ACS Sustainable Chemistry & Engineering

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Research Article

# Mitigating Algal Competition with Fouling-Prevention Coatings for Coral Restoration and Reef Engineering

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Cite This: *ACS Sustainable Chem. Eng.* 2025, 13, 5808−5817

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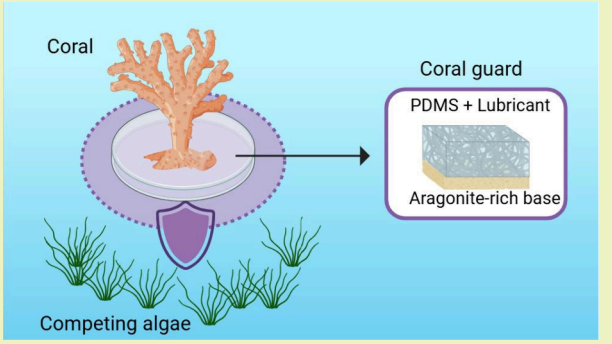
**ABSTRACT:** Coral reefs are undergoing unprecedented degradation due to rising ocean temperatures, acidification, overfishing, and coastal pollution. Despite conservation efforts, including marine protected areas and sustainable fishing practices, the magnitude of these challenges calls for innovative approaches to repair and restore coral reefs. In this study, we explore the application of bioinspired materials to address the challenge of algal competition, a key bottleneck for effective restoration approaches. We develop and optimize slippery liquid-infused porous surfaces (SLIPS), as a fouling-prevention coating tailored for coral reef restoration and engineering. Through aquarium experiments and *in situ* trials on O'ahu, Hawai'i, we assess the effectiveness of these coatings in mitigating algal competition and facilitating coral growth. Our results demonstrate that PDMS-based SLIPS coatings significantly reduce algal coverage compared to commercial aragonite-based surfaces, with up to 70% reduction observed over a 12-week deployment period *in situ*. We also develop coral-guards, which are slippery substrates customized for coral fragment outplanting. Coral-guards facilitate tissue growth of *Stylophora pistillata* fragments, without competitive turf algal growth. These approaches hold promise for advancing restoration efforts, including the engineering of hybrid reefs and targeted coral gardening approaches.



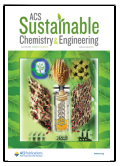

**KEYWORDS:** *coral restoration, hybrid reefs, artificial reefs, biofouling, coral competition, turf algae*

## 1. INTRODUCTION

Coral reefs are rapidly degrading due to rising ocean temperatures, ocean acidification, overfishing, and coastal eutrophication.[1,2] Even though coral reefs go through natural cycles of disturbance and recovery, current environmental conditions have led to an increased number of disturbance events that hurdle the ability of the reef community to recover effectively.[1] Mass bleaching events have become more frequent and prevalent in recent years.[3] It is estimated that since the 1950s, coral reef coverage and diversity have declined by half.[4] Coral reefs are vital components of the ecological landscape in tropical and subtropical regions and are hotspots of marine biodiversity. The global degradation of coral reefs thus has crucial implications for ocean productivity, biodiversity, and coastal resilience.[5] Reef loss also has far-reaching economic repercussions due to their vital role in fisheries, coastal protection as well as tourism and trade.[6] Such ecosystem goods and services amount to over $30 billion USD annually.[7,8]

There are a number of actions that need to be taken to both mitigate stressors and to effectively aid in the repair, rehabilitation and recovery of coral reef ecosystems.[9,10] Ultimately, reducing global climate threats and managing local stressors are two key strategies for managing the source of reef degradation. Local management approaches include the assignment of marine protected areas (MPAs),[11] the promotion of sustainable fishing practices,[12,13] and water quality management.[14] However, the threats facing coral reefs have overwhelmed many such efforts and are thus calling for more active reef restoration approaches, including coral gardening and the exploration of new restoration technologies.[15−17] Biologically driven approaches include increasing the thermal tolerance of corals via assisted evolution[18] and therapeutic treatments such as probiotic and microbiome modulation.[19,20] More recently, there has been a push to explore approaches from adjacent engineering disciplines, such as bioengineering and nanotechnology, in order to accelerate

