

## COLONISATION OF GASTROPOD SPECIES ON ARTIFICIAL COASTAL STRUCTURES IN PENANG ISLAND, MALAYSIA

AMANDA KAR MUN CHONG<sup>1</sup>, CHEE BAN CHEAH<sup>2</sup>, MOHD ALIF IKRAMI MUTTI<sup>3</sup>, YEE JEAN CHAI<sup>1</sup> AND SU YIN CHEE<sup>4\*</sup>

<sup>1</sup>Centre for Global Sustainability Studies, Universiti Sains Malaysia, 11800 Minden, Pulau Pinang, Malaysia. <sup>2</sup>School of Housing, Building and Planning, Universiti Sains Malaysia, 11800 Minden, Pulau Pinang, Malaysia. <sup>3</sup>Product Design Department, School of Arts, Universiti Sains Malaysia, 11800 Minden, Pulau Pinang, Malaysia. <sup>4</sup>School of Biological Sciences, Universiti Sains Malaysia, 11800 Minden, Pulau Pinang, Malaysia.

\*Corresponding author: [suyinchee@usm.my](mailto:suyinchee@usm.my)

<http://doi.org/10.46754/jssm.2025.05.009>

Submitted: 17 April 2024

Revised: 29 October 2024

Accepted: 8 December 2024

Published: 15 May 2025

**Abstract:** Intertidal organisms, especially marine gastropods, endure harsh marine conditions daily. In tropical regions marked by heat and desiccation, the absence of complexities in Artificial Coastal Structures (ACS) undermines biodiversity and exposes gastropods to thermal risks despite their adaptive thermoregulating strategies. Several ecological engineering approaches employing biomimicry have been conducted. However, studies in tropical regions remain underexplored. To address this, we investigated the habitat panels' performance by incorporating complexities mimicking natural habitats (e.g., grooves and crevices) on whether they promoted gastropod diversity and preferred eco-concrete (produced using a concrete blend composed of recycled materials) as the constructed material. 20 panels with five replicates per treatment: (1) Complex Portland cement habitat panels, (2) blank Portland cement panels (as control), (3) eco-concrete habitat panels, and (4) blank eco-concrete panels were installed onto a seawall at The Light Waterfront (TLW), Penang. Statistical analysis using repeated measures Analysis of Variance (ANOVA) indicated that the complex habitat panels had a significantly higher gastropod diversity compared to blank panels (Wilk's Lambda = 0.29,  $F(3, 8) = 6$ ,  $p = 0.01$ ), offering niche spaces. Whilst material differences between Portland cement concrete and eco-concrete did not significantly affect gastropod diversity, ACS construction utilising recycled materials has been proven beneficial for the environment.

**Keywords:** Blue-green infrastructure, coastal biodiversity, ecological engineering, marine gastropod species, structural complexity.

### Introduction

Coastlines worldwide are facing extensive threats of flooding, erosion, and degradation due to extreme climate events coupled with widespread coastal urbanisation (O'Shaughnessy *et al.*, 2020). In the past few decades, coastlines have progressively been transformed for urban use with Artificial Coastal Structures (ACS) as common features. Note that these structures are man-made features designed to protect coastlines and support coastal activities. The transformation involving the alteration of natural, sedimentary, and hard substrata to reclaim land and protect growing populations is referred to as "ocean sprawl" (Firth *et al.*, 2016a; Bishop *et al.*, 2017).

The costs associated with these trends further exacerbate the increasing demand for shoreline developments and protection in response to unpredictable climatic events such as sea level rise and storm surges. Consequently, the results of "ocean sprawl" are becoming more evident with various coastal development schemes worldwide such as the reclamation of coastlines and the construction of entire artificial islands (Chee *et al.*, 2017; 2023), as an adaptive societal response to expanding coastal cities. To counteract land scarcity and erosion, reclamation has become one of the few available options for this purpose. ACS has been employed for coastal protection, including seawalls, breakwaters,

jetties, piers, bulkheads, and marinas. However, this has come at the cost of natural habitats.

Meanwhile, ACS is designed to meet engineering and financial standards for public safety (Bisaro *et al.*, 2019; Woo, 2019). An ongoing debate exists about how marine organisms interact with and adapt to these new artificial habitats (Becker *et al.*, 2020). Although they provide a habitat for marine organisms similar to those on adjacent rocky shores (Firth *et al.*, 2016b), the trade-off to nature is the loss of a myriad of ecosystem services supported by those of natural habitats (Chee *et al.*, 2017; 2020; Evans *et al.*, 2019; O'Shaughnessy *et al.*, 2020). This leads to lower biodiversity, changes in community structure, and the domination of invasive and opportunistic species (Firth *et al.*, 2014; Becker *et al.*, 2020).

These changes can negatively affect coastal resilience, as natural habitats are often better at mitigating the impacts of storms, erosion, and pollution. Additionally, the loss of ecosystem services can affect coastal ecosystems' overall health and function, including fisheries productivity, water quality, and nutrient cycling. The main issue arises from the prevailing use of vertical concrete structures that lack surface complexities such as crevices, holes, pits, and pools commonly found in natural habitats. These features, which are absent in ACS, play a crucial role in providing refuge to marine organisms, shielding them from physical stressors and predators (Aguilera *et al.*, 2019; Loke *et al.*, 2019; Ushiyama *et al.*, 2019; Evans *et al.*, 2021).

The extensive use of featureless ACS has put gastropods at risk of dislodgment and eventual mortality, as they are located in high-energy environments, accelerating homogenisation (Strain *et al.*, 2018) and amplifying temperature regimes for organisms' settlement. Consequently, the decline of natural marine habitats due to rapid coastal development has compelled gastropods to adapt to these uniform structures, creating inhospitable conditions for many species. Additionally, ACS's lack of structural complexity limits the availability of suitable attachment sites for

gastropods, making them more susceptible to predation and competition. Climate change further exacerbates their risk as they live near their upper thermal limits. Therefore, it is imperative that we introduce complexity into these environments to support and safeguard gastropod populations.

Over the years, the rapid artificialisation of global coastlines has driven researchers to propose unprecedented solutions to curb biodiversity loss and enhance the marine-built environment. Ecological engineering (eco-engineering) solutions in the coastal zone have already been globally applied in ACS projects in several cities (Morris *et al.*, 2018; Bradford *et al.*, 2020) as part of "reconciliation ecology" (Rosenzweig & Michael, 2003), to promote biodiversity on these structures. The field of eco-engineering for ACS broadly encompasses three fundamental approaches (Figure 1) involving (i) hard (manipulations of non-removable ACS and in environments in which soft approaches cannot be applied) (Chapman & Underwood, 2011; Firth *et al.*, 2014); (ii) soft (an inclusion of natural elements such as marshes, mangroves, and sand dunes as natural coastal defenses) (Morris *et al.*, 2018); and (iii) hybrid (the combination of soft approaches such as vegetation and/or habitat-forming organisms onto ACS) (O'Shaughnessy *et al.*, 2020).

Note that adaptations of ACS take on various forms with multiple interventions. This includes design modifications focused on enhancing habitat complexity (e.g., artificial pools, crevices, grooves, holes, and pits) (Loke *et al.*, 2019; Ushiyama *et al.*, 2019; Chee *et al.*, 2020) to promote habitat heterogeneity. Additionally, there is a trend towards incorporating alternative construction materials to minimise the carbon footprint of ACS (Dennis *et al.*, 2018; McManus *et al.*, 2018; Sella *et al.*, 2022). Another strategy involves transplanting specific species onto ACS to provide support for threatened populations such as algae (Heery *et al.*, 2020; Orlando-Bonaca *et al.*, 2021), corals (Morris *et al.*, 2018; Mwaura *et al.*, 2022), and seeding native oysters (Bradford *et al.*, 2020; Strain *et al.*, 2020; Chee *et al.*, 2021).

Meanwhile, many methods work best when implemented alongside development. Some of these methods can be applied retrospectively. New or existing ACS can be planned or modified to serve as habitats for marine life, boosting biodiversity in constructed marine environments. Though the majority of the related studies and data have been geographically limited to temperate countries (e.g., Strain *et al.*, 2019; Ushiyama *et al.*, 2019; Evans *et al.*, 2021), studies in tropical regions remain underexplored (Loke & Todd, 2016; Chee *et al.*, 2020; Chee *et al.*, 2023).

The intertidal zone poses one of the harshest environments for organisms, particularly gastropods, severely testing their capacity to thrive amidst constant temperature, salinity, and moisture levels. Consequently, these changes occur rhythmically with the shifting tides, subjecting the shoreline to constant submersion and exposure (Dave & Chudasama, 2018; Halim *et al.*, 2019). Marine gastropods are one of the most extensive and diverse faunal groups in phylum Mollusca, exhibiting widespread distribution and adaptability to diverse habitats, with their presence influenced by the

varying environmental factors in the intertidal zone. These organisms are key in structuring intertidal assemblages and regulating intertidal communities by playing a significant role in coastal food chains as important food sources for animals and humans (Firth, 2021).

