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First-Year Performance of the Pervious Oyster Shell Habitat (POSH) along Two Energetic Shorelines in Northeast Florida

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Abstract: Novel living shoreline methods are being developed to minimize negative environmental impact while maintaining strength and effectiveness in high-energy systems. The "Pervious Oyster Shell Habitat" (POSH) is a novel structure composed of oyster shells bound by a thin layer of Portland cement into the shape of a dome. The structure's makeup greatly reduces its environmental impact while providing optimal substrate for the provision of oyster reef habitat. Previous laboratory testing has demonstrated that the structure is robust, and this follow-up study assesses the structure's performance in the estuarine environment. Oyster and barnacle densities were compared between POSH modules and the industry standard "Oyster Ball" model Reef Ball™ along two energetic shorelines in northeast Florida. Oyster densities on the POSH were high and significantly greater than on the Oyster Ball at both sites. Barnacle densities did not differ between structures and did not appear to affect oyster recruitment. The size distribution of oysters on POSH and Oyster Ball modules was measured to assess the demographics and growth of oysters over time. Overall, demographics were similar among the two structures. Differences in oyster densities and demographics were greater at our more energetic site. Results show that the POSH can be an optimal structure for early oyster recruitment and reef development in energetic systems and should be considered by restoration stakeholders.

Keywords: *Crassostrea virginica*; oyster; restoration; living shoreline; Florida; non-plastic; alternative substrates; Pervious Oyster Shell Habitat; POSH; Reef Ball™

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1. Introduction

The eastern oyster (*Crassostrea virginica*), hereafter *oyster*, is an important ecosystem engineer in the estuarine environment. Oysters provide many ecosystem services, including denitrification, water filtration, shoreline stabilization, and habitat provision for many ecologically and commercially important fish and crustaceans [1–7]. Oyster reefs have been lost over decades of overharvesting, disease, and degradation of water quality [8], with an estimated 85% loss of oyster reef habitat globally [9]. Much of the overall loss of biodiversity and ecosystem services in our estuaries has been directly and indirectly attributed to the decline of oyster reefs [10–12].

The dramatic decline of oyster reef habitat and growing pressure on saltmarsh habitats have led to the widespread implementation of shoreline restoration and enhancement projects to promote shoreline stabilization and the recovery of lost ecosystem services. There are a variety of restoration methods, each with varying levels of success and applicability. The need for innovation has led to the development of living shorelines and the use of natural or human-made resources to create a biogenic structure capable of protecting shorelines from erosion while enhancing or recovering lost ecosystem services. With growing recreational boat traffic along many waterways and threats of increasing storm intensities resulting from climate change, there is a clear need for methods that will remain resilient in increasingly energetic systems. Restoring or enhancing oyster reefs is a common living shoreline method as the oyster reef matrix helps attenuate wave energy and enhances other lost ecosystem services over time. Creating living shorelines through the formation of oyster reefs will be the focus of this paper.

Attempting to restore oyster reefs on high-energy shorelines presents challenges. There is a limit to the amount of wave energy that oysters can tolerate [13,14], making wave attenuation through porous structures necessary for shoreline stabilization [7]. Restoration materials need to withstand years of exposure to energy from boat wakes and storms while maintaining function. The following is a short review of current methods in the field, including the pros and cons associated with their use in high-energy systems.

Oyster shell is a commonly used substrate for restoration, as shells are known to release conspecific chemical cues, which promote oyster settlement and recruitment [15–17]. Oyster shells are either scattered loose or, more commonly, bagged in polyethylene mesh aquaculture netting. Bagged oyster shell has been one of, if not the most popular, restoration method for decades due to its price and ease for stakeholders to make and deploy. Though, this method can be ineffective in energetic systems, as shells are not stabilized, and plastic bagging materials can contribute to microplastic pollution over time through mechanical and photodegradation. The use of concrete as an alternative substrate for oyster reef restoration has shown promising results for oyster recruitment, settlement, and growth [18–20]. Concrete structures are a cost-effective method when oyster shell is unavailable, and they can be resilient in high-energy systems, though they demand a lot of cement to bind aggregate, an industry that contributes ~8% to global CO_2 emissions [21]. Sinking of heavy materials can result in the loss of vertical relief, affecting habitat quality [19], and concrete can be subject to biofouling in some systems [22]. A novel method involving biodegradable materials (BESE-elements®) greatly reduces negative environmental impact through its breakdown after reef formation. Though, BESE mats can be costly and degrade too quickly in energetic systems, limiting their sustainability [23]. Methods utilizing calcium sulfoaluminate (CSA) cement as a binding agent and rigid galvanized wire gabions to hold shells reduce the carbon footprint of production and eliminate the use of plastics while maintaining strength in energetic systems [24,25]. CSA cement can be significantly more expensive than Portland cement and is produced in only a few locations, increasing shipping costs. A living shoreline method pairing permeable breakwalls with oyster shell-filled gabions was shown to be successful at recruiting oysters, reducing wave energy, and facilitating the enhancement of ecosystem services, though this method can be costly and require too much maintenance for some stakeholders [7]. In addition to the substrate used, structural complexity and increased interstitial space are important considerations for enhancing recruitment of oysters and organisms that use intertidal oyster reef habitat [22]. Interstitial space can increase the survival of nekton that need shelter from predation, especially at the larval or juvenile stage [5,26]. Previous studies have demonstrated habitat complexity as a major factor in increasing the abundance and production of valuable fish and crustacean species found in oyster reefs and marsh habitats [5,27–37].