Received: September 16, 2024
Revised: March 25, 2025
Accepted: March 31, 2025
Published: April 15, 2025



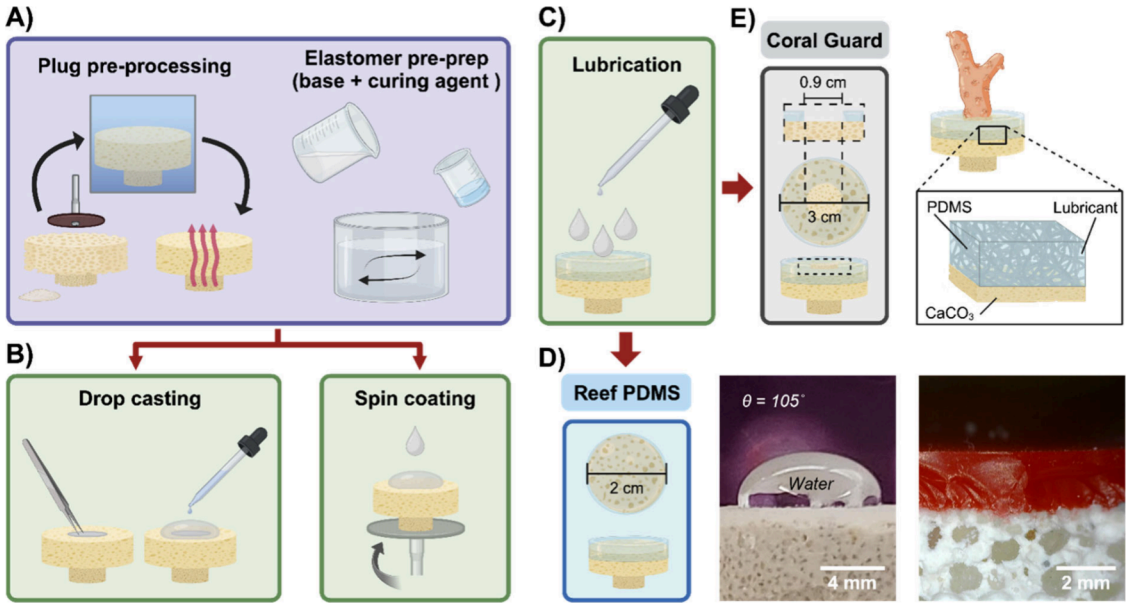



**Figure 1.** Fabrication process and design of reef-PDMS and coral-guards. (A) A preprocessing protocol ensured a stable and rough surface. The PDMS elastomer was mixed, and then (B) either drop-casted or spin-coated on top of the coral plugs. (C) Infusion with a lubricant yields the (D) i-PDMS fouling-prevention coatings on top of coral plugs (reef-PDMS). Example measurements of static contact angle are shown. Close-up image shows the PDMS layer (stained in red) firmly attached to the rough surface of a $CaCO_3$ coral plug. (E) Controlled application of slippery coatings creates a fouling-prevention ring, coral-guard, that enables coral fragment growth. (Created with BioRender.com.)

biodiversity restoration or to kickstart ecosystem processes.[17,21−23]

A major challenge in coral restoration and the engineering of hybrid reefs (i.e., engineered living reef structures) is to ensure the successful growth and propagation of outplanted corals, especially in areas where high nutrient levels and low herbivorous fish populations lead to elevated algal competition with coral fragments.[24] Effects of such high algal cover go beyond immediate space competition and alter the reef biochemistry, accelerating reef hypoxia and changes in reef microbial communities.[25,26] To enhance the competitive success of corals, managers have thus aimed to increase herbivorous fish populations and reduce nutrient levels to limit macroalgal productivity.[27,28]

