Oasis: 3D Printable Artificial Reef System to Combat Coastal Whitening Events

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Abstract

This research seeks to implement a 3D printable artificial reef design to restore the ecosystem degraded by coastal whitening events. Coastal whitening events refer to a phenomena where a coastal ecosystem experiences decline in biomass and diversity due to calcium carbonate in seawater destroying the habitat of seaweeds. Worldwide, coastal whitening events are increasingly becoming problematic, not only yielding disastrous impacts to the ecosystems but also to the economy of the seaside communities.

This research seeks to design, 3D-print, and deploy an artificial reef made out of biodegradable resin and iron sulfate to encourage the growth of seaweed. Presently, I have 3D modelled my prototype design of the pot on Sketchup. Next, I will test the prototype design against coastal conditions via an online CFD program and use the feedback to modify the design appropriately. The finalized model will be printed via a 3D printing firm. The model will be plated with seaweed and shellfish and deployed near aquaculture.

Motivation and approach

Oasis aims to combat degradation of coastal ecosystems caused by whitening events. Whitening events refer to the phenomena in the shallow subtidal zone where crustose coralline algae proliferate on rock surfaces, displacing seaweed. When coralline algae die, their calcium carbonate cell walls remain and cover the surface, hindering seaweed growth by preventing them from attaching (Isa et al., 2017). This creates deforested zones in the ocean where the ecosystem faces significant decline. Worldwide, seaweed populations have been declining, and subsequently the biodiversity of marine ecosystems have been degraded at an alarming rate (Monserrat et al., 2022; Geist & Hawkins, 2016; Kytinou et al., 2023).

Seaweeds are primary producers that play a key role in sustaining the marine ecosystem (Khan et al., 2016; Jangtaek Yoon, 2008; Zimmerman et al., 1994). They form natural seaweed beds known as kelp forest that serve as a critical source of food and habitat for various fishes and sea animals to breed and raise offsprings (Jung et al., 2022; Hwang et al., 2017; Teagle, 2017). In addition, seaweed biomass is an important medium to sequester carbon underwater (Kang et al., 2014). Whitening events destroy the habitat of seaweed and thereby reduce the diversity and biomass of marine life that rely on kelp forests for food, habitat, and reproduction, expediting the decline of the marine ecosystem (Geist & Hawkins, 2016). It further lowers the capacity of the ocean to sequester carbon and mitigate impacts of climate change.

A major cause of coastal whitening events is the increase of calcium carbonate in seawater. Calcium carbonate hinders seaweed growth by sticking to rock surfaces and blocking seaweed from attaching as well as by forming strong alkaline environments around rocks that are inhospitable to seaweeds, which thrive in neutral conditions. Further, climate change contributes to whitening events, meaning whitening events are projected to exacerbate in future. Increase in atmospheric carbon dioxide acidifies the seawater, which causes various carbonate ions to be released from bedrock or concrete artificial reefs, promoting the formation of calcium carbonate. Moreover, acidified seawater limits iron ion concentration—a vital nutrient for seaweed growth—in seawater, allowing coralline algae to take over rock surfaces (Lee, 2012). Further, the rising ocean temperature lowers the solubility of calcium carbonate in the sea water, encouraging the settlement of alkaline compounds on seabed rock surfaces (Kwak, 2024).

Calcium carbonate is introduced to the ocean through several anthropogenic means. Coastal constructions involving concrete creates a direct inflow of calcium carbonate to the ocean; use of quicklime in farms to neutralize acidic chemical fertilizer drains calcium hydroxide to the sea. Especially, the deployment of concrete artificial reefs to create artificial habitats for seaweed backfired, as calcium carbonate released from these artificial reefs actually worsened whitening events (Korea Environmental Industry & Technology Institute, 2017).

Artificial reefs have been deployed to recreate platforms for seaweed to grow on and restore the ecosystem degraded by whitening events. In the status quo, two main types of artificial seaweed reef designs exist, both of which are ineffective restoring the ecosystem, but also economically unsustainable and even environmentally detrimental.