Reef Innovations' "Oyster Ball" has become a popular method for oyster reef restoration due to its concrete construction and porous design [38]. It contains 6–8 large holes for fish and crustaceans to utilize, and each unit has a lot of surface area for larval oysters to settle on (Figure 1) [30,37–40]. This design can present challenges for oyster recruitment because many marsh environments have finer sediment where sinking of heavier materials and loss of vertical relief is a risk. In addition, smaller portions of interstitial space are important for harboring small organisms and decreasing wave velocity for larval oyster settlement and growth [41–43].

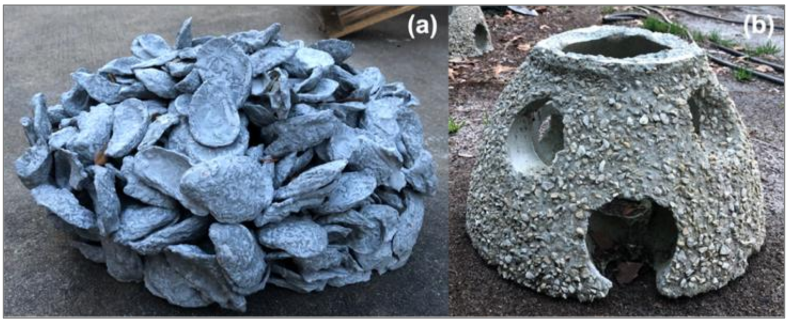

Figure 1. (**a**) POSH and (**b**) Oyster Ball module.

The "Pervious Oyster Shell Habitat" (POSH) was developed out of the apparent need for innovation of non-plastic and more sustainable living shoreline methods for high-energy systems [44]. The POSH is composed of 36 pounds of oyster shell (>2.5 cm) bound together by a thin layer (9 pounds) of Portland cement into the shape of a dome. The POSH's structural composition considers the success of cement-based substrates in recruiting and sustaining oysters, decreased weight for transportation, increased surface area, and the need for more interstitial space within the structure. The POSH's increased complexity is evident, and there is a more efficient use of surface area when compared to the Oyster Ball (Table 1). The POSH and Oyster Ball are around the same price per unit, though with minimized transportation costs and the use of recycled materials, the POSH can be substantially cheaper. Oyster shells used for POSH structures were donated from the *Friends of the Guana Tolomato Matanzas National Estuarine Research Reserve*'s oyster shell recycling program, which collects oyster shells from restaurants and events for the purpose of reuse in restoration projects. The POSH has a more effective use of oyster shell than bagged and loose-shell methods, which is beneficial considering the growing cost and diminishing availability of oyster shell [45,46]. Production of the POSH includes a decreased cement content, resulting in a 54% decrease in the carbon footprint of production per unit when compared to the Oyster Ball [44]. Construction is more labor intensive than the bag or gabion methods, and ~1 month must be set aside for the cement to cure, but restoration practitioners can alter the POSH module design as needed. In a laboratory study, the mechanical properties of the POSH were demonstrated to be robust, and this study is the first test of its effectiveness in the field [44].

Table 1. POSH and Oyster Ball module form comparison.

Property	POSH	Oyster Ball
Weight	14 kg	22.7 kg
Height	26 cm	27 cm
Diameter	44 cm	24–44 cm (top-base)
Volume	~6100 cm^3	~10,800 cm^3
Void Space	58%	0%

To assess the initial performance of the POSH in rebuilding oyster reefs, monitoring recommendations were adopted from Baggett et al., including oyster density, size frequency distribution, and reef height [47]. The POSH has been assessed against the Oyster Ball due to its similar cementitious makeup, size, and differences in complexity. In this paper, oyster settlement describes the early attachment of oyster spat (<2.5 cm) to live oysters and structures. Oyster recruitment describes juvenile and adult-sized oysters (>2.5 cm) remaining alive on structures after one year. A preliminary study compared monthly oyster spat and barnacle settlement on shells coated in Portland cement and untreated oyster shell over the course of two months in the fall of 2020. This was performed before the deployment of structures in the summer of 2021. The settlement was measured as the # of oysters and barnacles per shell each month. Oyster recruitment in # of oysters/100 cm^2 was assessed on POSH and Oyster Ball modules a year following the deployment of structures. Barnacle recruitment (# of barnacles/100 cm^2) was also assessed to observe the potential effects of competition on oyster recruitment and substrate preference of barnacles. Oyster size distributions were measured 4 months post-deployment, following optimal oyster spat settlement and growth conditions in the area, then again at 1 year post-deployment with recruitment sampling. Module or "reef" height above the sediment surface was measured at the time of recruitment sampling to observe any differences in vertical relief from sinking modules or settled oysters. For the preliminary spat settlement study, we hypothesized that (H_1) oyster spat settlement per shell would be greater on untreated oyster shell due to known preference and release of cues from conspecifics [15–17]. As a result of greater spat settlement, we hypothesized that (H_2) barnacle settlement per shell would be greater on cement-coated shell. For the structure comparison, we hypothesized that (H_3) oyster density would be greater on the POSH at both sites due to the increased complexity and surface area and the use of the oyster shell in the matrix, and (H_4) barnacle density would be greater on the Oyster Ball at both sites resulting from the lower oyster densities predicted. Oyster size distribution and reef heights were not measured for statistical comparison.

2. Materials and Methods

2.1. Study Sites

The study sites were Kingsley Plantation at the Timucuan Ecological and Historic Preserve (81.4367451° W, 30.4401693° N) and Wright's Landing at the Guana Tolomato Matanzas National Estuarine Research Reserve (GTMNERR) (81.3358119° W, 30.0026511° N) (Figure 2). These are ecologically impaired, high-energy areas along two major river systems. These shorelines have experienced significant degradation through the loss of oyster reefs and smooth cordgrass (*Spartina alterniflora*; hereafter, *spartina*).