Here, we leverage advances in nanoengineering and materials science to develop new solutions to managing algal competition in coral reef restoration.[21] The field of fouling-prevention coatings has recently seen the development of novel types of nontoxic solutions.[29] Specifically, slippery liquid-infused porous surfaces (SLIPS) have emerged as a simple, nontoxic technology that applies an immobilized lubricant layer that changes the foulant-surface interactions from a solid−solid to a solid−liquid interaction, therefore minimizing the adhesion of unwanted organisms in the process.[30] The SLIPS principle can be exploited using different materials (e.g., Teflon, synthetic polymers, steel) to create a micronanoporous substrate that is infused with a lubricant/oil.[31−33]

Building on this foundation, we integrated a lubricant-infused 3D polydimethylsiloxane (PDMS) polymer network (i-PDMS)[34] and tailored it specifically for coral reef restoration and engineering applications- an area that has previously not been explored with SLIPS-based materials. This process involved developing a simple method to ensure that stable attachment of i-PDMS to common calcium carbonate-based restoration substrates. We comprehensively test the suitability of this infused PDMS reef substrate (hereafter reef-PDMS) by quantifying algal coverage in both aquarium settings and *in situ* in two locations surrounding the fringing reefs in O'ahu, Hawai'i, which represent diverse environmental conditions. Importantly, we extended the application of the SLIPS principle to develop 'coral-guards', a novel and scalable solution designed to reduce direct competitive interactions between coral fragments and adjacent benthic organisms. Further, we evaluated potential negative effects of such coral-guards on coral photophysiology and tissue growth rates to ensure their ecophysiological compatibility. Our results highlight that reef-PDMS and coral-guards effectively prevent the buildup of competitive algae, while coral tissue can overgrow the slippery coatings, an important result that offers practical solutions to reduce competitive pressure for outplanted corals in coral nurseries and other restoration efforts.

## 2. MATERIALS AND METHODS

**2.1. Fabrication of Reef-PDMS Surfaces.** To incorporate i-PDMS SLIPS coatings onto coral restoration substrates, we developed a protocol that uses standard coral fragmentation plugs made from aragonite sand (Figure 1A-B). These were chosen as the ideal model substrate as they are frequently used in *ex situ* coral nurseries and *in situ* coral gardening approaches.[35] A common approach for improving PDMS adhesion to glass is through oxygen plasma treatment.[34] Preliminary experiments on our aragonite plugs (Ocean Wonders, Agrocrete- item: 804879061113) however, suggested that this approach did not improve attachment noticeably. To overcome this challenge, we developed a simple approach for long-term attachment of PDMS to common aragonite-based coral restoration substrates. First, a preconditioning protocol was developed to reduce leaching of any materials from the plugs (e.g., calcium carbonate), which can interfere with adhesion. Aragonite plugs were dried in a convection oven (Cole Parmer- model EW-52411−04) at 60 °C overnight to eliminate residual moisture. Plugs then underwent sand layer removal to prevent loose sand particles from creating an unstable fabrication base, as preliminary experiments showed that this results in weak adhesion of the PDMS due to rough edges that are prone to tearing and peeling. A 150-grit sandpaper was utilized, and sanding was


https://doi.org/10.1021/acssuschemeng.4c07508
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carried in rotary motion with a circular sanding attachment on a FASTPRO 20 V drill. Plugs were then soaked in DI water and shaken vigorously to remove any loose particles, followed by water drainage. The described washing process is repeated three times. Following washing, the plugs are dried again to ensure moisture removal. This protocol ensured a rough and stable aragonite surface, which promotes mechanical interlocking as well as improved bonding and peeling strength of PDMS.[36]