In rocky habitats, they are vital for maintaining shore dynamics and ecological balance on beaches, which contributes substantially to nutrient recirculation (Putro *et al.*, 2023) whilst serving as bioindicators for pollution to researchers (Zaki *et al.*, 2021; Chowdhury *et al.*, 2022). However, tropical gastropods are often exposed to threats due to climate change-induced extreme weather events, residing near their upper thermal limits and exhibiting sensitivity to even slight temperature shifts (Chapperon *et al.*, 2011; Chan *et al.*, 2022; Franklin *et al.*, 2022).

Although equipped with sophisticated thermoregulatory mechanisms like shell-stacking to augment convective cooling (Waltham & Sheaves, 2020; Ng *et al.*, 2021), their reliance on specific habitats such as rocky shores, magnifies their susceptibility. When compounded with uncomplicated, solid concrete

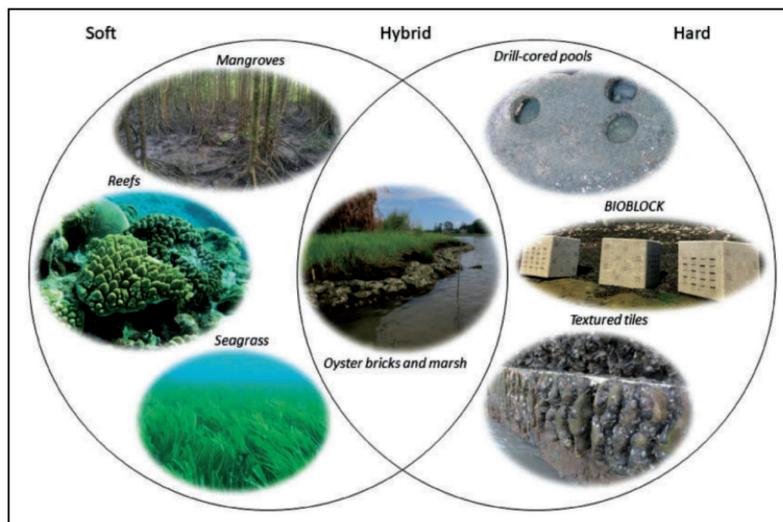


Figure 1: Ecological engineering approaches. Soft approaches involve the incorporation of natural habitats for coastal defence; hybrid approaches involve the combination of hard and soft approaches; and hard approaches involve physically manipulating artificial structures

Source: Chee *et al.* (2020)

structures, these factors diminish biodiversity and escalate stress levels, potentially leading to heightened mortality rates among these already vulnerable organisms existing at the brink of their heat tolerance limits. Moreover, additional threats emerge from habitat loss due to reclamation activities, moderately accommodating these creatures (Chee & Yee, 2016). This habitat disturbance further intensifies the vulnerability of gastropods within the ecosystem, emphasising the need for comprehensive conservation strategies to address both climate-induced challenges and anthropogenic impacts.

Malaysia is one of the fastest-growing countries in Southeast Asia, with a large coastal population. This coastal region covers 70% of the country's land area. It is home to various industries, including agriculture, fisheries, aquaculture, manufacturing, transportation communication, oil and gas, and mineral resources (Ehsan *et al.*, 2019) can be witnessed in most of these areas. To date, there has been a continuous surge in developments along the coastlines of Malaysia. Notably, the most pronounced development is observed on Penang Island, where coastal reclamation initiatives have evolved from transforming shorelines to reclaiming entire islands. This transformation is driven by the need to accommodate a high-density coastal population, reaching around 860 people per square kilometre on Penang Island (Chee *et al.*, 2017). Typically, fortified structures, including seawalls, breakwaters, and rock revetments are built to combat coastal erosion and flooding in new developments (Chee *et al.*, 2020).

In this study, we investigated the performance of complex habitat panels (referred to as "complex treatment" hereafter) mimicking natural rocky shore characteristics on the seawall at a developed Penang shoreline. Our objective is to compare the differences in gastropod species among (1) two distinct habitat panel treatments and (2) two types of concrete materials. Gastropods were chosen as previous studies involving the manipulation of concrete

complexity in Penang Island only highlighted colonising taxa of sessile animals because mobile species were not always visible in the photographs (Chee *et al.*, 2021).

Furthermore, there is also considerable opportunity to utilise the establishment of gastropods as bio-indicators of environmental health in monitoring coastal pollution (Halim *et al.*, 2019; Azhari *et al.*, 2022). As they are particularly common on intertidal rocks but do not readily colonise ACS like ecosystem engineers (e.g., barnacles, oysters, and mussels), we hypothesised that (i) the complex treatments will support a greater gastropod species richness compared to the blank panels; (ii) eco-concrete habitat panels will support greater gastropod species richness and community structure compared to the Portland cement panels; and (iii) gastropod diversity on the complex eco-concrete panels will be comparable to that found in natural habitats.

Eco-engineering interventions at intertidal zones have been known to affect the richness of mobile organisms greatly (Strain *et al.*, 2018) as ACS have been reportedly known for its scarcity in mobile organisms (Evans *et al.*, 2016; Lawrence *et al.*, 2021). Therefore, the influence of gastropods on the different panel treatments is an important question we aimed to address in this study. We anticipated that the complex habitat panels would support a higher species richness of gastropods compared to the blank treatments in Penang's tropical environment due to the added complexities and the presence of refuge.

## Materials and Methods

### Study Site

The experiment was undertaken at The Light Waterfront (TLW), Penang Island, Malaysia, on the eastern side of Penang Island at geographical coordinates 5°22'0.28"N and 100°19'0.14"E (Figure 2). TLW was selected as our study area as it represents a typical reclaimed site, characterised by two different coastal defence structures: A vertical seawall extending from

the shallow subtidal to the supratidal zone and granite rock revetments backing the now-reclaimed land. Other than that, the site was easily accessible, granting convenience during field surveys. This land was previously a mudflat with no neighbouring natural rocky shores. There have been human-related activities such as fishing and oyster harvesting by locals during low tides on the rock revetments and during high tides on the platform (Figure 3).

Furthermore, construction activities for The Light City, situated behind the seawall, have been in progress since the commencement of this study and persisted up to the current timeframe. Vessel traffic approximately 500 metres off the revetments occasionally generated medium ship wakes. At the same time, food waste and marine

debris such as plastics and wood debris were often observed lodged between or on the closely packed and well-ordered rocks. A drainage channel connected to nearby residential and commercial buildings is also present (Figure 3). Prior to the experiment, the seawall was predominantly inhabited by native organisms, mainly littorinids (*Littoraria articulata*) and oysters (*Saccostrea culcullata*), with occasional populations of nerite snails (*Nerita articulata*).

### Baseline Monitoring

Baseline studies were conducted in natural and artificial (TLW) habitats during low tide periods prior to the experiment. Miami Beach in Penang was selected due to its closest proximity (~19 km) as a natural rocky shore to TLW. A total

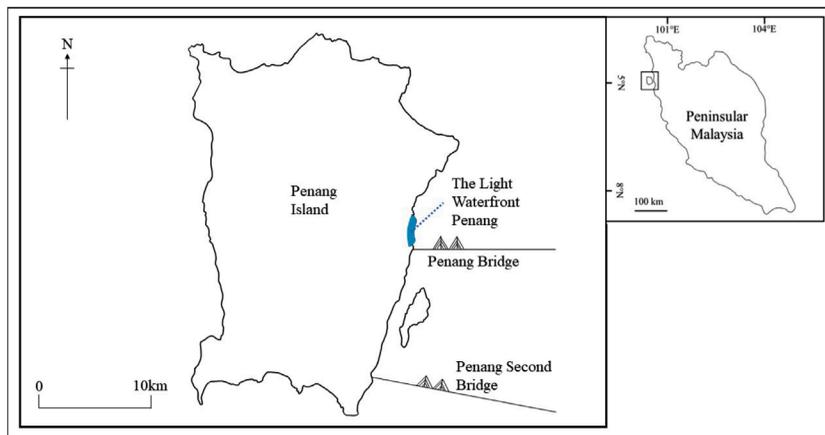


Figure 2: Location of The Light Waterfront, Penang



Figure 3: Satellite imagery of the study site at The Light Waterfront, Penang  
Source: Google Maps (2017)

of  $n = 15$  replicates were sampled at both sites, respectively. Emergent rock surfaces at Miami Beach, Penang, were sampled, where the total number of gastropod species was observed and counted using a 25 x 25 cm quadrat. Note that preliminary observations between February 2022 and March 2022 revealed that *L. articulata* was the dominant gastropod species inhabiting the seawall. As the seawall structure is predominantly flat with vertical surfaces devoid of important microhabitats, these gastropods are observed to forcefully aggregate in the narrow, available crevices to seek refuge from environmental stresses.

### Experimental Design

A total of 20 panels were deployed on the seawall of TLW in September 2022 during low tide. There were five replicates per treatment: (1) complex Portland cement habitat panels (CC), (2) blank Portland cement panels (BC) (used as a control), (3) eco-concrete habitat panels (CE), and (4) blank eco-concrete panels (BE) (Figure 4). The panels having dimensions of (40 x 8 x 75 cm) in length, width, and height, respectively were designed to fit into the recesses of the seawall.

