; BD = below detection.

Material	Time Deployed	Material wt.	Mn	Fe	Zn	Pb
	years	*g*	*μg L^{-1}*	*μg L^{-1}*	*μg L^{-1}*	*μg L^{-1}*
Control (SSW)	–	–	2.56 ± 0.57	4.93 ± 0.93	53.5 ± 8.09	0.00 ± 0.00
Gabion	0	5.97 ± 0.06	0.68 ± 0.32	23.6 ± 14.3	1479 ± 364	0.57 ± 0.48
	1	5.40 ± 0.14	834 ± 71.1	17,271 ± 3719	806 ± 177	20.6 ± 7.09
	2	5.31 ± 0.13	70.4 ± 15.9	925 ± 673	2381 ± 959	9.80 ± 6.24

3.3. Microbial respiration

Microbial respiration was highest in incubations with BESE (33.3 ± 8.4 mg CO_2-C kg $soil^{-1}$ h^{-1}) and jute (27.6 ± 5.0 mg CO_2-C kg $soil^{-1}$ h^{-1}). BESE and jute were greater than all other treatments and controls, which together averaged 0.69 ± 0.11 mg CO_2-C kg $soil^{-1}$ h^{-1} ($p < 0.001$; Fig. 3d). The stimulating effect of BESE on microbial respiration was most evident for fresh material and declined with time post-deployment. However, BESE was still higher (6.4 ± 1.8 mg CO_2_C kg $^{-1}$ h^{-1}) than the control condition (1.0 ± 0.2 mg CO_2_C kg $^{-1}$ h^{-1}) through the first 4 years of deployment (Fig. 4b).

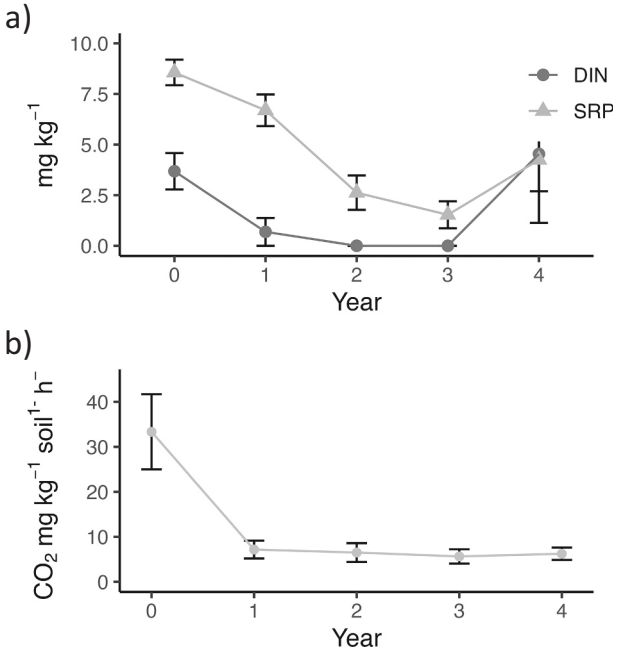

Fig. 4. Mass release of a) dissolved inorganic nitrogen (DIN) and soluble reactive phosphorus (SRP) from BESE material based on time deployed in the field, and b) microbial respiration rate per kg of BESE material based on time deployed. Data points represent means (n = 5) and error bars represent standard error.

4. Discussion

4.1. Plastic materials released microplastics, but not nutrients

Despite the documented success of PE materials in promoting oyster recruitment, reef building, and diverse reef faunal community development (e.g., Comba et al., 2023; Hadley et al., 2010; Stiner and Walters, 2008), the use of plastic restoration materials is now typically discouraged (or even prohibited) to avoid introducing macro- and/or micro-plastics in coastal waters. Oysters do ingest MPs, with one study documenting an average of 16.5 MPs per adult oyster (Waite et al., 2018). The oysters sampled by Waite et al. (2018) were collected on natural (not restored) oyster reefs and the MPs identified in their tissue were predominately fibers (95.6%), particularly blue-colored fibers; this suggests synthetic boat ropes or clothing are the likely origins, rather than PE restoration materials. Still, the concern remained: could PE restoration materials release MPs into the environment?