To prepare the slippery coatings, PDMS-based elastomers were prepared by using the commercially available SYLGARD 184 elastomer kit (Dow Corning, Midland, MI, USA).[37] The elastomer base and curing agent were manually mixed at a 10:1 ratio using a spatula for 10 min. Any bubbles induced during the mixing process were removed by vacuum degassing the mixture for up to 15 min in a desiccator at a vacuum pressure of 31 mbar. The coral plugs were coated by slowly pouring 0.7 gr of the mixture on top of the disk-shaped crown and spin-coated at 800 rpm for 10 s using a spin coater (model SCK-300, Instra Scientific LLC, USA). The coated plugs were cured for 48 h in a convection oven (model EW-52411−04, Cole Parmer, USA) at 50 °C. Next, the coatings were lubricated for 48 h by complete immersion of the PDMS-coated coral plugs in trimethylsiloxy-terminated PDMS oil with a viscosity of 10 cSt (Gelest, PA, USA- DMS-T11). After lubrication, samples were tilted at 90° and rotated for 24 h, allowing gravity to aid in removing any excess oil.

**2.2. Coral-Guard Fabrication.** Corals require a stable substrate to support attachment and growth of outplanted fragments.[38] Coral fragmentation plugs made out of materials such as ceramic and calcium carbonate-based sand are widely used as anchoring bases in both ornamental and restoration-focused fragmentation.[35] To reduce the potential for direct competition between macroalgae and coral fragments used in restoration, we developed coral-guards, which are slippery coral restoration substrates (Figure 1E). First, a circular adhesive with a diameter of 0.95 cm, made from duct tape, was placed at the center of the preconditioned plug surface as a placeholder for the coral fragment prior to the deposition of PDMS (Figure 1B). The base and curing agent of the SYLGARD TM 184 elastomer kit were mixed in a planetary centrifugal mixer (Thinky mixer, Model ARM-310) at a 10:1 ratio for 210 s at 2000 rpm. This automated approach enables consistent and homogeneous mixing of larger quantities of SYLGARD 184 in a shorter time without inducing bubbles. 0.9 gr of the premixed elastomer was drop-cast to ensure full coverage of the coral plug disk, including the edges to improve adhesion, and cured as described above. A circular stamp (0.95 cm in diameter) was used to create a disk in the cured coating. The disk and the sticker were then carefully removed using a tweezer, leaving an outer PDMS ring (Figure 1C). Next, the coatings were lubricated for 48 h by full immersion of the fabricated samples in trimethylsiloxy-terminated PDMS oil with a viscosity of 10 cSt (Gelest, PA, USA).

**2.3. Reef-PDMS Laboratory Experiments.** To test the effectiveness of the reef-PDMS coatings in preventing algal biofouling, we evaluated their efficacy in two flow regimes under laboratory conditions. For the low-flow treatment, flowing seawater was pumped from the SIO (Scripps Institution of Oceanography) pier, and delivered at a flow rate of ∼ 100 mL $s^{-1}$ via a 10-gallon flow-through aquarium system (51 × 27 × 32 cm). For the high-flow treatment, we added four circulation pumps (AQUANEAT, 480 GPH, USA) at the four corners of the aquarium system to create a turbulent flow environment (Figure S1). The local flow rate created by the pumps was about ∼ 504 mL $s^{-1}$ per pump. For each flow treatment, 12−15 reef-PDMS and control plugs (uncoated), were randomly distributed on plastic crates (Figure S1). Samples were exposed to natural seawater for up to 10 days. During these tests, experimental parameters mimicked coral gardening maintenance conditions.

**2.4. Reef-PDMS *in Situ* Experiments.** We tested the feasibility of reef-PDMS for *in situ* applications on Hawaiian coral reefs at two sites with differing flow regimes next to the Hawai'i Institute of Marine Biology (HIMB) at Kāne'ohe Bay Bay, O'ahu, Hawai'i. These sites were chosen for testing the coatings under environmental conditions relevant to coral cultivation and restoration. These conditions include a low-flow protected coral nursery (21°25′58″N 157°47′24″W) and a high-flow, exposed reef environment (21°26′15″N 157°47′25″W). Reef-PDMS were attached to custom-made coral trees, which are PVC structures commonly used in outplanting efforts. Our coral trees facilitated a multidirectional sample placement in order to test the effectiveness of reef-PDMS in response to variations in irradiance, flow regime, and sedimentation effects, thus mimicking natural variations within a coral reef. At each study site two coral trees were placed with a total number of 25 reef-PDMS and 30 control plugs per structure.