The panels were produced from moulds designed to mimic natural habitat characteristics by incorporating grooves, crevices, and holes preferred by native marine organisms observed at Miami Beach, Penang, during baseline

monitoring. The eco-concrete panels were designed to reduce the carbon footprint of traditional concrete using a concrete mixture that included recycled materials from the food and construction industry. Two type of concrete blends were utilised to prepare the Portland cement panels and eco-concrete panels, respectively: (1) Ground Granulated Blast-furnace Slag (GGBS) with quarry dust and (2) GGBS with shells.

All existing flora and fauna on the recesses were physically cleared by scraping to create a bare surface before the panels' installation. Consequently, two holes were drilled on each side of the cleared seawall's surface to secure the heavy-duty C-channels with Dynabolts. The panels were inserted from above to fit between the C-channels, with the base resting on the rock revetments. They were deployed in a single horizontal row along the recesses of the seawall, in random order with respect to their treatments.

Field surveys were carried out once every month during daytime low tides (< 1.0 m above chart datum) (Figure 5) between October 2022 and August 2023 on clear days. During each field survey, gastropods on the panels were photo-documented and recorded in counts over 11 months prior to the initial course of colonisation (T-zero). Upon each survey, we quantified the species richness and densities of gastropods per panel. As per (Chee *et al.*, 2020), marine gastropods on the panels were

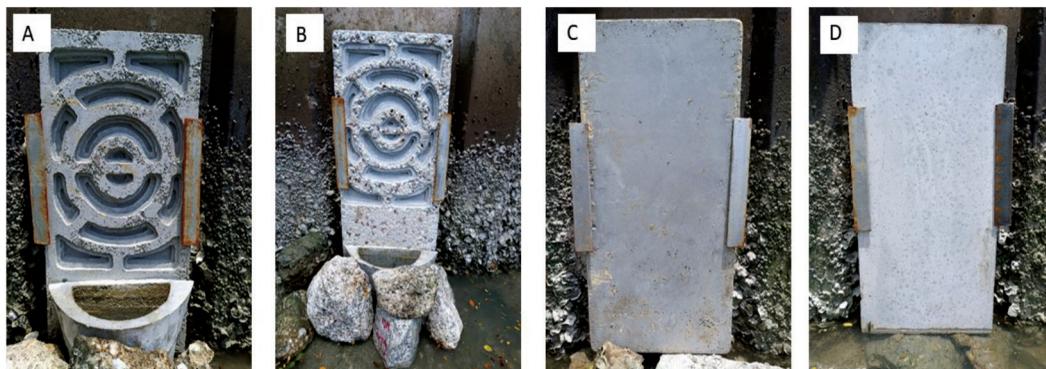


Figure 4: (A) complex Portland cement panel with Portland cement artificial pool, (B) complex eco-concrete panel with eco-concrete artificial pool, (C) blank Portland cement panel, and (D) blank eco-concrete panel installed at The Light Waterfront

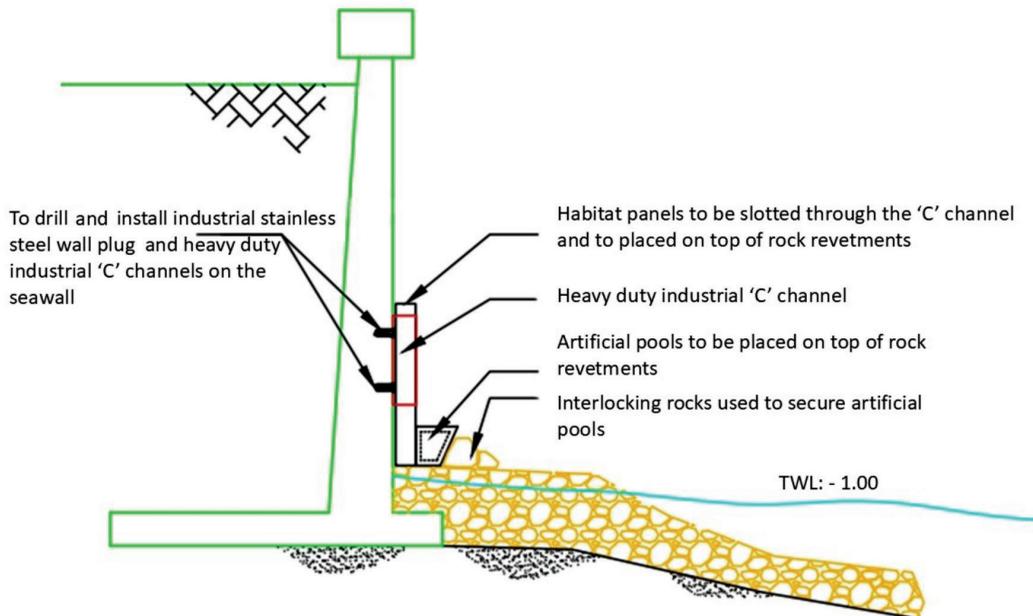


Figure 5: A visual representation illustrating the panel installation process at The Light Waterfront  
Source: IJM Berhad Corporation

identified to their species level through non-destructive sampling while morphospecies were assigned when species cannot be identified unless through destructive sampling. These classifications indicate preferential habitat and material type, with the presence of gastropods indicative of preferred habitat and the absence of gastropods indicative of limited suitability across the different panel treatments.

### Data Analysis

The overall species richness of gastropods on all the panels was analysed to address hypothesis 1, asserting that the complex treatments will support a more substantial gastropod species richness than the blank treatments. This analysis involved repeated measures ANOVA in SPSS version 27 (IBM Corp., Armonk, NY, USA) based on data pooled over replicates ( $n = 5$ ) and plotted over 11 months. To address hypothesis 2, the eco-concrete habitat panels will support more significant gastropod species richness and community structure compared to the Portland cement panels. The same analysis using measures ANOVA in SPSS version 27 (IBM

Corp., Armonk, NY, USA) was conducted. Hypothesis 3 posited that the biodiversity index on the complex treatments would surpass that of the blank treatments. Subsequently, gastropod species were calculated for each panel treatment based on species density and the average Shannon's Diversity Index was determined after 11 months of field survey.

### Results

#### Species Richness of Gastropods on the Panels

An appreciable recruitment of intertidal gastropods occurred on both types of panels throughout the 11 months of the field survey. A total of 10 gastropod species were documented during the survey, with nine being native species and one (*Siphonaria guamensis*) identified as non-native in Malaysia. Of the 10 gastropod species, six (60%) were adapted to the mid to high intertidal zone while four (40%) inhabited the low to mid-intertidal zone.

All panel treatments were predominantly populated by the *L. articulata* gastropod species. The presence and absence of each gastropod

species clearly distinguished between the blank and complex treatments (Table 1). The complex treatments exhibited the highest number of gastropod species absent on the seawall, including limpets, nerite snails, murex snails, periwinkle snails, and onch sea slugs. In contrast, the blank treatments only showed the presence of *L. articulata*, *S. guamensis*, and *Peronia* sp. compared to the complex treatments. Although the total species richness of gastropods varied over the monitoring period, it was revealed that the CE panels supported the highest number of gastropod species throughout the survey (Figure 6). Species accumulation curves indicated a steady increase in the total species supported by both complex treatments (CC and CE) while fluctuating for both blank treatments. This suggests a significant interaction between the inclusion of complexities and between months regarding gastropod composition in response to the varying temporal seasons of Malaysia. The highest numbers of gastropod species were observed in June 2023, coinciding with the CE panels.

Over the 11 months, marine gastropods exhibited a positive correlation towards the complex treatments compared to the blank treatments. Cumulative species richness on the (1) complex Portland cement habitat panels (six species), (2) blank Portland cement panels (three species), (3) complex eco-concrete habitat panels (10 species), and (4) blank eco-concrete panels (three species) were recorded (Figure 6). A significant difference in gastropod species between the panels was observed, with Wilk’s Lambda = 0.29, F (3, 8) = 6,  $p = 0.01$ . Post hoc pairwise comparisons, adjusted for multiple comparisons using the Bonferroni method, revealed significant differences between panels. Specifically, CC had a significantly higher gastropod species compared to BC (MD = 0.136,  $p = 0.02$ ) and BE (MD = 1.09,  $p = 0.01$ ). Similarly, CE demonstrated significantly higher gastropod species compared to BC (MD = -1.73,  $p = 0.03$ ) and BE (MD = 1.46,  $p = 0.03$ ). There was no significant difference in gastropod species between CC and CE, as well as BC and BE. Here, mean richness was higher on CE (2.82

Table 1: Presence and absence of marine gastropod species on the panels

Marine Gastropods Species	Panels			
	CC	BC	CE	BE
<i>Cellana radiata</i>	X		X	
<i>Littoraria articulata</i>	X	X	X	X
<i>Morula fusca</i>			X	
<i>Monodonta labio</i>	X		X	
<i>Nerita chameleon</i>			X	
<i>Nerita lineata</i>	X		X	
<i>Siphonaria guamensis</i>	X	X	X	X
<i>Siphonaria javanica</i>	X		X	
<i>Peronia</i> sp.		X	X	X
<i>Thais</i> sp.			X	
<b>Total species</b>	<b>6</b>	<b>3</b>	<b>10</b>	<b>3</b>