Incubating 1.3 g pieces of Vexar® and Naltex® in IRL site water under artificial light for one year demonstrated the potential of these plastic materials to release MPs into the marine environment. Per mass, Naltex® and Vexar® released 88 and 34 times more MPs than found in the water only control. However, because Naltex® is thinner and less

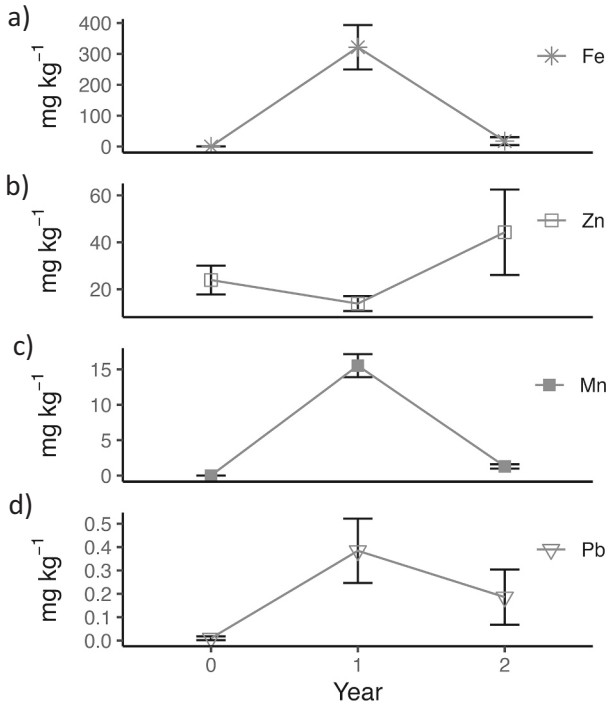

Fig. 5. Mass release of a) iron (Fe), b) zinc (Zn), c) manganese (Mn), and d) lead (Pb) from galvanized metal gabion based on time deployed in the field. Data points represent means (n = 5) and error bars represent standard error.

dense than Vexar®, per area (i.e., the amount of material needed to cover a surface during restoration) Vexar® would release more MPs. Ultraviolet radiation is considered a primary mechanism for PE degradation (Cai et al., 2018; Yao et al., 2022), suggesting these numbers are an underestimate of the MPs that would be released in the natural environment when exposed to sunlight and mechanical weathering (e.g., wave energy, sediment scouring). However, the material needed to be cut into smaller pieces to fit into the incubation bottle, creating a higher cut-surface to volume ratio than when used in the field. Therefore, future experiments under field conditions are recommended.

Based on Walters et al. (2022), an estimated 1.4 trillion MPs were present in the IRL at any given time in 2019–2020. If our laboratory results were extrapolated to an average-sized restoration project, a 500-ft (152.4 m) long living shoreline utilizing Naltex® (1200 bags, roughly 0.9 × 0.46 × 0.1 m each) could release an average of 20 million MPs in a year. Similarly, a "living dock" that included 50 Vexar® mats (0.61 m × 0.61 m^3) could generate an average of 3 million MPs after a year. The MPs found in the Naltex® and Vexar® samples were primarily gray or black colored fragments (>98%), unlike the blue fibers that appear to dominate the IRL water (Waite et al., 2018).

In the nutrient and respiration experiments, PE material release of SRP and DOC, and stimulation of microbial respiration, was all very low or below detection. The fresh PE materials did release low concentrations of DIN (7.5 ± 1.5 mg kg^{-1}). Being composed of long chains of ethylene (C_2H_4), PE materials should not contain any N but may include manufacturing additives or carry contaminants (e.g., experiments were conducted in non-sterile environments to mimic field deployment conditions). The study of the impacts of MP on N cycling and biogeochemical processes in the environment is still in its infancy, with initial results being highly variable based on material type and concentration (Zhou et al., 2024).