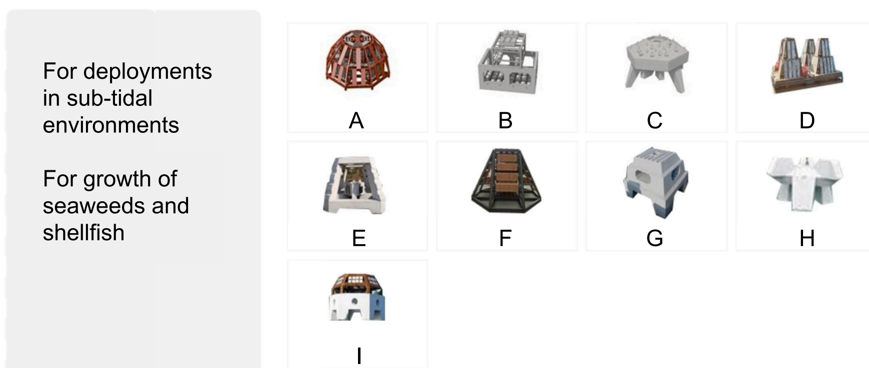

Figure 1. Existing designs of artificial reefs (Adapted from the image of Integrated fisheries resource information system of Korea)

The first type is concrete reefs, which are solid concrete structures of several feet (Diagram B, C, E, G, H, I in Figure 1). These are put on the seabed to provide surface for seaweed to land on and colonize. Ironically, the concrete in these structures release strong alkali such as sodium hydroxide to their surrounding, hindering seaweeds from latching onto the structures, effectively exacerbating the whitening events. In addition, constructed out of solid concrete, they are costly to make and install.

The second type is steel frame reefs with attachments of ceramic panels, which provide the surface for seaweed to plant on (Diagram A, D, F in Figure 1). Although steel and ceramic does not contribute to whitening events, it increases the cost of manufacture and installment. Further, the steel structure is susceptible to corrosion and breaking down by seawater. Further, the seabed location of these reefs make maintenance and retrieval practically impossible. The seabed location also makes them prone to being displaced by current and covered up by sand. Further, they also pick up floating trash such as fishing nets. (Cheon, 2023; Ko & Kim, 2018).

A new method is needed to artificially create habitats for seaweeds while solving the problems of existing concrete or metal reefs. I designed Oasis, a 3D printable artificial reef system that combines the concept of artificial reef, fertilization agent, and aquaculture to restore the ecosystem destroyed by whitening events. As an all-in-one platform, Oasis is designed to provide habitat not only for seaweed, but also for shellfish, fish, and other marine animals. It comprehensively mimics the role of a natural reef, and allows for a full settlement of the ecosystem. Oasis is composed of two parts: the pot structure and the suspension structure connecting it to the surface of the water.

The reef platform itself is shaped like a cylindrical ‘flower pot’ of approximate 2 ft diameter and 1.5 ft depth. The inside of the pot is used to cultivate seaweed and shellfish like abalone and conches that feed on the seaweed. The outside is used to cultivate shellfish such as oysters and mussels that feed mainly on plankton [Figure 2]. The method in which seaweed and shellfish are planted on the pot is inspired from the technology in seafood aquaculture. The pot will be wrapped around with a string embedded with seaweed juveniles. Oyster and abalone will be attached to the pot by immersing and curing in a pool containing juveniles before deployment to the ocean The inner and outer surfaces of the pot contain ridges of approximately 2 inches to provide space for shellfish such as oysters, and conches to live while avoiding the stress of the current. The ridges and the inside of the pot also provide shelter for juvenile fish and spawning ground for adults. The upper and lower ends of the pot are open to allow current to circulate, by which the excrements of the organisms living inside may be discharged. The open ends of the pot also enable fish and other organisms to enter the structure with ease. The tapering design enables maximum exposure of sunlight, which will expedite seaweed growth.