CC = Complex Portland cement habitat panels  
 BC = Blank Portland cement panels  
 Ce = Complex eco-concrete panels  
 BE = Blank eco-concrete panels

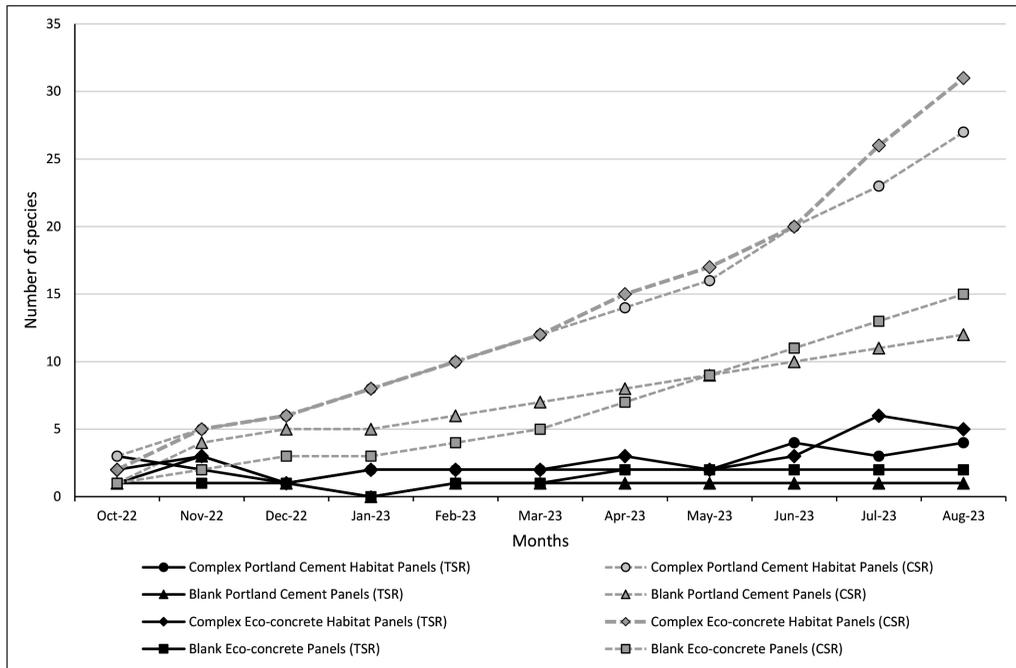


Figure 6: Total Species Richness (TSR: Solid Lines) and Cumulative Species Richness (CSR: Dashed lines) recorded on the panels over 11 months at The Light Waterfront, Penang

$\pm 0.44$ ) compared to CC ( $2.46 \pm 0.28$ ), but post hoc tests failed to report significant pairwise differences.

### Portland Cement vs. Eco-concrete Material

In our investigation, the partial replacement of Portland cement with (1) GGBS and quarry dust (for Portland cement panel treatments) and (2) GGBS and seashells (for eco-concrete panel treatments) did not exhibit a discernible influence on the recruitment of gastropod species. Post hoc pairwise comparisons of the results revealed no significant difference in the total species of gastropods between the blank Portland cement panels (MD = 0.136,  $p = 0.02$ ) and eco-concrete panels (MD = 1.09,  $p = 0.01$ ). Moreover, the gastropod species recruited on the blank treatments were consistent in both number and species, suggesting a lack of preference towards the constructed materials of the panels. Contrastingly, higher numbers of gastropod species were observed in the complex treatments, indicating a stronger correlation with

physical attributes such as surface roughness and complexities than with material type.

### Biodiversity of Gastropods on the Panels

In contrast to species richness, CC had the highest average species diversity index of (0.10), followed by CE (0.06), BE (0.05), and BC (0.03), respectively (Table 2). The analysis of Shannon's Diversity Index across different panels revealed a substantial variation in gastropod species richness (Wilk's Lambda = 0.29,  $F(3, 8) = 25.80$ ,  $p = 0.00$ ). Post hoc Tukey HSD tests with Bonferroni adjustment exposed significant differences between panel panels and the natural emergent rocks (Miami Beach, Penang). Specifically, CC exhibited a significantly higher gastropod species richness than BC (MD = 0.07,  $p = 0.18$ ) and BE (MD = 0.04,  $p = 0.61$ ). CE demonstrated higher richness compared to BC (MD = 0.03,  $p = 0.82$ ) and BE (Mean Difference = 0.01,  $p = 0.99$ ). On the other hand, natural emergent rocks displayed significantly higher richness than all other panels

( $p < 0.00$ ). Meanwhile, there were numerical differences in mean richness. Post hoc tests did not reveal significant pairwise differences within the CC, CE, BC, and BE panels.

Although CC abstained from the highest average species diversity index, the results were incomparable to the diversity index of natural rocky shores (0.31) based on baseline monitoring. All the panels had the highest biodiversity index in August 2023, whereas March 2023 was the lowest, with all the panels having zero biodiversity index. *L. articulata* was the only dominant species recorded on all the panel treatments, followed by *S. guamensis* (Table 3). The average density of *L. articulata* had the same values (0.02) in both the complex treatments and was the highest compared to the blank treatments. *N. articulata* was only present in high percentages from the 9<sup>th</sup> month (June 2023) onwards. Meanwhile, *Morula fusca* and *Thais* sp. were only observed once on CE on the 10<sup>th</sup> month (July 2023). As the panels were partially composed of man-made materials, which have stark similarities to ACS, it was indicated that the panels would not be equivalent to natural shore in terms of abundance and diversity.

## Discussion

Previous studies on mobile invertebrate communities have demonstrated that ACS exhibit poor performance compared to natural rocky habitats regarding community structure and diversity (Sedano *et al.*, 2020). There has been an increasing advocacy to incorporate complexity into ACS through eco-engineering approaches to enhance native biodiversity

over the years. However, only a few studies on eco-engineering ACS have been conducted in Malaysia (e.g., Yee *et al.*, 2018; Chee *et al.*, 2020; 2021). Our study tested how complexities play a role in recruiting intertidal gastropod species on ACS in Penang, Malaysia. After 11 months, gastropod species showed a positive correlation towards the complex treatments, which were not found on the blank treatments.

Incorporating topographic complexities into our complex treatments has encouraged a significant increase in gastropod species richness living on the seawall of TLW, Penang. However, there were slight fluctuations in the total species among the different treatments over 11 months sampling period, with a decrease in the total species of gastropods in December and an increase in April. The dry season on the West Coast, running from October to April with elevated local temperatures, may have contributed to decreased total species richness in December due to increased heat and desiccation exposure. On the contrary, the total number of species richness on the observed panels increased after April, corresponding to the West Coast's wet season, during which gastropod species may be less stressed due to moderate local temperatures. Despite the fluctuations observed in the total species richness of gastropods on the panels, the complex treatments consistently demonstrated higher values than the blank treatment.

Manipulations of ACS through eco-engineering interventions such as on seawalls are known to promote biodiversity and protect marine organisms in urban environments that would otherwise be considered inhospitable (Loke *et al.*, 2019). This is achieved through

Table 2: Shannon's diversity index and total species richness of gastropods

Treatments	Shannon's Diversity Index	Gastropod Species Richness
CC	0.10	6
CE	0.06	10
BC	0.05	3
BE	0.03	3

Table 3: Dominant species based on gastropods density over 11 months

Treatments	Gastropod Species	Density (Individuals/cm <sup>2</sup> )	Percentage of Total Density (%)	Frequency
CC	<i>Cellana radiata</i>	$1.52 \times 10^{-4}$	0.76	3.89
	<i>Littoraria articulata</i>	0.02	97.66	90.91
	<i>Monodonta labio</i>	$2.53 \times 10^{-5}$	0.13	2.6
	<i>Nerita articulata</i>	$3.61 \times 10^{-5}$	0.18	6.49
	<i>Siphonaria guamensis</i>	$2.45 \times 10^{-4}$	1.23	29.87
	<i>Siphonaria javanica</i>	$7.22 \times 10^{-6}$	0.04	0.12
CE	<i>Cellana radiata</i>	$5.05 \times 10^{-5}$	0.25	1.52
	<i>Littoraria articulata</i>	0.02	97.35	89.39
	<i>Monodonta labio</i>	$2.53 \times 10^{-5}$	0.13	4.55
	<i>Morula fusca</i>	$8.42 \times 10^{-6}$	0.04	1.52
	<i>Nerita chameleon</i>	$2.53 \times 10^{-5}$	0.13	4.55
	<i>Nerita articulata</i>	$1.01 \times 10^{-4}$	0.51	12.12
	<i>Siphonaria guamensis</i>	$2.52 \times 10^{-4}$	1.26	25.76
	<i>Siphonaria javanica</i>	$4.21 \times 10^{-5}$	0.21	6.06
	<i>Peronia</i> sp.	$1.68 \times 10^{-5}$	0.08	3.03
	<i>Thais</i> sp.	$8.42 \times 10^{-6}$	0.04	1.52
BC	<i>Littoraria articulata</i>	$9.91 \times 10^{-4}$	91.59	49.1
	<i>Siphonaria guamensis</i>	$8.02 \times 10^{-5}$	7.41	7.27
	<i>Peronia</i> sp.	$1.08 \times 10^{-5}$	1	3.64
BE	<i>Littoraria articulata</i>	$2.01 \times 10^{-3}$	93.93	56.36
	<i>Siphonaria guamensis</i>	$7.60 \times 10^{-5}$	3.55	14.55
	<i>Peronia</i> sp.	$5.39 \times 10^{-5}$	2.52	1.82