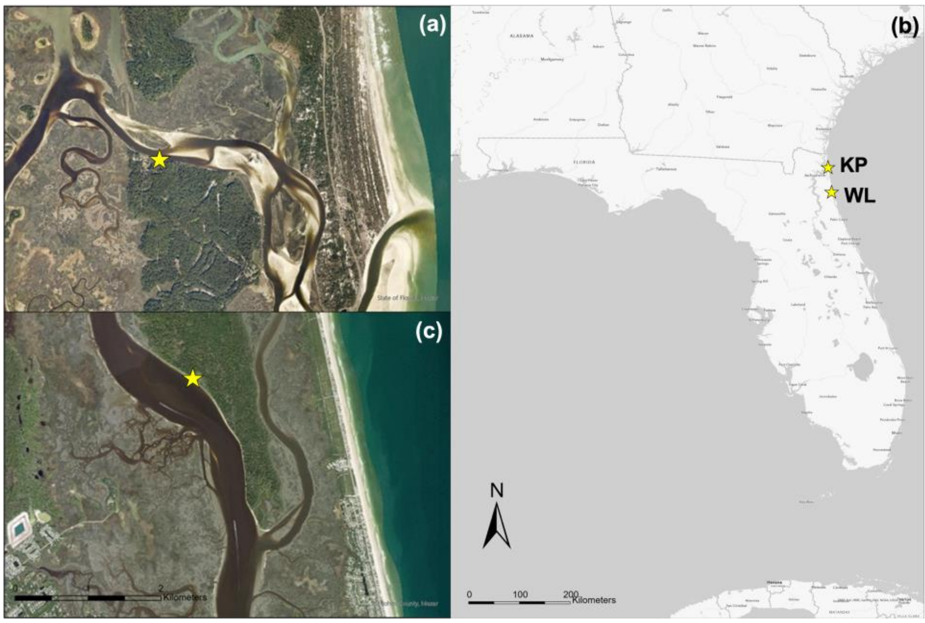

Figure 2. Study sites. (**a**) Kingsley Plantation (KP) along the Fort George River (81.4367451° W, 30.4401693° N), (**b**) both sites in northeast Florida, and (**c**) Wright's Landing (WL) along the Tolomato River (81.3358119° W, 30.0026511° N).

The shoreline along Kingsley Plantation is best described as an open beach, with dispersed live and dead oyster clusters and sparse patches of spartina seedlings. Adjacent is a natural oyster reef preceding healthy spartina and scattered *Batis maritima.* Bricks and other artifacts from the plantation have been buried along the open shoreline and are slowly eroding from the sediment. The Fort George River has experienced interruptions in flow and sedimentation since the construction of the Fort George Inlet North Jetty in 1886. This has resulted in severe erosion of Little Talbot Island in the northern inlet, northern migration of the inlet, and substantial sediment buildup along the Fort George River channel [48]. These sandbars along the river channel have become a popular destination for recreational boaters, and marsh erosion continues to be substantial with high daily recreational boat traffic and no local limitations on boating speed. Recent storms in the area, such as tropical storm Ian, have continued to erode the exposed upland forest behind the Kingsley Plantation shoreline.

We have estimated a 15.9-hectare loss of marsh edge cover along the main Fort George River channel from 1960–2020 (Figure 3). A 35.8-hectare gain in marsh cover was measured along the center of the main channel due to the substantial sediment accretion. This has likely resulted in the narrowing of certain channels and increased pressure on the marsh edge in those areas. To perform the analysis, two historical aerial images of the Fort George River were downloaded from the University of Florida's George A. Smathers aerial photography library [49]. Photos were georeferenced to fit the same elevation and area of the 2020 base map in ESRI ArcGIS Pro. The marsh area along the main channel was then digitized with polygons on the historical imagery and the 2020 base map. Differences in polygon area between the two periods were calculated to assess change in marsh edge cover from 1960 to 2020. Marsh loss may be underestimated due to differences in tidal heights in the imagery from the different periods.

Figure 3. Changes in marsh cover along the Fort George River (1960–2020). Orange polygons represent three areas with the greatest loss of marsh edge cover and green polygons represent areas of marsh gain. The star marks the Kingsley Plantation study site. Map by Hunter Mathews. Sources: ESRI 2022, University of Florida, George A. Smathers Libraries, Labins.org.

The shoreline at Wright's Landing is an open beach with scattered oyster beds from previous restoration projects, preceding a thin patch of spartina, saltwort (*Batis maritima*), and dense black mangrove (*Avicennia germinans*). The Tolomato River is a heavily trafficked river with daily use by recreational and commercial vessels. A study found that from 1970–2002, ~70 hectares of shoreline habitat were lost along 64.8 km of channel margin of the river, likely caused by consistent boat wake energy [50]. Recent data collected along the Tolomato River south of Wright's Landing has shown that marsh grasses are eroding at a rate of ~1 m/year [51]. A previous restoration project at Wright's Landing took place from January 2012 to May 2014 along ~457 m of shoreline. Restoration materials included coir fiber/coconut logs, mesh bags with recycled oyster shell, and planted spartina seedlings [52]. The restoration project resulted in improved sediment deposition behind structures [53] and habitat provision [54]. Most materials were removed or did not remain along the shoreline.