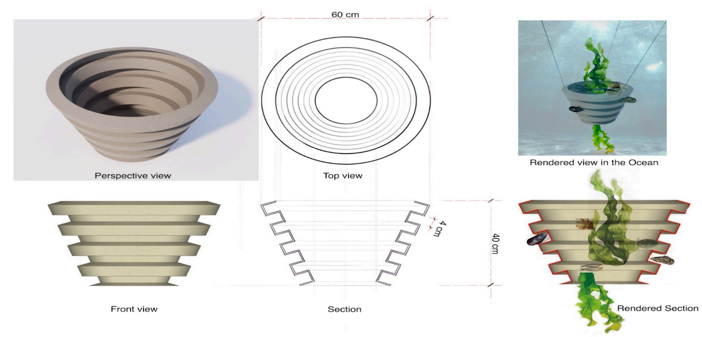

Figure 2. Pot Design

The pot will be 3D printed using a mixture of biodegradable resin and iron sulfate. Iron sulfate will be retrieved from slag, a waste byproduct created from iron extraction. The inclusion of iron sulfate in the material is inspired from pelleted fertilization agents for seaweed which use a mixture of iron sulfate and diatomite to bolster seaweed growth. Within the pot, the iron sulfate content will release iron ion, a vital nutrient to seaweed growth. Iron ions also encourage plankton growth, which will help feed oysters and mussels grown on the outside of the pot (Coale et al., 2004). The 3D printable nature of pots allows Oasis to be produced cost-effectively and at a mass, efficient scale. Further, 3D printing enables the design of the pot to be easily modified in size, shape, and material composition to suit specific environments, species, and locations as required.

Figure 3 (Left). Suspension system (Recreated from the images of (1) Lee, S., April 10, 2013 and the image taken from the video of (2) Anysmart, February 28, 2019).

The suspension system of Oasis took inspiration from seaweed and shellfish aquaculture. Oasis utilizes ‘hanging culture’ to suspend pots by a buoy at the surface of the water [Figure 3]. Hanging culture has proven effective in cultivating Oysters, mussels, sea cucumbers, kelp, etc. in aquaculture. Hanging culture enhances the productivity of cultivation because it utilizes horizontal space efficiently.

Figure 4 (Left). Artificial Reef Colony (Adopted from the images taken from the video of Anysmart, February 28, 2019).

Hanging culture is particularly effective in inducing seaweed growth because it brings the seaweed in closer proximity to light. Further, the reef structures, connected by cords, are immune to issues of dislocation by current and are able to be easily maintained [Figure 4]. Cords used to suspend the cylinders in water will be made out of discarded fishing nets, which is one of the most deadly plastic waste in the ocean (Laville, 2021). Hanging culture enables vertical stacking of pots, meaning pots are able to be deployed in larger groups to restore large-scale ecosystems, such as kelp forests. Furthermore, within the stack, each pot in different depths may be customized to cater for ecosystems in different levels within the ocean. The level of the pots may be adjusted to cater for targeted species and ecosystems that exist in lower levels with less sunlight and lower temperature.

Oasis solves the proposed problem three ways: 1) It restores coastal ecosystems destroyed by whitening events by directly cultivating seaweed, the primary producers of marine ecosystems, as well as other constituents of the ecosystem such as shellfish and fish. 2) It reduces the calcium carbonate in sea water by enabling the harvest of shellfish. Cultivating and harvesting shellfish [oyster, conch, etc.] that accumulate calcium carbonate in their shells enables a reduction in calcium carbonate in water. 3) It enables the cultivation of seaweed and shellfish in natural harmony without the need of outside, artificial management. Oasis encourages the growth of seaweed and plankton, which can help mitigate carbon footprint and alleviate the effect of climate change on oceans, which includes whitening events.

<u>Oasis improves upon exiting solution in the following ways:</u>

Oasis is effective in cultivating seaweeds in zones with whitening events. encourages the formation of permanent ecosystem by encouraging settlement of marine animals such as shellfish, fish and other animals. <u>Oasis is environmentally sustainable</u>. Oasis is made of biodegradable resin and iron sulfate, which are harmless to the ocean environment, as opposed to the concrete exacerbate whitening events; reef pots can be easily maintained through hanging culture, as opposed to unmaintainable existing reef designs. <u>Oasis is economically feasible</u>. 3D printing allows for cost-effective and efficient production; shellfish are grown in structures may be harvested for profit, and may be used to fund maintenance; maintenance is easy and cheap thanks to hanging culture; biodegradable resin and iron sulfate creates a durable structure that can easily be amended with 3D printing. Oasis encourages the growth of plankton and seaweed, which increases oxygen levels in the ocean and captures carbon dioxide. Easy accessibility of reefs via hanging culture creates potential for Oasis to be used for monitoring health of the ocean environment.

Logistics and organization

Presently, I have 3D modelled my prototype design of the pot on Sketchup. Next, I will test the prototype design against coastal conditions via an online CFD program and use the feedback to modify the design appropriately. The finalized model will be made via a 3D printing firm. The model will be plated with seaweed and shellfish and deployed near acquaculture.