the intervention of structural complexity (Loke & Todd, 2016; Ushiyama *et al.*, 2019; Evans *et al.*, 2021) and research has repeatedly portrayed a rise in species richness and density of intertidal organisms through this approach (Loke *et al.*, 2019). Similarly, our complex treatments positively affected the biodiversity of gastropods, which also consistently differed from the blank treatments. Our complex treatments, incorporated with multiple types

of habitat complexities (crevices, grooves, and holes), provided greater microhabitat diversity besides greater surface area.

Previous studies have demonstrated that the addition of complexities like crevices and grooves mitigate environmental (i.e., heat, desiccation, and wave impacts) (Chan *et al.*, 2022) and physical pressures [i.e., predation (Loke *et al.*, 2016; Strain *et al.*, 2018; 2020)] whilst supporting distinct mobile invertebrates.

Additionally, unlike smooth concrete surfaces of ACS, increasing heterogeneity on these developed structures through eco-engineering interventions also retain more moisture for intertidal organisms to flourish during low tides (Strain *et al.*, 2018; Bradford *et al.*, 2020; O'Shaughnessy *et al.*, 2020). This indicated that there was a positive correlation between the densities of grazers and the availability of shaded surfaces offered with the presence of crevices and grooves (Firth *et al.*, 2016b) on our panels. Note that tracks cleared by limpets and littorinids indicate feeding activity and were predominantly identified in both complex treatments.

Marine organisms such as algae and barnacles, have also been known for their roles as biological facilitators and key resources in establishing intertidal populations through the provision of physical habitat structure (Silva *et al.*, 2015; Coombes *et al.*, 2017) as well as being ecosystem buffers for gastropods (Bagur *et al.*, 2019). In this present study, post-settlement barnacles (*Amphibalanus amphitrite*) mortality on all the panels promoted additional biogenic microhabitat for gastropods to thrive in their matrix from detrimental forces such as predation, heat, desiccation, and wave dislodgement (Chappon *et al.*, 2017), particularly the smaller individuals of *L. articulata* gastropod species. Gastropods associated with empty barnacle tests were found to be 1°C cooler than their surroundings compared to those located on bare surfaces (Lathlean *et al.*, 2012; Chappon *et al.*, 2017).

Although the percentage cover of barnacles was not assessed in this study, field data showed higher abundances of living *A. amphitrite* on the complex treatments compared to the blank treatments, which might have encouraged the high densities of *L. articulata* on the complex treatments. This occurrence and the rise in two pulmonate limpet species (*S. guamensis* and *Siphonaria javanica*) in the 10<sup>th</sup> and 11<sup>th</sup> months might have been the contributing factor that promoted the presence of predatory tropical gastropods such as *M. fusca* and *Thais* sp. to

forage on the CE panels. As predation by these predatory snails focuses on eating only the cirri and drilling the opercular plates of barnacles and limpets (Chim & Ong, 2012), the panel-attached empty tests are one of the likely factors contributing to post-settlement mortality of barnacles. However, further studies on the other underlying factors (e.g., biological factors or environmental factors) are required.

The dominance of the *L. articulata* gastropod on all the panels was linked to the organism's ability to thermoregulate effectively, with higher tolerance to heat stress (Waltham & Sheaves, 2020), which explained its presence on the blank treatments as well. Although adapted to occupy high intertidal zones, on every occasion, these individuals were seen consistently homed in empty barnacle tests on the blank treatments as its thermally favourable site for short-term thermoregulation. This indication further emphasises the importance of adding design features that include complexities with shading attributes, as gastropods actively seek thermal refuges during certain daylight hours, especially when low tide coincides with the midday period (Waltham & Sheaves, 2020). Interestingly, numerous gastropod species (e.g., nerite snails, pulmonate limpets, predatory tropical snails) chose to seek refuge in our complex treatments, highlighting that other species benefit more from adding habitat enhancements than conventional ACS.

For concrete manipulation in our study, we found no significant difference in the total species of gastropods between the control (blank Portland cement panels) and eco-friendly concrete (blank eco-concrete panels) despite records of increased diversity and colonising species on eco-friendly materials (Dennis *et al.*, 2018; Becker *et al.*, 2020; Natanzi *et al.*, 2021) in temperate regions. Studies involving concrete blends consisting of hemp and shells (Becker *et al.*, 2020) provided equal or better habitat suitability for intertidal biodiversity compared to standard GGBS-based concrete. However, the species richness of gastropods did not vary, irrespective of material types in our experiment.

The negligible differences between eco-friendly and controlled concrete our findings align with that of Potet *et al.* (2021) and Dodds *et al.* (2022), whereby interventions with surface complexity had a more significant ecological outcome compared to concrete's chemistry modifications. Other than that, Dodds *et al.* (2022) noted comparable findings in studies conducted in temperate regions, indicating that effects of material type are expected to be greater for sessile species which settle directly onto the substrate than for mobile species or transient predators such as fish that do not directly interact with the primary substrate.

Higher densities of *L. articulata* on both the blank treatments in our study suggested that these gastropods are able to withstand a wide variety of substrates, which physical properties of different substrata are much less apparent at higher tidal levels (Vermeij, 1971; Chapperon *et al.*, 2017) as they are able to adapt on a certain substratum type for life. This proved that certain gastropod species exhibit varied responses to habitat fragmentation depending on their distinct development modes, as portrayed in a study by Cacabelos *et al.* (2021). This also applies to the high intertidal species, *S. guamensis*. Although concrete manipulation proved insignificant in our analysis, results showed that material type affects the density of gastropods. It suggests that its inclusion in the design and construction of multifunctional ACS can be useful for marine organisms to thrive, especially in Malaysia's temperature regimes.

Effective measures for improving biodiversity in mobile invertebrates are associated with increased shade and texture on ACS (Strain *et al.*, 2018; Sedano *et al.*, 2020). Several studies have reported low biodiversity on ACS due to the scarcity of mobile organisms (Evans *et al.*, 2016; Lawrence *et al.*, 2021) influenced by factors involving habitat variability (e.g., grooves, pits, pools, overhangs, and availability) (Firth *et al.*, 2016a). This corresponded with our findings on the blank treatments. The incorporation of complexities (e.g., grooves, recesses, and holes)

in the complex treatments to create topographic diversity in our study has similarly proven effective, resulting in a significant increase in the species richness of marine gastropods.

Collectively, these findings suggest that the presence of complexities encourages higher marine gastropod diversity compared to conventional seawalls lacking these features. It highlights the ecological dynamics at play in the studied environment. Note that increased areas and broadened overlaps in niches can offer significant advantages for specialist species. Specialists typically have specific habitat needs and narrower niche breadths compared to organisms with broader tolerances and adaptable requirements (Slatyer *et al.*, 2013).

The availability of these features in our complex treatments positively corresponds to their needs. This may clarify why ACS tends to be dominated by only a limited number of prevalent specialist species, such as nerite snails, which were observed during our preliminary observations. In contrast, nerite snails were not sighted on blank treatments over the 11 months. Meanwhile, the complex treatments exhibited a higher diversity index than the blank treatments. The diversity index of gastropods was significantly higher on the natural emergent rocks at Miami Beach, Penang. This suggests that despite the effectiveness of our complex treatments, the natural emergent rocks, with their substrate heterogeneity at the intertidal level, play a crucial role in promoting biodiversity by providing shelter against stressful environmental conditions (e.g., heat, desiccation, stress, and wave impacts during low tide).

In our study, eco-engineering aimed to reduce environmental pressures on tropical gastropods by providing protective spaces (i.e., crevices, grooves, and holes) from heat and desiccation. Developments of new, hard, and artificial substrata have welcomed non-native species and opportunistic species to be more prevalent in ACS than in any other natural habitats (Pister, 2009; Chapman & Underwood, 2011; Firth *et al.*, 2014) where the main cause of this lies in topographic complexity loss. Hence, a

key objective of science-driven eco-engineering is to create habitat improvements that closely emulate natural features. This approach aims to promote the establishment of native species while hindering the spread of invasive ones.