2.2. Experimental Design

This study took place over thirteen months, beginning in June 2021. Both locations have nine POSH modules and nine Oyster Balls. Modules were placed as "reefs" near the mean low water line (MLW) into groups of three, each reef being separated by 2 m to reduce the risk of stranding marine mammals as required by federal permits (Figure 4). Each unit of the reef was spaced about 5 cm apart to allow the growth of oysters, though close enough to allow for aggregation of modules over time. The three-module reefs were initially separated by type by 3 m to allow for a more accurate assessment of fish and crustacean utilization with seine and trawl. The faults of this design are addressed in the discussion. The orientation of the two treatments was decided by coin flip. The entire restoration area at both sites is separated from any natural or restored oyster beds by at least 20 m. Deployment of the modules at Kingsley Plantation took place on 2 June 2021, and deployment at Wright's Landing took place on 2 July 2021. Deployment dates were chosen based on increased spat settlement in the area during this season (Mathews, H. Pers. obs., GTMNERR staff 2020).

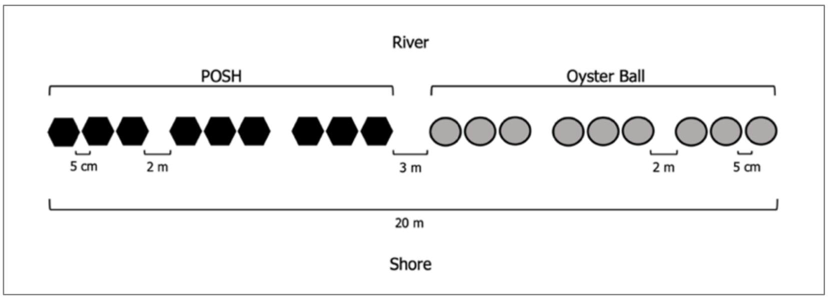

Figure 4. Living shoreline design schematic for Kingsley Plantation and Wright's Landing. Each group of three structures is referred to as a "reef".

2.3. Data Collection

2.3.1. Oyster Spat Settlement on Cement-Coated and Untreated Oyster Shell

Monthly oyster spat and barnacle settlement on cement-coated and untreated oyster shell were assessed from 15 September–15 October and 15 October–25 November 2020. Sampling methods followed the Florida Fish and Wildlife Research Institute's spat monitoring protocols [55]. Spat t-bars constructed from PVC pipe were placed into four replicate pairs along the beach at Kingsley Plantation. Each t-bar held six cement-coated shells on its east arm and six untreated oyster shells on its west arm, strung on galvanized wire 13 cm from the bottom shell to the sediment surface. Oyster spat and barnacle densities, as the # per underside of the shell, were assessed on the inner four shells using a dissection scope for oyster spat and ImageJ for barnacles.

2.3.2. Oyster and Barnacle Densities on Artificial Reef Modules

Densities of oysters and barnacles per 100 cm^2 were assessed on each module a year after deployment (May–July 2022). VIVOSUN elastic trellis netting with 15 × 15 cm grids was laid over the surface of each module to define 225 cm^2 squares over the entirety of the structure. This allowed us to systematically sample a standard area within squares that conformed to the modules' surface. Within each square, the total number of juvenile and adult oysters (>2.5 cm) and barnacles were counted to assess the number of individuals/225 cm^2. Oyster spat (<2.5 cm) density was separately assessed as new settlement to the structures. Organisms that settled under the gridlines were included in counts of the grid where the majority of their shell was attached. Due to differences in module composition, the Oyster

Ball's internal and top surfaces could not be accurately compared for densities; therefore, only the sides of each module were statistically compared for recruitment. The entirety of each structure's surface was assessed at the Kingsley Plantation site, so all full 225 cm^2 squares on the sides (upstream, downstream, landward, seaward) of structures were used for assessment, leading to uneven sample sizes. One square per side (upstream, downstream, landward, seaward) was assessed at Wright's Landing. Three squares for the POSH at the Wright's Landing site could not be accurately assessed due to proximity to nearby modules and were omitted for analysis. Densities were adjusted to individuals/100 cm^2 by multiplying density values by the proportion of 100 cm^2/225 cm^2 (=0.44) to assess the number of oysters and barnacles per 100 cm^2.

2.3.3. Oyster Size Distribution on Artificial Reef Modules

Shell heights of oysters on each module were measured at 4- and 12-months post-deployment. Early measurements were taken after optimal oyster spat settlement and growth conditions at both sites. Due to the limited availability of samples at 4 months, all oysters that could be reliably measured on each module were measured. At 12 months, oysters were sampled for shell height using a stratified random sampling design. Directional degrees were selected by a random number generator, then a compass was used to locate these degrees, and beaded chains were draped along the corresponding axes. Any oysters that fell under the chain were measured. If there were no oysters under the chain, oysters within 5 cm of the chain on either side were measured. Three degrees were used on POSH modules at Kingsley Plantation, and all measurable oysters were measured on Oyster Balls due to limited recruitment. Four degrees were used at Wright's Landing due to greater recruitment on both structure types. Shell heights were measured with calipers to the nearest millimeter from the base of the umbo to the farthest grown edge of the shell. Oysters were classified as spat (<2.5 cm), juvenile (2.5–7.5 cm), and adult (>7.5 cm) [20].

2.3.4. Reef Height of Artificial Reef Modules

The total height of each module was measured at the time of recruitment sampling, one year after the modules were deployed. Due to noticeable differences in sediment accretion on the seaward and landward ends of each structure, separate measurements were taken on either end. One POSH and Oyster Ball module was moved at the Kingsley Plantation site due to shifting, so these modules were omitted from the assessment. A bubble level was hung from nylon string and run from the highest point of the module, whether it be structure, oyster shell, or barnacle, to a meter stick held at the perimeter of the module on the landward and seaward sides [56]. The same high point was used for both measurements. Total height was measured to the nearest centimeter. Initial measurements were not taken upon deployment, so changes in reef height could not be accurately assessed.