**2.5. Coral-Guard Experiments.** Coral-guards were tested in our in-house aquaria at Scripps Institution of Oceanography (Figure S1), where natural seawater introduced a mixed community of temperate filamentous algae. These algae are not typically competitors of corals in tropical reefs but provided a useful model to evaluate the potential of SLIPS-based materials to limit algal fouling and assess coral tissue overgrowth. This proof-of-concept study was specifically designed to test whether coral-guards could simultaneously support coral tissue growth and prevent fouling. Physiological characterization of corals was conducted to ensure there were no adverse effects on coral tissue overgrowing the slippery coatings. We tested the efficacy of the coral-guards compared to coral plug controls (uncoated aragonite-based plugs) as well as PDMS-coated plugs that were not infused with the lubricant. Nonlubricated PDMS-coated plugs were tested to assess potential changes in coral physiology, due to contact with the lubricant in our coral-guards. For each replicate, a single coral fragment of *Stylophora pistillata* was glued to the center of the plug using cyanoacrylate-based aquarium glue (RA Aqua Tech, USA). Experiments were performed using a with seven replicates for each treatment (Figure S1).

**2.6. Coral Cultivation.** Colonies of *Stylophora pistillata* obtained from Birch Aquarium at SIO (San Diego, USA) were cultivated in a flow-through aquarium. The seawater temperature in the aquarium was maintained at 25 °C, and colonies were kept under a 10:14 h light-dark cycle, with an incident downwelling irradiance of 100 $\mu$mol photons $m^{-2}$ $s^{-1}$ as provided by aquarium lights (Orbit Marine LED Current Loop, USA). Corals were fragmented to 2.5−4 cm in length by transversely cutting the tips of the branches for experimental tests.

**2.7. Algal Coverage Analysis.** An underwater camera (Olympus TG-6 12 MP) was used to obtain top-view images from surfaces tested for algal coverage/biofilm coverage in flow-through aquarium systems. *In situ* underwater images were taken using a Canon G15 camera with underwater housing. Adobe lightroom (Adobe Inc., CA, USA) software was used for contrast and exposure adjustment on the images. During the *in siu* deployment period, a few of the samples experienced cracking or breakage of the aragonite plugs. Additionally, several images obtained underwater did not meet a satisfactory quality for image analysis due to challenges in maintaining comparable exposure underwater and were thus excluded from the analysis (<13% of images). Algal coverage was characterized as the two-dimensional area covered by macroalgae (primarily epiphytic turf algal communities) and/or visible biofilms using the open software ImageJ (Fiji, USA). For this, manual segmentation was performed to identify areas of coverage (Figure S2).

**2.8. 3D Photogrammetry.** We used 3D photogrammetry[39] to quantify coral tissue growth in coral-guard experiments. For this, samples were removed from the aquarium and placed on a motorized turntable (azimuthal rotation= 0−360°). To optimize contrast and lighting, illumination was provided by an LED panel (Neewer 20W) at a color temperature of 4000K in front of a white background, and photos were taken with an Olympus TG6 12MP digital camera. Each replicate surface was photographed over two zenith angles (45° and 30°) to yield up to 100 photos per sample taken from different azimuthal angles. A commercial software (Agisoft Metashape Professional, v2.0.3 2023) was used to generate 3D point clouds from the 2D images (Figure S3). During this process, low-quality images were identified using Metashape's built-in image quality assessment tool, which evaluates images based on contrast, sharpness, and signal-to-noise ratio. Images with a quality score below 0.5 were flagged and visually inspected. If they were found to be obviously blurry or had motion artifacts, they were removed from the data set.