Although natural habitat characteristics were mimicked in designing the complex treatments, it facilitated colonising one non-native species (*S. guamensis*). The occasional observation of limpet eggs on the designs of our complex treatments also further supports the notion that habitat enhancements, characterised by complexities, can serve as potential breeding or nursery grounds for organisms (Seabra *et al.*, 2020). However, the creation of habitats or corridors that may facilitate the presence of invasive or harmful species on the site such as providing refuge for predators in what is meant to be a nursery area, is of equal concern as well.

In addition to fostering natural habitats on man-made structures and mitigating biodiversity loss caused by ecosystem development, habitat enhancements can also be tailored to facilitate the colonisation of economically valuable species (Chapman & Blockley, 2009; Dugan *et al.*, 2011). For instance, eco-engineering of shellfish reefs around the world has yielded greater biodiversity and ecosystem benefits (Chan *et al.*, 2022) whilst serving as shoreline protection and boosting commercial species through the provision of additional ecosystem services (i.e., quality microhabitats and shelter and prey resources) (Coen & Humphries, 2017; Chowdhury *et al.*, 2021).

This could generate essential income for coastal communities facing impoverishment due to the effects of sea level rise and other climate changes (Chowdhury *et al.*, 2021). In the course of our study, we observed that the gastropods inhabiting our complex treatments did not hold direct commercial significance. However, the panels supported the thriving presence of other marine organisms, including oysters and mussels, which play a vital role in contributing to Malaysia's fisheries economy. This ecological interaction underscores the intricate web of relationships within marine ecosystems. Hence,

establishing primary inhabitants fosters a habitat conducive to the prosperity of commercially important species and acts as a catalyst for the indirect attraction and diversity of gastropod species. This interconnected ecological dynamic highlights the importance of understanding and preserving the holistic connectivity within marine environments.

This study examining the effectiveness of eco-engineering interventions to promote gastropod biodiversity on ACS in Penang, Malaysia, showed significant results in an increase in gastropod species on the complex treatments compared to the blank treatments. It was proven that eco-engineering interventions can improve habitat suitability for marine organisms, offering benefits such as protection from environmental stressors and increased food availability. Although eco-concrete did not exhibit significant differences in gastropod diversity compared to traditional materials, the overall findings emphasise the importance of incorporating habitat complexity into ACS to support marine biodiversity and ecosystem function.

## Conclusions

Eco-engineering of ACS has made significant advances in the past few decades, with promising results proving that such interventions enhanced the abundance and richness of ecological communities associated with these structures. In Malaysia, developers and coastal engineers have shown interest in considering integrating ecological principles into their extensive reclamation initiatives (Chee *et al.*, 2023). We sought to demonstrate that habitat enhancements made of partial eco-friendly materials on ACS could enhance the species richness of gastropods and promote biodiversity in the tropical environment of Penang Island.

Our results portrayed a clear difference in higher species richness on the complex treatments than the blank treatments, suggesting that they are better surrogates in habitat provisions of mobile gastropods, as previously identified in several studies. In general, we

showed that homogenous surfaces contributed to lower gastropod richness compared to surfaces with the addition of complexities. Even so, it is essential to note that the compositions of artificial habitats provided by the complex treatments cannot be directly compared to those found in natural habitats, as preliminary observations from the nearest natural rocky habitat (Miami Beach, Penang) had the overall highest diversity index. Contrastingly, we determined that concrete type did not significantly affect the gastropod's species richness and biodiversity compared to other studies in temperate regions that have proven otherwise. This discrepancy might be attributed to the environmental conditions in Malaysia, where gastropod species are consistently exposed to thermal stress. Consequently, their priorities for survival may differ and substrate preferences may not play a crucial role in their ecological dynamics.

Meanwhile, eco-friendly materials did not show significant results in organism recruitment in this study. Further research is needed to achieve the potential of eco-engineering efforts on ACS in meeting biodiversity precision goals. This implementation will provide a greener approach towards coastal developments in Malaysia and help the country transition to a circular economy through eco-materials, especially with coastal urbanisation on the rise. Thus, more work must be done so that Malaysia can fully transition towards a circular economy through this approach. Little steps could be taken through the engagement of coastal zone developers to adopt this intervention.

### Acknowledgements

This article is a part of research funded by a Short Term Grant (304/PCGSS/6313184) and a Research University Grant (1001/PCGSS/816308) awarded by Universiti Sains Malaysia. We would like to thank IJM Corporation Berhad for the permit allowing us to carry out our fieldwork at their project site. The authors wish to express their heartiest gratitude to all other parties involved directly or indirectly in this research.

### Conflict of Interest Statement

The authors declare that they have no conflict of interest.

### References

- Aguilera, M. A., Arias, R. M., & Manzur, T. (2019). Mapping microhabitat thermal patterns in artificial breakwaters: Alteration of intertidal biodiversity by higher rock temperature. *Ecology and Evolution*, 9(22), 12915-12927. <https://doi.org/10.1002/ece3.5776>
- Azhari, F. A., Ismail, M. R., Astuty, S., & Zallesa, S. (2022). Microplastic accumulation in various sizes of *Nerita articulata* A. Gould, 1847 snails in the mangrove area of Batukaras Pangandaran West Java, Indonesia. *WSN*, 163, 16-29.
- Bagur, M., Gutiérrez, J. L., Arribas, L. P., & Palomo, M. G. (2019). Vacant bivalve boreholes increase invertebrate species richness in a physically harsh, low intertidal platform. *Diversity*, 11(3), Article 39. <https://doi.org/10.3390/d11030039>
- Becker, L. R., Ehrenberg, A., Feldrappe, V., Kröncke, I., & Bischof, K. (2020). The role of artificial material for benthic communities – Establishing different concrete materials as hard bottom environments. *Marine Environmental Research*, 161, Article 105081. <https://doi.org/10.1016/j.marenvres.2020.105081>
- Bishop, M. J., Mayer-Pinto, M., Airoidi, L., Firth, L. B., Morris, R. L., Loke, L. H. L., Hawkins, S. J., Naylor, L. A., Coleman, R. A., Chee, S. Y., & Dafforn, K. A. (2017). Effects of ocean sprawl on ecological connectivity: Impacts and solutions. *Journal of Experimental Marine Biology and Ecology*, 492, 7-30.
- Bisaro, A., de Bel, M., Hinkel, J., Kok, S., & Bouwer, L. M. (2019). Leveraging public adaptation finance through urban land reclamation: Cases from Germany, the

- Netherlands, and the Maldives. *Climatic Change*, 160(4), 671-689.
- Bradford, T. E., Astudillo, J. C., Lau, E. T., Perkins, M. J., Lo, C. C., Li, T. C., Lam, C. S., Ng, T. P., Strain, E. M., Steinberg, P. D., & Leung, K. M. (2020). Provision of refugia and seeding with native bivalves can enhance biodiversity on vertical seawalls. *Marine Pollution Bulletin*, 160, Article 111578. <https://doi.org/10.1016/j.marpolbul.2020.111578>
- Cacabelos, E., Neto, A. I., & Martins, G. M. (2021). Gastropods with different development modes respond differently to habitat fragmentation. *Marine Environmental Research*, 167, Article 105287. <https://doi.org/10.1016/j.marenvres.2021.105287>
- Chan, S. H. M., Ong, D. R. Y., Williams, G. A., Crickenberger, S., Loke, L. H. L., & Todd, P. A. (2022). Behaviour broadens thermal safety margins on artificial coastal defences in the tropics. *Marine Environmental Research*, 177, Article 105618. <https://doi.org/10.1016/j.marenvres.2022.105618>
- Chapman, M. G., & Blockley, D. J. (2009). Engineering novel habitats on urban infrastructure to increase intertidal biodiversity. *Oecologia*, 161(3), 625-635.
- Chapman, M., & Underwood, A. (2011). Evaluation of ecological engineering of “armoured” shorelines to improve their value as habitat. *Journal of Experimental Marine Biology and Ecology*, 400(1-2), 302-313. <https://doi.org/10.1016/j.jembe.2011.02.025>
- Chappon, C., & Seuront, L. (2010). Behavioral thermoregulation in a tropical gastropod: Links to climate change scenarios. *Global Change Biology*, 17(4), 1740-1749.
- Chappon, C., Studerus, K., & Clavier, J. (2017). Mitigating thermal effect of behavior and microhabitat on the intertidal snail *Littorina saxatilis* (Olivi) over summer. *Journal of Thermal Biology*, 67, 40-48.
- Yin, C. S., & Kwang, S. Y. (2016). Coastal macroinvertebrate study in Penang Island, Malaysia. *Tropical Life Sciences Research*, 27(Supp. 1), 39-44. <https://doi.org/10.21315/tlsr2016.27.3.6>
- Chee, S. Y., Othman, A. G., Sim, Y. K., Adam, A. N. M., & Firth, L. B. (2017). Land reclamation and artificial islands: Walking the tightrope between development and conservation. *Global Ecology and Conservation*, 12, 80-95. <https://doi.org/10.1016/j.gecco.2017.08.005>
- Chee, S. Y., Wee, J. L. S., Wong, C., Yee, J. C., Yusup, Y., & Mujahid, A. (2020). Drill-Cored artificial rock pools can promote biodiversity and enhance community structure on coastal rock revetments at reclaimed coastlines of Penang, Malaysia. *Tropical Conservation Science*, 13, 1-15. <https://doi.org/10.1177/1940082920951912>
- Chee, S. Y., Yee, J. C., Cheah, C. B., Evans, A. J., Firth, L. B., Hawkins, S. J., & Strain, E. M. A. (2021). Habitat complexity affects the structure but not the diversity of sessile communities on tropical coastal infrastructure. *Frontiers in Ecology and Evolution*, 9, Article 673227. <https://doi.org/10.3389/fevo.2021.673227>
- Chee, S. Y., Tan, M. L., Tew, Y. L., Sim, Y. K., Yee, J. C., & Chong, A. K. M. (2023). Between the devil and the deep blue sea: Trends, drivers, and impacts of coastal reclamation in Malaysia and way forward. *Science of the Total Environment*, 858, Article 159889. <https://doi.org/10.1016/j.scitotenv.2022.159889>
- Chim, C. K., & Ong, Y. Y. B. (2012). Diet of an intertidal predator, *morula fusca* (Neogastropoda: Muricidae) on St. John’s Island, Singapore. *Contributions to Marine Science*, 2012, 153-158.
- Chowdhury, M. S. N., La Peyre, M., Coen, L. D., Morris, R. L., Luckenbach, M. W., Ysebaert, T., Walles, B., & Smaal, A. C. (2021). Ecological engineering with oysters enhances coastal resilience