2.4. Data Analysis

Analyses were performed through *Minitab* to observe any differences in oyster and barnacle settlement for substrate comparison and to compare recruitment between the two module types. Data were tested for homogeneity of variance and normality using the Ryan-Joiner test (similar to Shapiro–Wilk) and logarithmically transformed to fit a normal distribution if necessary. Independent samples *t*-tests were run to compare oyster spat and barnacle settlement to cement-coated and untreated oyster shells, oyster and barnacle densities between the modules at both sites and oyster spat densities between the modules at Wright's Landing. Normal distributions were not achieved for oyster densities on the Oyster Ball at Kingsley Plantation or barnacle densities at either site, so the nonparametric Mann–Whitney U test was run. The top and interior sides of the Oyster Ball cannot be accurately quantitatively compared to the POSH, so only the landward, seaward, upstream, and downstream sides were used for comparison. Size distribution and reef height were not compared with statistical tests.

3. Results

3.1. Oyster Spat Settlement on Cement-Coated and Untreated Oyster Shell

Oyster spat settlement was significantly greater on cement-coated oyster shells for both October ($p < 0.01$) and November ($p < 0.01$). Mean settlement (±1 SE) on cement-coated shells for October was 24.0 ± 2.1 spat/shell, and for November, 3.9 ± 0.4 spat/shell. Mean settlement on untreated shells for October was 17.2 ± 1.4 spat/shell, and for November, 2.6 ± 0.3 spat/shell (n = 32/treatment/month) (Figure 5).

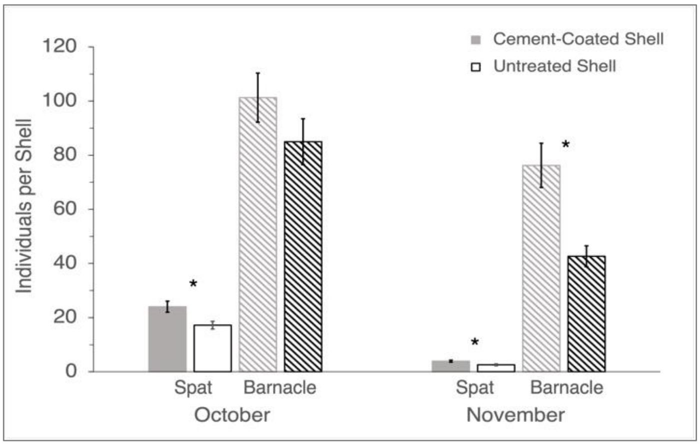

Figure 5. Settlement substrate comparison. The number of oyster spat per shell on cement-coated and untreated oyster shells at Kingsley Plantation. Error bars represent ±1 SE. Significant differences (*) in oyster spat were found for both months, and a significant difference in barnacle settlement was found for November (independent samples t-test).

Barnacle settlement did not differ between the two substrates in the month of October ($p > 0.05$) but was significantly greater on cement-coated oyster shells in November ($p = 0.001$). Mean barnacle settlement on cement-coated shells for October was 101.3 ± 9.1 barnacle/shell, and for November, 76.3 ± 8.2 barnacle/shell. Mean settlement on the untreated shells for October was 85.0 ± 8.5 barnacle/shell, and for November, 42.7 ± 3.9 barnacle/shell (Figure 5).

3.2. Oyster Densities on Artificial Reef Modules

Oyster densities were significantly greater on the POSH at both Kingsley Plantation ($p < 0.000$) and Wright's Landing ($p < 0.01$). Oyster recruitment was high and consistent on the POSH at both sites. Mean density (±1 SE) at Kingsley Plantation for the POSH was 5.0 ± 0.2 oysters/100 cm^2 (n = 69), and at Wright's Landing, 5.0 ± 0.3 oysters/100 cm^2 (n = 33) (Figure 6a). Recruitment on the top of the POSH at Kingsley Plantation was similar to that of the other sides of the structure (Table 2). At Wright's Landing, recruitment was significantly lower on the top of the POSH, possibly due to differences in elevation and inundation period. Recruitment on the Oyster Ball was more variable between sites. Mean density at Kingsley Plantation was 0.9 ± 0.1 oysters/100 cm^2 (n = 39), and at Wright's Landing, 3.9 ± 0.2 oysters/100 cm^2 (n = 36). The interior side of the Oyster Balls at Wright's Landing had dense oyster settlement, with 70–100% cover by visual estimation (Table 2). The interior side of Oyster Balls at Kingsley Plantation resembled densities on the exterior sides. Oyster spat settlement at Kingsley Plantation was negligible at the time of sampling, so not enough samples were collected to compare densities between modules. Oyster spat densities at Wright's Landing were similar among the POSH, 6.6 ± 0.8 spat/100 cm^2 and Oyster Ball, 8.2 ± 0.8 spat/100 cm^2 ($p > 0.05$) (Figure 6b).