All elements of Oasis' design borrow from technologies that have already been proven to be feasible and successful in other industries. There exist 3D print firms that are able to mix biodegradable resin and to materialize my artificial reef design, and aquaculture farms to allow reefs to be deployed. I will need to obtain funding to print 5 prototypes of my reef design using 3D printing firms, which will be granted by the THINK program. I will reach out to 3D printing firms to print out my design and reach out to aquaculture firms to deploy my reefs.

Milestones of this project are: 1) Finalize prototype design, 2) Print prototype, 3) Deploy prototype, and 4) Analyze and evaluate success from collected data. Since Oasis seeks to solve the concrete artificial reefs' inability to host seaweed because they release calcium hydroxide, a strong alkaline, the completion criteria of Oasis would be to see the growth of kelp.

To evaluate progress, I will visit the aquaculture where my artificial reefs are deployed every other week for a total of six times. During every visit, I will film the environment surrounding the artificial reef with an underwater camera to evaluate the reef's success in hosting an ecosystem. Also, I will take out the pot to measure and record the growth and health of the kelp and the attached shellfishes. Then, I will compare the growth of kelp on the reef to the kelp grown in aquaculture and assess how my reef enhanced kelp cultivation productivity.

Potential issues and solutions:

1. If the pots float to the surface because it is too light before the kelp and shellfish gain enough mass, a weight can be attached by a line under the pot to keep it fully taut and prevent it from flying away.
2. If the warm sea temperature affects seaweed growth towards the later months, the pot can be lowered for Seaweed to be cultivated at a colder temperature.

3. If a storm or a natural disaster disturbs the growth of seaweed, I can seek safer and more closed locations to fasten the reef against.

Timeline:

Now 3D model the pot design on Sketchup (Already Done)

2/24 Assess the prototype design (fluid dynamics, structural integrity, dimensions, etc) of the pot against coastal environments e.g. wave action, seabed formation, etc using CFD software and make necessary modifications

3/10 Print the prototype using a blend of biodegradable resin and iron sulfate using low resolution mode through 3D Print Firms. Use a seaweed aquaculture firm to plant seaweed protoplasts onto prototype by immersing.

3/17 Use an oyster aquaculture firm to plant juvenile abalone and oyster protoplast onto the prototype. Deploy 4 prototypes out in the ocean at the coast of the said aquaculture firm

3/31 [Visit #1] Visit the aquaculture firm every other week for 6 times total until 5/26 to measure and record the growth and health of seaweed (mass, height, etc.) and ecosystem around the reef system.

4/7, 4/21, 5/5 [Visits #2,3,4]

5/12 Conduct mid-point check to assess the performance of the 4 reefs deployed; note improvements for reef design using the feedback from the result; send request to 3D Print Firm for printing final design.

5/19/25 [Visit #5]

5/26/25 [Visit #6]; produce final report; retrieve printed final design

To document the implementation process, I will create a log every week detailing my progress between each step in the timeline. I also will anticipate any changes that I would have to account for should any occur in advance. Currently I have made the initial prototype design on sketchup. I will need funding to print out 5 prototypes from 3D Print Firms and also acquire. Previously, I have designed a steel artificial reef structure on Sketchup. So far, I have made the initial prototype design on Sketchup and identified the list of 3D print firms and kelp/shellfish aquaculture firms I may use/work with:

3D printing firms: D-Shape, WASP, Sulapac, 3D Systems, GREENFILL3D

Kelp/shellfish aquaculture firms: STONINGTON KELP CO. (Stonington, CT), Copps Island Oysters (Norwalk, CT), SoundWaters (Stamford, CT)

It remains to improve my initial design by running tests on CFD, print out the prototype through a 3D firm, plant kelp and shellfish onto prototypes at aquaculture firms, and deploy the reefs to the sea.

Funding will go to printing prototypes of my artificial reef design from a 3D printing firm. Because the reefs must have rough surface texture to allow for kelp and shellfish to latch, they will be printed on low resolution, which makes printing cheaper.

Item	Amount	Estimated Cost	Link
Prototype 3D printing - Low Resolution	5	$600	https://buly.kr/2fcpvOI
Kelp and Oyster stock	4 pot-worth	$200	Purchase stock at aquaculture firm

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