- efforts. *Ecological Engineering*, 169, Article 106320. <https://doi.org/10.1016/j.ecoleng.2021.106320>
- Chowdhury, A. J. K., Aqilah, N. S., Abdullah, R., Salihah, N. T., Basir, K. H., & Marsal, C. J. (2022). Macrobenthic community towards sustainable aquatic ecosystem: A systematic review along the coastal waters of Malaysia. *Geology Ecology and Landscapes*, 8(1), 57-70. <https://doi.org/10.1080/24749508.2022.2095088>
- Coen, L.D., Humphries, A., (2017). Oyster-generated marine habitats: Their services, enhancement, restoration, and monitoring. In Murphy, S., & Allison, S. (Eds.), *Routledge handbook of ecological and environmental restoration* (pp. 275-295). Taylor & Francis Group, Routledge, Cambridge.
- Coombes, M. A., Viles, H. A., Naylor, L. A., & La Marca, E. C. (2017). Cool barnacles: Do common biogenic structures enhance or retard rates of deterioration of intertidal rocks and concrete? *Science of the Total Environment*, 580, 1034-1045.
- Dave, T. H., & Chudasama, B. G. (2018). Survey and diversity of intertidal mollusks along the coast of Veraval (Gujarat), Arabian Sea. *International Journal of Science, Environment and Technology*, 7(1), 353-360.
- Dennis, H. D., Evans, A. J., Banner, A. J., & Moore, P. J. (2018). Reefcrete: Reducing the environmental footprint of concretes for eco-engineering marine structures. *Ecological Engineering*, 120, 668-678. <https://doi.org/10.1016/j.ecoleng.2017.05.031>
- Dodds, K. C., Schaefer, N., Bishop, M. J., Nakagawa, S., Brooks, P. R., Knights, A. M., & Strain, E. M. A. (2022). Material type influences the abundance but not richness of colonising organisms on marine structures. *Journal of Environmental Management*, 307, Article 114549. <https://doi.org/10.1016/j.jenvman.2022.114549>
- Dugan, J. E., Airoidi, L., Chapman, M. G., Walker, S. J., Schlacher, T., Wolanski, E., & McLusky, D. (2011). Estuarine and coastal structures: Environmental effects, a focus on shore and nearshore structures. *Treatise on Estuarine and Coastal Science*, 8, 17-41.
- Ehsan, S., Begum, R. A., Nor, N. G. M., & Maulud, K. N. A. (2019). Current and potential impacts of sea level rise in the coastal areas of Malaysia. *IOP Conference Series Earth and Environmental Science*, 228, 012023. <https://doi.org/10.1088/1755-1315/228/1/012023>
- Evans, A. J., Firth, L. B., Hawkins, S. J., Morris, E. S., Goudge, H., & Moore, P. J. (2016). Drill-cored rock pools: An effective method of ecological enhancement on artificial structures. *Marine and Freshwater Research*, 67(1), 123-130.
- Evans, A. J., Firth, L. B., Hawkins, S. J., Hall, A. E., Ironside, J. E., Thompson, R. C., & Moore, P. J. (2019). From ocean sprawl to blue-green infrastructure – A UK perspective on an issue of global significance. *Environmental Science and Policy*, 91, 60-69. <https://doi.org/10.1016/j.envsci.2018.09.008>
- Evans, A. J., Lawrence, P. J., Natanzi, A. S., Moore, P. J., Davies, A. J., Crowe, T. P., McNally, C., Thompson, B., Dozier, A. E., & Brooks, P. R. (2021). Replicating natural topography on marine artificial structures – A novel approach to eco-engineering. *Ecological Engineering*, 160, Article 106144. <https://doi.org/10.1016/j.ecoleng.2020.106144>
- Firth, L. B., Thompson, R. C., Bohn, K., Abbiati, M., Airoidi, L., Bouma, T. J., Bozzeda, F., Ceccherelli, V. U., Colangelo, M. A., Evans, A., Ferrario, F., Hanley, M. E., Hinz, H., Hoggart, S. P. G., Jackson, J. E., Moore, P., Morgan, E. H., Perkol-Finkel, S., Skov, M. W., Strain, E. M., ... Hawkins, S. J. (2014). Between a rock and a hard place: Environmental and engineering considerations when designing coastal

- defense structures. *Coastal Engineering*, 87, 122-135. <https://doi.org/10.1016/j.coastaleng.2013.10.015>
- Firth, L. B., Browne, K. A., Knights, A. M., Hawkins, S. J., & Nash, R. (2016a). Eco-engineered rock pools: A concrete solution to biodiversity loss and urban sprawl in the marine environment. *Environmental Research Letters*, 11(9), Article 094015. <https://doi.org/10.1088/1748-9326/11/9/094015>
- Firth, L. B., White, F. J., Schofield, M., Hanley, M. E., Burrows, M. T., Thompson, R. C., Skov, M. W., Evans, A. J., Moore, P. J., & Hawkins, S. J. (2016b). Facing the future: The importance of substratum features for ecological engineering of artificial habitats in the rocky intertidal. *Marine and Freshwater Research*, 67(1), 131-143.
- Firth, L. B. (2021). What have limpets ever done for us? On the past and present provisioning and cultural services of limpets. *International Review of Environmental History*, 7(2). Retrieved from [https://press-files.anu.edu.au/downloads/press/n9154/pdf/01\\_firth.pdf](https://press-files.anu.edu.au/downloads/press/n9154/pdf/01_firth.pdf)
- Franklin, A. M., Rankin, K. J., Hugall, A., & Stuart-Fox, D. (2022). Exposure to thermal extremes favors higher solar reflectivity in intertidal gastropods. *iScience*, 25, Article 105674. <https://doi.org/10.1016/j.isci.2022.105674>
- Halim, S. S. A., Shuib, S., Talib, A., & Yahya, K. (2019). Species composition, richness, and distribution of molluscs from intertidal areas at Penang Island, Malaysia. *Songklanakar Journal of Science and Technology*, 41(1), 165-173. <https://doi.org/10.14456/sjst-psu.2019.20>
- Heery, E. C., Lian, K. Y., Loke, L. H., Tan, H. T., & Todd, P. A. (2020). Evaluating seaweed farming as an eco-engineering strategy for 'blue' shoreline infrastructure. *Ecological Engineering*, 152, 105857. <https://doi.org/10.1016/j.ecoleng.2020.105857>
- Lathlean, J. A., Ayre, D. J., & Minchinton, T. E. (2012). Using infrared imagery to test for quadrat-level temperature variation and effects on the early life history of a rocky-shore barnacle. *Limnology and Oceanography*, 57, 1279-1291.
- Lawrence, P. J., Evans, A. J., Jackson-Bué, T., Brooks, P. R., Crowe, T. P., Dozier, A. E., Jenkins, S. R., Moore, P. J., Williams, G. J., & Davies, A. J. (2021). Artificial shorelines lack natural structural complexity across scales. *Proceedings of the Royal Society B: Biological Sciences*, 288(1951), Article 20210329. <https://doi.org/10.1098/rspb.2021.0329>
- Loke, L. H. L., & Todd, P. A. (2016). Structural complexity and component type increase intertidal biodiversity independently of area. *Ecology*, 97(2), 383-393. <https://www.jstor.org/stable/24703098>
- Loke, L. H. L., Liao, L. M., Bouma, T. J., & Todd, P. A. (2016). Succession of seawall algal communities on artificial substrates. *Raffles Bulletin of Zoology, Supplement No. 32*, 1-10. <http://zoobank.org/urn:lsid:zoobank.org:pub:40011974-8509-40E4-B8DD-0B9FDEE1691A>
- Loke, L. H. L., Heery, E. C., Lai, S., Bouma, T. J., & Todd, P. A. (2019). Area-independent effects of water-retaining features on intertidal biodiversity on eco-engineered seawalls in the tropics. *Frontiers in Marine Science*, 6, Article 16. <https://doi.org/10.3389/fmars.2019.00016>
- McManus, R. S., Archibald, N., Comber, S., Knights, A. M., Thompson, R. C., & Firth, L. B. (2018). Partial replacement of cement for waste aggregates in concrete coastal and marine infrastructure: A foundation for ecological enhancement? *Ecological Engineering*, 120, 655-667. <https://doi.org/10.1016/j.ecoleng.2017.06.062>
- Morris, R. L., Porter, A. G., Figueira, W. F., Coleman, R. A., Fobert, E. K., & Ferrari, R. (2018). Fish-smart seawalls: A decision tool for adaptive management of marine