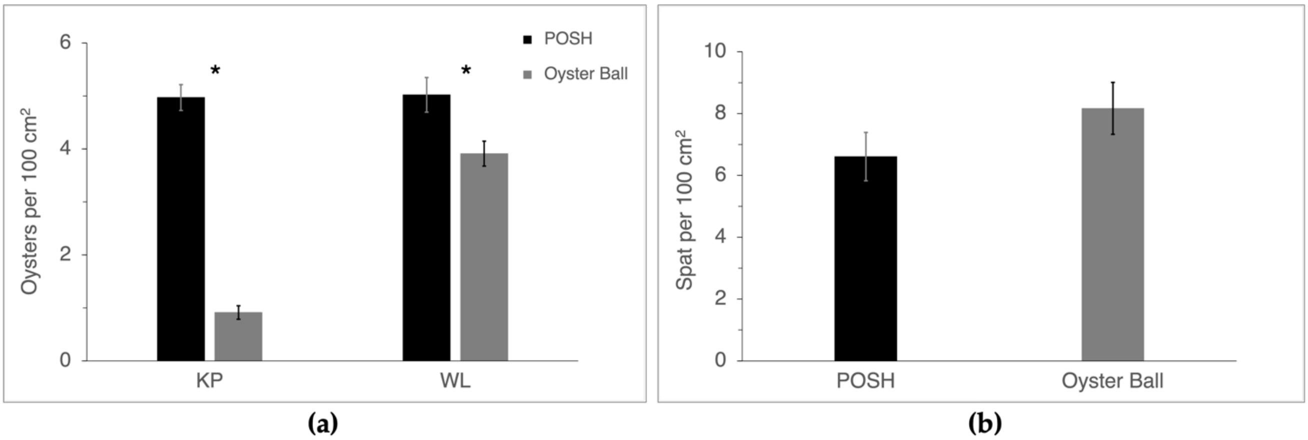

Figure 6. (**a**) Oyster density comparison. Number of oysters per 100 cm^2 on the POSH and Oyster Ball at Kingsley Plantation and Wright's Landing. Error bars represent ±1 SE. Significant differences (*) were found at both sites (KP, Mann–Whitney U *t*-test; WL, independent samples *t*-test). (**b**) Spat density comparison at Wright's Landing. The number of oyster spat per 100 cm^2 on the POSH and Oyster Ball at Wright's Landing. Error bars represent ±1 SE. No significant difference was found (independent samples *t*-test).

Table 2. Oyster and barnacle density averages for non-tested sides of POSH and Oyster Balls (OB).

Site	Module	Side	n	Oyster	SE	Barnacle	SE	Spat	SE
KP	POSH	Top	35	5.1	0.3	1.7	0.6	NA	NA
	OB	Top	9	1.1	0.3	0.0	0.0	NA	NA
	OB	Interior	9	4.1	0.9	1.5	0.5	NA	NA
WL	POSH	Top	36	2.9	0.2	0.2	0.1	8.4	0.9
	OB	Top	9	3.4	0.5	0.3	0.1	12.2	2.2
	OB	Interior	9	18.0	1.7	NA	NA	NA	NA

3.3. Barnacle Densities on Artificial Reef Modules

Barnacle densities were low and highly variable among both module types at either site (Figure 7). Densities were similar among both groups at both Kingsley Plantation ($p > 0.05$) and Wright's Landing ($p > 0.05$). Barnacle densities on the POSH were 0.7 ± 0.2. barnacles/100 cm^2 at Kingsley Plantation and 0.4 ± 0.1 barnacles/100 cm^2 at Wright's Landing. Barnacle densities on the Oyster Ball were 1.2 ± 0.4 barnacles/100 cm^2 at Kingsley Plantation and 0.4 ± 0.2 barnacles/100 cm^2 at Wright's Landing. Barnacle densities were similar among all other sides of the POSH and Oyster Ball modules (Table 2).

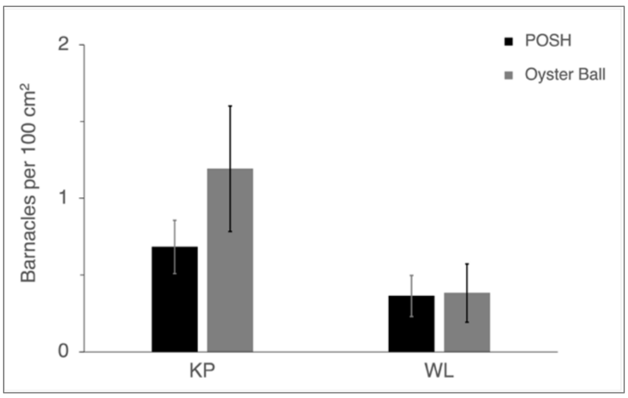

Figure 7. Barnacle density comparison. Number of barnacles per 100 cm^2 on the POSH and Oyster Ball at Kingsley Plantation and Wright's Landing. Error bars represent ±1 SE. Significant differences were not found at either site (Mann–Whitney U *t*-test).

3.4. Oyster Size Distribution on Artificial Reef Modules

The average size of oysters was greater on the POSH at Kingsley plantation. Growth rates, as change in average size, were much greater at Kingsley Plantation than at Wright's Landing. At Kingsley Plantation, there was an average growth of 25.5 mm for POSH and 21.6 mm for Oyster Ball over 8 months. At Wright's Landing, there was an average growth of 8.7 mm for the POSH and 13.1 mm for the Oyster Ball (Figure 8).