https://doi.org/10.1021/acssuschemeng.4c07508
ACS Sustainable Chem. Eng. 2025, 13, 5808−5817

This ensured that only high-quality images were used in subsequent modeling steps. The remaining photos were aligned in Metashape with a key point limit set to 0 and a tie point limit set to 10,000. After alignment, a dense point cloud was constructed with accuracy set to high and depth filtering set to mild. The point cloud was scaled using the scaling disk captured in the photos and replicated in the point cloud (Figure S3). Following scaling, all points except those belonging to the lateral coral tissue were trimmed away. This trimmed point cloud was then exported to CloudCompare (v2.12.2022), and a mesh was constructed and trimmed using the PoissonRecon plugin with Octree depth set to 12 and output density as SF selected. Finally, this mesh was exported to Meshlab (2022.02), and the 3D surface area was calculated.

**2.9. Pulse Amplitude Modulation (PAM) Fluorometry.** PAM fluorometry was performed on the laterally growing coral tissue areas to evaluate the maximum quantum yield of photosystem II ($F_v/F_m$) for different coral fragmentation samples (control, PDMS, coral-guard) used in the coral-guard experiment. Three individual coral fragments per base material type were tested across five regions on the lateral tissue using an Imaging pulse amplitude-modulated chlorophyll *a* fluorometer (Imaging PAM, mini version; WALZ GmbH, Effeltrich, Germany) that employs a blue measuring light (460 nm). For each measurement, coral fragments were removed from the experimental system and placed in a black acrylic chamber and dark-adapted for 20 min before employing a saturation pulse (using default settings) to $F_V/F_m$. Fifteen areas of interest for $F_V/F_m$ analysis were limited to laterally growing tissue that was directly in focus and not obstructed by the coral branch itself.

**2.10. Optical Coherence Tomography (OCT) Imaging.** OCT imaging was used to visualize 3D coral tissue growth and attachment to the underlying substrate. OCT scans were performed using a Thorlabs Ganymede II (Thorlabs, GmbH, Dachau, Germany) spectral domain system as described previously.[40,41] The instrument has an effective focal length of 36 mm, a lens working distance of 25.1 mm and at the described configuration, the instrument creates scans with axial and lateral resolutions of 5.8 and 8 $\mu$m, respectively. Coral fragment samples were placed in a cylindrical glass container filled with seawater. The water level was adjusted at the lateral tissue level to facilitate effective focus on the growth of lateral coral tissue on both the fabricated surface and the aragonite-based control.

**2.11. Microcomputed Tomography.** To further evaluate coral skeletal deposition on fouling-prevention coatings, samples were scanned using a Skyscan 1076 $\mu$CT scanner (Bruker, Kontich, Belgium). Samples were mounted horizontally and scanned at 18 × 18 × 18 $\mu$m voxel size, applying an electrical potential of 50 kVp, a current of 200 $\mu$A, 180° in 0.8° steps, and using a 0.5 mm Al filter. The interfacial layer for coral skeletal deposition was visually observed using custom-written codes in Matlab (Mathworks, Natick, MA).

**2.12. Statistical Analysis.** Two-way analysis of variance (ANOVA), followed by Tukey HSD post hoc tests were performed to evaluate the efficacy of reef-PDMS coatings in reducing algal cover for different flow environments. Effects of coral guards on lateral tissue growth and $F_v/F_m$ were tested using a one-way ANOVA. All data was tested for normality of distribution and heterogeneity of variances. Data was $\log_{10}$ transformed if necessary.