- infrastructure. *Frontiers in Ecology and the Environment*. <https://doi.org/10.1002/fee.1809>
- Mwaura, J. M., Murage, D., Karisa, J. F., Otwoma, L. M., & Said, H. O. (2023). Artificial reef structures and coral transplantation as potential tools for enhancing locally-managed inshore reefs: A case study from Wasini Island, Kenya. *Western Indian Ocean Journal of Marine Science*, 21(2), 83-94. <https://doi.org/10.4314/wiojms.v21i2.8>
- Natanzi, A. S., Thompson, B. J., Brooks, P. R., Crowe, T. P., & McNally, C. (2021). Influence of concrete properties on the initial biological colonisation of marine artificial structures. *Ecological Engineering*, 159, Article 106104. <https://doi.org/10.1016/j.ecoleng.2020.106104>
- Ng, T. P. T., Lau, S. L. Y., Davies, M. S., Stafford, R., Seuront, L., Hutchinson, N., Hui, T. T. Y., & Williams, G. A. (2021). Behavioral repertoire of high-shore littorinid snails reveals novel adaptations to an extreme environment. *Ecology and Evolution*, 11(12), 7114-7124. <https://doi.org/10.1002/ece3.7578>
- O'Shaughnessy, K. A., Hawkins, S. J., Evans, A. J., Hanley, M. E., Lunt, P., Thompson, R. C., Francis, R. A., Hoggart, S. P. G., Moore, P. J., Iglesias, G., Simmonds, D., Ducker, J., & Firth, L. B. (2020). Design catalogue for eco-engineering of coastal artificial structures: A multifunctional approach for stakeholders and end-users. *Urban Ecosystems*, 23(4), 431-443. <https://doi.org/10.1007/s11252-019-00924-z>
- Orlando-Bonaca, M., Pitacco, V., Slavinec, P., Šiško, M., Makovec, T., & Falace, A. (2021). First Restoration Experiment for *Gongolaria barbata* in Slovenian Coastal Waters. What Can Go Wrong? *Plants*, 10(2), Article 239. <https://doi.org/10.3390/plants10020239>
- Perkins, M. J., Ng, T. P. T., Dudgeon, D., Bonebrake, T. C., & Leung, K. M. Y. (2015). Conserving intertidal habitats: What is the potential of ecological engineering to mitigate impacts of coastal structures? *Estuarine, Coastal and Shelf Science*, 167, 504-515. <https://doi.org/10.1016/j.ecss.2015.10.033>
- Pister, B. (2009). Urban marine ecology in southern California: The ability of riprap structures to serve as rocky intertidal habitat. *Marine Biology*, 156(5), 861-873. <https://doi.org/10.1007/s00227-009-1130-4>
- Potet, M., Fabien, A., Chaudemanche, S., Sebaibi, N., Guillet, T., Gachelin, S., Cochet, H., Boutouil, M., & Pouvreau, S. (2021). Which concrete substrate suits you? *Ostrea edulis* larval preferences and implications for shellfish restoration in Europe. *Ecological Engineering*, 162, Article 106159. <https://doi.org/10.1016/j.ecoleng.2021.106159>
- Putro, S. P., Anarizta, L. A., Muhammad, F., Adhy, S., & Helmi, M. (2023). The roles of macrobenthic molluscs structure in assessing ecological status at mangrove and aquaculture areas. *Jurnal Teknologi*, 85(6), 27-35. <https://doi.org/10.11113/jurnalteknologi.v85.20068>
- Rosenzweig, M. L., & Michael, L. (2003). *Win-win ecology: How the earth's species can survive in the midst of human enterprise*. New York: Oxford University Press.
- Seabra, M. I., Hawkins, S. J., Espírito-Santo, C., Castro, J. J., & Cruz, T. (2020). Rock-pools as nurseries for co-existing limpets: Spatial and temporal patterns of limpet recruitment. *Regional Studies in Marine Science*, 37, Article 101339. <https://doi.org/10.1016/j.rsma.2020.101339>
- Sedano, F., Navarro-Barranco, C., Guerra-García, J. M., & Espinosa, F. (2020). Understanding the effects of coastal defence structures on marine biota: The role of substrate composition and roughness in structuring sessile, macro- and meiofaunal communities. *Marine Pollution*

- Bulletin*, 157, Article 111334. <https://doi.org/10.1016/j.marpolbul.2020.111334>
- Sella, I., Hadary, T., Rella, A. J., Riegl, B., Swack, D., & Perkol-Finkel, S. (2022). Design, production, and validation of the biological and structural performance of an ecologically engineered concrete block mattress: A nature-inclusive design for shoreline and offshore construction. *Integrated Environmental Assessment and Management*, 18, 148-162. <https://doi.org/10.1002/ieam.4523>
- Silva, A. C. F., Mendonça, V., Paquete, R., Barreiras, N., & Vinagre, C. (2015). Habitat provision of barnacle tests for overcrowded periwinkles. *Marine Ecology*, 36, 530-540. <https://doi.org/10.1111/maec.12161>
- Slatyer, R. A., Hirst, M., & Sexton, J. P. (2013). Niche breadth predicts geographical range size: A general ecological pattern. *Ecology Letters*, 16(8), 1104-1114.
- Strain, E. M. A., Morris, R. L., Coleman, R. A., Figueira, W. F., Steinberg, P. D., Johnston, E. L., & Bishop, M. J. (2018). Increasing microhabitat complexity on seawalls can reduce fish predation on native oysters. *Ecological Engineering*, 120, 637-644.
- Strain, E. M. A., Morris, R. L., Bishop, M. J., Tanner, E., Steinberg, P., Swearer, S. E., ... & Alexander, K. A. (2019). Building blue infrastructure: Assessing the key environmental issues and priority areas for ecological engineering initiatives in Australia's metropolitan embayments. *Journal of Environmental Management*, 230, 488-496. <https://doi.org/10.1016/j.jenvman.2018.09.047>
- Strain, E. M. A., Cumbo, V. R., Morris, R. L., Steinberg, P. D., & Bishop, M. J. (2020). Interacting effects of habitat structure and seeding with oysters on the intertidal biodiversity of seawalls. *PLOS ONE*, 15(7), e0230807. <https://doi.org/10.1371/journal.pone.0230807>
- Ushiana, S., Mayer-Pinto, M., Bugnot, A., Johnston, E., & Dafforn, K. (2019). Eco-engineering increases habitat availability and utilisation of seawalls by fish. *Ecological Engineering*, 138, 403-411. <https://doi.org/10.1016/j.ecoleng.2019.07.022>
- Vermeij, G. J. (1971). Gastropod evolution and morphological diversity in relation to shell geometry. *Journal of Zoology*, 163(1), 15-23. <https://doi.org/10.1111/j.1469-7998.1971.tb04522.x>
- Waltham, N. J., & Sheaves, M. (2020). Thermal exposure risks to mobile tropical marine snails: Are eco-engineered rock pools on seawalls scale-specific enough for comprehensive biodiversity outcomes? *Marine Pollution Bulletin*, 156, Article 111237. <https://doi.org/10.1016/j.marpolbul.2020.111237>
- Woo, J. S. Z. (2020, May 9). Evaluating the Penang South Reclamation (PSR) project according to the United Nations' sustainable development goals. *Penang Institute Issues* (pp. 1-12). <https://penanginstitute.org/wp-content/uploads/2020/05/Evaluating-the-Penang-South-Reclamation-Project.pdf>
- Yee, J. C., Firth, L. B., Cheah, C. B., Strain, E., Tan, A., & Chee, S. Y. (2018). It is in the details: Simple structural complexity modification could restore ecological function on seawall. In *The 11<sup>th</sup> IMT-GT UNINET Conference 2018 – Bioscience for A Sustainable Future*, Penang, Malaysia, December 11-12, 2018.
- Zaki, M. R. M., Zaid, S. H. M., Zainuddin, A. H., & Aris, A. Z. (2020). Microplastic pollution in tropical estuary gastropods: Abundance, distribution and potential sources of Klang River estuary, Malaysia. *Marine Pollution Bulletin*, 162, Article 111866. <https://doi.org/10.1016/j.marpolbul.2020.111866>