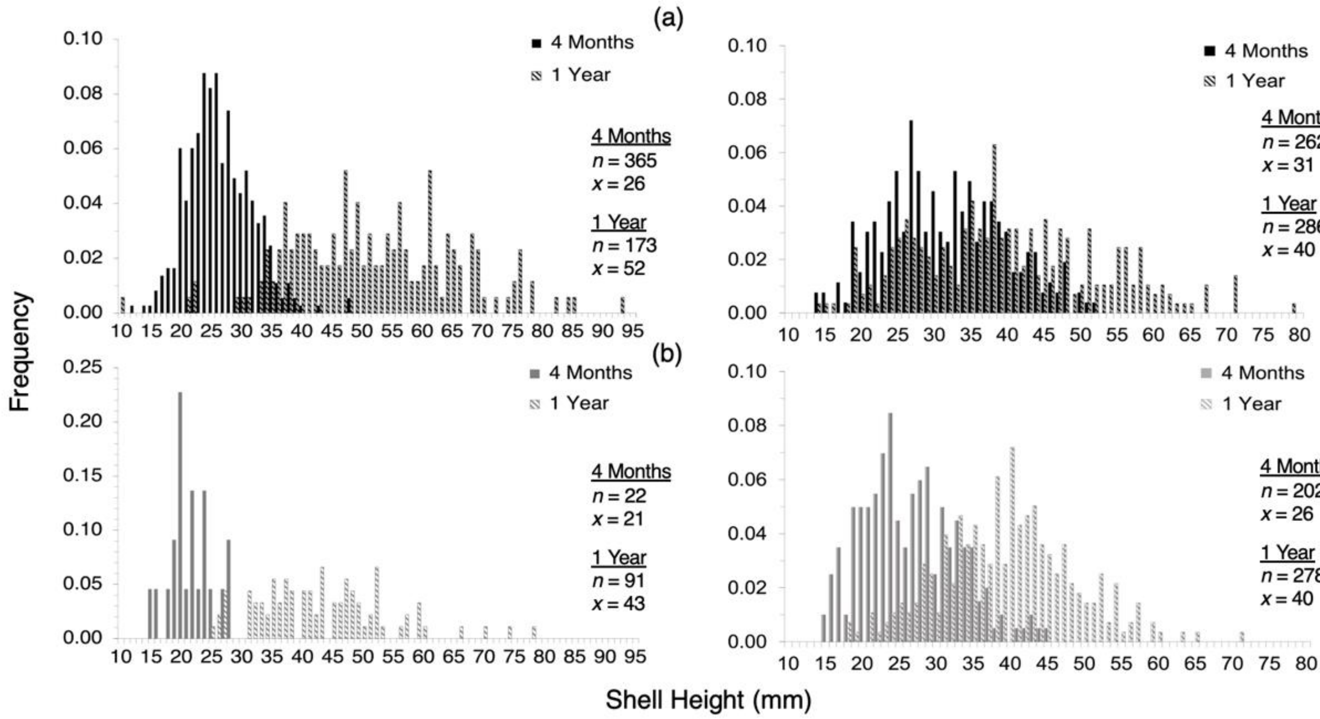

Figure 8. Oyster size distributions. Distributions at Kingsley Plantation on the (**a**) POSH and (**b**) Oyster Ball at 4 months and 1 year. Note the different frequency range for the Oyster Ball due to a limit in sampled oysters. Distributions at Wright's Landing on the (**c**) POSH and (**d**) Oyster Ball at 4 months and 1 year.

3.5. Reef Height of Artificial Reef Modules

Significant sediment accretion on the landward side of the modules and scouring along the seaward side of the modules led to large differences in reef height on either side (Figure 9). Reef heights were greater on the POSH at Kingsley Plantation and the Oyster Ball at Wright's Landing, though similar overall (Table 3).

Figure 9. (**a**) POSH and (**b**) Oyster Ball modules at Kingsley Plantation and (**c**) POSH and (**d**) Oyster Ball modules at Wright's Landing after 1 year in situ.

Table 3. Average height of artificial reef modules over the sediment surface after 1 year.

Site	Module	n	Landward (cm)	Seaward (cm)
KP	POSH	8	22	26
	OB	8	21	25
WL	POSH	9	21	25
	OB	9	24	28

4. Discussion

Our early findings for the Pervious Oyster Shell Habitat show that the novel artificial reef structure can be a durable and effective substrate for facilitating oyster recruitment and the rapid development of healthy oyster populations in energetic systems. Restoration stakeholders should consider using the structure where other methods may not be as sustainable.

Monthly oyster spat settlement was significantly greater on oyster shells coated in Portland cement than the untreated oyster shell, inconsistent with our first hypothesis. These results support findings from studies, which have found that cement-based substrates can recruit oysters as well or better than oyster shell [57–59]. Monthly barnacle settlement did not differ between treatments in October but was significantly greater on cement-coated shells in November. Only the results from November were consistent with our second hypothesis. The monthly settlement study was performed in the fall when water temperature and oyster spat densities decrease substantially, and barnacle settlement increases (Mathews, H. Pers. obs.) [60].

Oyster densities on the POSH were significantly greater than on the Oyster Ball at both sites, consistent with our third hypothesis. Unlike the Oyster Ball, the POSH had similar oyster recruitment at both sites, demonstrating the structure's optimal form under varying water quality and energetic conditions. The effective use of the oyster shell in the POSH may have the added advantage of released chemical cues for promoting oyster spat settlement [15–17,61]. Rapid settlement of barnacles on the Oyster Balls at Kingsley Plantation likely limited early oyster settlement and subsequent recruitment. Dense oyster recruitment on the interior side of the Oyster Balls at WL shows the benefit of the large open space protected from consistent wave energy. Diggles (2018) also found a significant portion (91.6%) of subtidal rock oyster (*Saccostrea glomerata*) spat settlement on the interior surface of Oyster Balls in Moreton Bay, Australia [40]. This study supports the use of small volumes of cement as a binding agent and substrate for oyster recruitment, a practice becoming more common for oyster reef restoration [25]. Recruitment on the complex oyster shell matrix of the POSH resembled that of natural oyster reefs with upright-positioned oysters attached to the substrate at the umbo. Many oysters that were settled on the Oyster Balls at both sites had a majority of their shell flush laterally with the structure, limiting the upward oyster development seen on natural reefs (Figure 9). Findings support having a structure with more interstitial space and increased surface area for the rapid development of healthy oyster populations resembling those of natural oyster reefs [22].