The aged Naltex® collected from the field (4-years post-deployment) released exceptionally high DIN, in addition to stimulating microbial respiration at rates similar to organic materials (Table 2). It is believed this is due to the development of a layer of algae on the Naltex® in the field that could not be completely removed, as was achieved with the other materials. Naltex® is a very fine PE mesh with pits and indents where the mesh strands meet, making 100% removal of the algal film impossible. Many studies have documented that plastics can serve as a substrate for biofilm development (i.e., consortia of bacteria, algae, and fungi) in aquatic environments (e.g., Lobelle and Cunliffe, 2011; Smith et al., 2021) and that biofilm development is most rapid on small plastics (Chen et al., 2019), which may explain the observed DIN release from post-deployment Naltex®. No other post-deployment materials demonstrated the dramatic increase in DIN seen with Naltex®, suggesting the cleaning efforts on those materials were more effective, but this limitation should be considered in the interpretation of the results.

Finally, it is noteworthy that the PE evaluation conducted in this study only identified MPs (the 0.025–5.0 mm size range) and did not quantify nanoplastics (< 0.001 mm), a contaminant of emerging concern in marine environments (Gonçalves and Bebianno, 2021). While few studies have quantified nanoplastics in the ocean due to the analytical challenges involved (Ter Halle et al., 2017), data suggest potential detrimental effects on organisms due to exposure or ingestion (Zaki and Aris, 2022). In this study, a gray film remained on the gridded filter paper of samples that contained Naltex® and Vexar®, but not on the water only control samples (see Supp. Fig. 1). Through SEM analysis and consultation with nanoscientists, this material is suspected to be nanoplastics, but this is speculative and additional analysis would be necessary to confirm and quantify.

4.2. Organic materials released N, P, and DOC and stimulated microbial respiration

Nitrogen and/or P are typically the major limiting nutrient(s) in coastal ecosystems, with the dissolved inorganic forms (DIN and SRP) being most easily assimilated by phytoplankton responsible for harmful algal blooms (Howarth, 1988). The IRL, like many developed coastal estuaries, has a history of nutrient enrichment (Sigua and Tweedale, 2003), which has been linked to decreased water quality, harmful algal blooms, and seagrass loss (Brewton and Lapointe, 2023; Lapointe et al., 2015). Because of the nutrient sensitivity of the study system, the possible contribution of N and P from organic restoration materials should be considered.

In our trials, per g of material, fresh jute released significantly more N than all other materials, including ~4.7 times more DIN than PE materials. By concentration, the ~5 g of fresh jute produced ~13.5 times greater DIN than the typical IRL background DIN concentration of 0.19 ± 0.02 mg L^{-1} (Chambers et al., 2018; Locher et al., 2021). BESE was not a notable source of DIN in this study, which differed from Nitsch et al. (2021), who found fresh BESE released low concentrations (0.02 ± 0.001 mg L^{-1}) of DIN.

Organic materials were predicted to show decreased nutrient release over time deployed, following the theory of pulse priming (Kuzyakov, 2010). However, BESE showed the highest rate of DIN release after 4 years of field deployment, roughly 23% greater than when fresh, and an increase in SRP release (Fig. 3d). The reason for this is unclear. All deployed materials were heavily coated with biofilms that had to be gently removed prior to incubation, but the coverage and success of removal of these biofilms was not noted to be different on the year 4 materials compared to years 1–3. Potentially, the initial composition of the BESE material differed over time (see *Experimental Considerations* below). Alternatively, the BESE biopolymers may be fabricated in layers, such that outer coatings degrade, exposing inner layers of a different composition. Multi-layer fabrication and coating techniques are used in other types of biopolymer manufacturing (Florez et al., 2023; Grzebieniarz et al., 2023), but its use in BESE is unknown and only speculative. The mean half-life of BESE was estimated to be 4.4 to 6.7 years in the IRL (Nitsch et al., 2021), so significant degradation was underway for this material. It was also noted that year 4 BESE had a unique appearance, including stains of gray, purple, and orange that were not as prominent on the BESE material from years 1–3 (see Supp. Fig. 2). Future work

should investigate the biogeochemical reactions that occur on deployed BESE and other biopolymers over time in the natural environment.