Barnacle recruitment did not differ among the two structures at either site, inconsistent with our fourth hypothesis. Recruitment was low and highly variable at both sites. Barnacle mortality was high at both sites at the time of sampling, potentially due to warm water temperatures and the low elevation where the modules were placed. The size and distribution of barnacles varied greatly at both sites. On the POSH at Kingsley Plantation, barnacles were mostly in the 2–5 mm size range and settled on live oysters in scattered clusters. Barnacles settled on modules at Wright's Landing, were often ~1 cm, and settled on oysters and the module itself. Barnacle sizes on the Oyster Ball were similar to those of the POSH, but recruitment was higher on the concrete substrate itself. Barnacle recruitment at the time of sampling did not seem to affect oyster recruitment for either group at either site, though it likely inhibited initial oyster settlement on the Oyster Balls at Kingsley Plantation. The interior side of the Oyster Balls at Kingsley Plantation recruited five to ten anemones per structure. Concrete may be a preferred substrate for barnacles and other biofouling organisms [22], which should be considered when choosing a restoration method in systems with high abundances of biofouling organisms, as barnacles and other sessile fouling organisms can affect oyster survival and growth [13,62].

Reproductive-sized oysters were seen on both POSH and Oyster Ball modules by the end of the year (Figures 8 and 9). Growth rates were high at Kingsley Plantation and moderate at Wright's landing, consistent with previous observations and potentially due to more turbid conditions at this site. Hanke et al. found oyster growth to be limited over four years while using mesh shell bags [63], which may be due to shells being compacted in bags and the potential shifting of oyster clusters seen with the method. Our results support the benefit of an open, sturdy, and complex structure in facilitating oyster growth. Early oyster recruitment and growth under a variety of conditions have shown to be key factors in sustained healthy reefs [64–66]. La Peyre et al. found reproductive-sized oysters to be more resilient under stressful conditions over a 10- to 11-year period, a factor that contributed to the sustainability of constructed reefs through periods of low spat settlement [66]. Their work highlights the importance of rapidly recruiting large oysters to increase the chances of long-term reef success. High recruitment and growth rates of oysters on the POSH at both anthropogenically influenced sites show the potential of the structure as a restoration method appropriate for degraded, high-energy systems.

No noticeable damage was observed on deployed POSH or Oyster Ball modules over the course of the year. Cemented oyster shells on the POSH remained intact, and successful reef development will likely enhance structural integrity over time. The POSH's structure is prone to shells chipping off during transportation and installation if the shells are hit hard or if the structures are dropped. The interior of the Oyster Ball modules at Wright's Landing were filled about halfway with sediment and loose oyster shell at the end of the year, likely trapped by the large hole on the top of the structure. Both structures underwent similar shifting at each site. One module per treatment shifted laterally about 0.5 m away from their reef and 0.5 m inshore of the reef at both sites. Both structures underwent some slight burial from accreted sediment on the landward side of the reefs and scour on the seaward side, resulting in differences in reef heights on the landward and seaward sides. The burial of live oysters following storms or consistent wave energy can be a threat to reef success [13,66–68], highlighting the benefit of deploying structures with high vertical relief [19]. With the passing of tropical storm Ian in September 2022 and Nicole in November 2022, no additional shifting or sedimentation was seen on the structures.

Long-term monitoring of oyster reef development on the POSH through seasonal shifts, long-term exposure to wave energy, and other changing biotic and abiotic conditions is needed to more accurately assess the structure's viability to restore oyster reefs in high-energy systems. Oyster densities and demographics can change significantly over time, and restoration studies should continue monitoring success for at least 5 years to better understand the sustainability of a method [66,69]. Initially, modules were separated by type to allow for a more accurate assessment of utilization by nekton with a seine or trawl (Figure 4). In the months of spring 2022, significant erosion at the Kingsley Plantation site facilitated the sinking of the first POSH reef to a slightly lower elevation than the rest of the reefs. However, this did not seem to affect oyster recruitment or growth, as oyster densities and sizes were similar to the other POSH reefs. In the future, experimental reefs should be organized in a random manner that allows for a more unbiased design when working in dynamic systems.

Though the POSH has shown to recruit oysters under high-energy conditions, a better understanding of its abilities to stabilize shorelines is needed. The height of the structure may not be great enough to significantly reduce erosion on high-energy shorelines with steep slopes [70–72]. Oyster-recruiting structures should be placed at low elevations to maximize survival and growth [73], while shoreline erosion may be greatest at higher elevations [70]. Pairing reef restoration devices with wave-reducing structures, such as breakwalls, may be needed in some systems to avoid the tradeoff that is found between optimal oyster recruitment and shoreline stabilization [7,70]. Alteration of the POSH design and gains in vertical relief from oyster reef development may also mitigate this issue. Research is being performed by engineers at the University of North Florida's Taylor Engineering Research Institute to find more effective orientations of POSH structures to reduce erosion using computational fluid dynamic modeling [72,74] and studying wave attenuation through structures in situ [71].

This study contributes to the growing development and research of sustainable and effective oyster reef restoration devices. Like other novel structures, the POSH is an attempt to minimize our environmental impact while maximizing oyster reef development and stabilization of shorelines in our increasingly energetic estuarine systems. Here, we have shown the benefits of combining an alternative substrate, such as cement with oyster shell, to create a complex artificial reef structure that recruits and sustains healthy oyster populations within the first year of deployment. The POSH should be considered for living shoreline projects aiming to enhance oyster reef habitat in high-energy systems.

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