Similar to DIN, fresh jute also served as the largest source of SRP (nearly 37 times greater than the PE), followed by BESE (nearly 9 times greater than the PE). By concentration, ~5 g of fresh jute and fresh BESE produced, ~86 and 21 times greater SRP, respectively (Table 2), than the typical background SRP concentration of 0.03 ± 0.002 mg L^{-1} at the study site (Chambers et al., 2018; Locher et al., 2021).

While jute dominated in the magnitude of N and P release, BESE showed the greatest DOC release and stimulation of microbial respiration. Releasing 8940 ± 321 mg DOC kg^{-1} of BESE, the concentration of DOC in the BESE treatments averaged 60 times greater than the background concentration of the study site (i.e., 9.2 ± 0.6 mg DOC L^{-1}; Chambers et al., 2018; Locher et al., 2021); meanwhile, jute averaged 16 times greater DOC than study site background concentrations. Dissolved organic matter, which includes DOC and associated nutrients, fuels the growth and survival of the ocean's heterotrophic bacterial community (Lønborg et al., 2018, 2009), transferring energy into higher trophic levels (Carreira et al., 2021). The connection between DOC and bacteria is supported by our respiration data, which demonstrates BESE also produced the highest rate of microbial respiration, approximately 32 times greater than the control bottles (Fig. 3d). High DOC release and elevated heterotrophic respiration should be considered as a concerning ecological impact of organic restoration materials because it can alter biogeochemical cycling and contribute to the development of anoxic sediments (Middelburg and Levin, 2009), which can negatively impact benthic organisms (Rabalais et al., 2002).

4.3. Cement materials do not contribute nutrients and reduce degradation of organic materials

Cementitious restoration materials (including concrete, which is a mixture of cement and aggregates) come in varied shapes, sizes, and formulas, with the primary benefits being wave-energy dissipation, longevity, and a hard substrate for oyster recruitment. Maximizing surface area for spat settlement and managing alkalinity are important considerations when designing cement and concrete restoration materials (Rupasinghe et al., 2024; Uddin et al., 2021; Wallace et al., 2022). Our results indicate cement may have an additional benefit of sorbing N, P, and C and reducing the degradation rate of organic materials when mixed together. Specifically, jute alone was the largest source of DIN and SRP of all the materials studies, but when coated in cement (i.e., the jute+cement treatment), DIN, SRP, and microbial respiration decreased by 79, 100, and 99%, respectively. The impact of the cement coating on jute was less pronounced for DOC (~21% reduction). Other studies have found cement can remove phosphate ions from aqueous solutions through binding with minerals in the cement, such as Ca^{2+} (Agyei et al., 2002). Decreases in other analytes could be a result of the cement coating restricting microbial access to jute.

4.4. Metal materials corrode and release metals

Galvanized metal materials can be found in marine environments, such as crab traps, or gabion baskets filled with stone or rip rap for shoreline armament. The process of galvanizing, or the coating of metal with Zn, is intended to protect it from rust (Mackowiak and Short, 1979), but corrosion of galvanized metal increases in the presence of sodium chloride (Suzumura and Nakamura, 2004), the primary component of seawater. The resilience of gabions to corrosion is highly dependent on the local conditions and the type of structure, with studies indicating rigid gabions deployed in freshwater environments can last for decades (Thompson et al., 2016), while gabions, such as those used in this study, may have a much shorter longevity. For example, 18 gauge (1.024 mm diameter), hot-dipped galvanized steel mesh gabions were filled with oyster shells and deployed in the IRL in 2021 to reduce shoreline wave energy. Within the first 3 years of field deployment (at an average salinity of 29–45 ppt; Locher et al., 2021), all the exposed gabion wires were completely gone (100% degraded), with the only remaining evidence being piles of loose shell and fragments of intact and rusted wire buried beneath the sediment surface (Jensik, 2025). Sediments adjacent to where the galvanized wire gabions were deployed contained more Zn (35.7 ± 3.8 mg kg^{-1}) than nearby control sediment (5.1 ± 0.3 mg kg^{-1}), suggesting Zn coating leached from the material into the sediment (Jensik, 2025).

Our study found that ~5 g fresh (pre-deployment) gabion wire (18 gauge) increased Zn concentration in water an average of 2665% compared to the SSW control, and by roughly 4350% after 2-years of deployment (Table 3). While Zn is necessary for many cellular functions, at high concentrations it can be toxic to many organisms, causing both acute toxicity and chronic toxicity responses. Zinc can interfere with respiration and photosynthesis (Klimek, 2012; Sarker et al., 2021; Sieber et al., 2022), reduce growth rates of marine cyanobacteria (Sarker et al., 2021) and have species-specific impacts on estuarine benthic invertebrates (Watzin and Roscigno, 1997). The Zn concentration range recorded in this laboratory experiment (i.e., 169 to 5975 μg Zn L^{-1}) were at, or well above, the US EPA Aquatic Life Criteria for saltwater (i.e., 58 μg Zn L^{-1} for 24-h exposure and 170 μg Zn L^{-1} for the maximum exposure level; US EPA, 1980). In the natural environment, the Zn released from gabions would be diluted and dispersed in the water. However, as demonstrated by Jensik (2025), some Zn would remain stored in the sediment. Many factors, such as sediment organic matter content and pH, can impact the balance between Zn sediment sorption and surface water dissolution (Martínez et al., 2006; Singh et al., 2008).

Iron, Mn, and Pb were also elevated in gabion samples collected from the field, particularly those that had been deployed for 1 year. While galvanized wire is assumed to be steel (i.e., carbon and Fe) coated in Zn, other alloying metals can be added to improve properties, or they may be present due to impurities in manufacturing (Cocheci et al., 2018). The Zn coating is intended to slow corrosion, but the observed release of Fe was evidence that the coating was damaged. This can be caused by pitting corrosion, which has been observed within 14 days of submerging galvanized steel plates in seawater (Sun et al., 2013). The Fe, Mn, and Zn are all documented constituents of commercially available galvanized wire (Marandi and Sen, 2019), but the Pb is not, to our knowledge. The highest Pb concentration was released by 1-year deployed gabion (20.6 ± 7.09 μg Pb L^{-1}). The US EPA data on saltwater species suggest a threshold of 5.6 μg Pb L^{-1} for chronic exposure and 140 μg Pb L^{-1} for acute exposure but acknowledges factors like hardness impact the toxicity of Pb (USEPA, 1985).

4.5. Experimental considerations

This research leveraged real-world oyster reef restoration projects performed over the preceding four years in the IRL. Using actual projects is advantageous in improving external validity (i.e., the results are more comparable to what other real-world restoration practitioners may find), but the study design also decreases experimental control. For example, restoration practitioners typically buy materials as funds become available, and when permits are approved. Subsequently, sources and types of materials can change over time. Additionally, most restoration materials are privately manufactured, often internationally, with limited regulations or quality control/quality assurance guidelines required to be followed. Therefore, the chemical composition of a product is often unknown and could vary greatly with time, or by batch. The lack of transparency in product manufacturing, and the potential for undisclosed changes to the formula, make it difficult to evaluate material performance over time. For example, the DIN released from BESE in this study differed from that documented in a previous study (Nitsch et al., 2021), but anecdotally the product itself changed– the BESE purchased for the 2021 study was off-white in color, while the same product was gray when purchased for the current study. Leveraging actual restoration projects increased the applied external validity of our

findings for restoration practitioners, but also prevented the ability to control the exact properties of the previously deployed materials. This makes it impossible to determine if, for example, the observed increase in nutrient release from BESE after 4-years deployed (Fig. 4) is a result of unique chemical processes as it ages, or production changes over time. Similarly, the spike in metal concentration (i.e., Fe, Mn, Pb) released from gabion after 1-year deployed (Fig. 5) could be due to the loss of the Zn coating, or qualitatively different products supplied.

This study utilized closed microcosms in a laboratory setting to quantify the effects of different materials on an aqueous solution. Efforts were made to mimic field conditions to the extent possible (e.g., salinity, nutrient content, temperature, and water movement were chosen based on typical IRL conditions), but we could not control for dilution, dispersion, and the complex array of biotic and abiotic factors that impact materials in nature. Additional research in a field setting is necessary.

4.6. Diverse factors contribute to restoration material choices

While the biogeochemical releases of alternative restoration materials documented in this study are an important consideration when choosing products, they are not the only consideration. Typically, the primary interests in oyster reef restoration projects are recruitment success metrices (e.g., oyster density, number of live oysters, reef height, etc.). Although not the focus of this study, our data indicates similar oyster recruitment on BESE and jute+cement after 1 and 2 years deployed. After 4 years, BESE recruitment was comparable to a nearby natural reference reef.

Other trade-offs to consider in choosing a material include public perception, longevity, cost, and volunteer friendliness. Generally, the cost per unit is higher for non-plastic materials (e.g., $20–$45 m^{-2}) compared to plastics (e.g., $3–$10 m^{-2}) and some alternative materials may have lower volunteer friendliness due to fragility (e.g., BESE mats are brittle) or hazards (e.g., caustic chemicals or dust, in the case of cement) (Walters et al., 2022). Overall, it is important to weigh all costs and benefits before choosing a material, including studying the microbial and biogeochemical impacts of it before deploying it into the natural environment at a large scale.

5. Conclusions

Based on our laboratory results, the concern that PE restoration materials may be releasing MPs into the environment is well supported, as ~1.3 g of Naltex® released between 190 and 800 individual MPs in one year, while Vexar® released between 24 and 396 in laboratory conditions. This concern for marine MPs, coupled with public and regulatory pressure to utilize more "eco-friendly" materials, has resulted in a rapid shift toward diverse, and largely untested, alternative restoration materials. This study quantified the biogeochemical release and microbial respiration of two fully synthetic PE plastics that were historically common in aquaculture and restoration (Naltex® bags and Vexar® mats), two non-organic, non-plastic materials (cement and galvanized metal gabions/crab pots), two organic materials (BESE and jute), and one combination organic/non-organic material (jute+cement).

As hypothesized, the organic materials studied (BESE and jute) were a source of N, P, DOC, and CO_2-C under laboratory conditions. Specifically, jute was the largest contributor of N and P to the water, while BESE had a higher release of DOC and CO_2-C. Although quantified in a laboratory setting, the magnitude of the concentrations observed suggests they may be ecologically significant, even in a field setting. Specifically, 14- and 86-times greater concentrations of DIN and SRP, respectively, were observed for jute incubations when compared to background site water concentrations, and a 60-times greater concentration of DOC was observed for BESE incubations than background site water. In contrast, cement showed promise as being relatively inert for the properties measured (all releases were near or below the detection limit) and may even sorb nutrients from organic materials when they are mixed with cement. Finally, galvanized metal gabion had low or no nutrient releases, but high leaching of certain metals in this study. Zinc, Fe, Mn, and Pb were all released from laboratory incubated gabion, sometimes at concentrations well above aquatic life standards. Restoration practitioners should include these biogeochemical properties and potential chemical releases as considerations when weighing the trade-offs of alternative restoration materials.

CRediT authorship contribution statement

Lisa G. Chambers: Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Sara Gay:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Naija Cheek:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation. **Cadie Barnes:** Writing – review & editing, Visualization, Formal analysis, Data curation. **Megan Jensik:** Writing – review & editing, Writing – original draft, Methodology. **Melinda Donnelly:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Paul E. Sacks:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Investigation, Conceptualization. **Melanie Beazley:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Conceptualization. **Linda J. Walters:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Lisa G. Chambers reports financial support was provided by Indian River Lagoon National Estuarine Program. Linda J. Walters reports financial support was provided by Indian River Lagoon National Estuarine Program. Melinda Donnelly reports financial support was provided by Indian River Lagoon National Estuarine Program. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was funded by the Indian River Lagoon National Estuarine Program (IRL NEP) under grant IRLNEP 2022-14 to L.J. Walters, L.G. Chambers, and M. Donnelly. The authors would like to acknowledge all participating CEELAB and ABL lab members for their assistance with field and laboratory work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2026.119329.

Data availability

Data will be made available on request.

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