## 3. RESULTS AND DISCUSSION

**3.1. Reef-PDMS Effectiveness in Reducing Algal Cover.** Coral restoration efforts are often challenged by the rapid growth of opportunistic biofilms, filamentous turf algae, and other macroalgae on deployed restoration substrates.[42] This rapid growth results in direct competition with outplanted corals[43] and can additionally have secondary effects on important ecosystem parameters such as reef oxygenation.[44] Coral restoration is often performed in areas that are highly eutrophic and overfished and are thus prone to enhanced growth of coral competitors. To accelerate ecosystem recovery and provide new means for ecosystem engineering, we here developed and tested fouling-prevention coatings for coral restoration substrates. Short-term laboratory experiments revealed the effectiveness of reef-PDMS coatings in reducing early stage biofilm and algal coverage compared to control coral plugs (Figure 2). For experiments performed under low-flow (see detailed description of flow regime in Figure S1), reef-PDMS coatings showed an approximate 2.5-fold reduction in algal coverage compared to uncoated controls (34% ± 12.5% SD vs 84% ± 6% SD, respectively, Tukey HSD post hoc test, $p < 0.001$, Figure 2). For experiments performed under high-flow (Figure S1), this effect was substantially enhanced and reef-PDMS reduced algal coverage >7-fold compared to uncoated controls (12% ± 7% SD vs, 92% ± 3% SD, Tukey HSD post hoc, $p < 0.001$, Figure 2). The lower coverage observed for reef-PDMS in the high-flow treatment compared to the low-flow treatment can be attributed to the fouling control mechanism of i-PDMS.[34,37] The inert nature of PDMS combined with the presence of lubricant oil at the interface of aragonite SLIPS and seawater creates unfavorable conditions for strong adhesion of algal spores. Even though soft fouling assemblages such as algal biofilms may form on SLIPS materials over time, they cannot strongly adhere to the substrate (Supplementary File S1).[37,45] As a result, increased drag forces present in the high-flow environment can displace the loosely attached material and organisms from the substrate and disrupt biofilm/algal turf formation and growth.

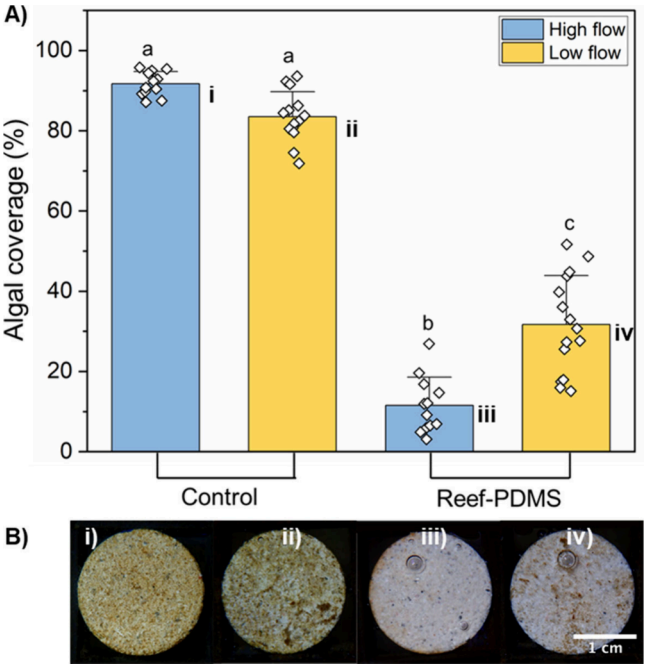


**Figure 2.** Laboratory tests of fouling-prevention coating efficacy on coral plugs. (A) Algal coverage (% of total planar surface area) for control surfaces (coral calcium carbonate plugs) and reef-PDMS plugs exposed to high and low flow treatments after 6 days of incubation of natural seawater ($n$ = 12−15 plugs, Tukey HSD post hoc, Means that do not share a letter are statistically significant, $p < 0.01$) (B) Example images of plugs at 6 days of incubation (letters i−iv correspond to data shown in panel (A)).

To test the long-term *in situ* efficacy of reef-PDMS, we deployed them in two contrasting reef environments (a sheltered coral nursery and open ocean environment) in Hawai'i for over 3 months (Figure 3A-B). Our results show


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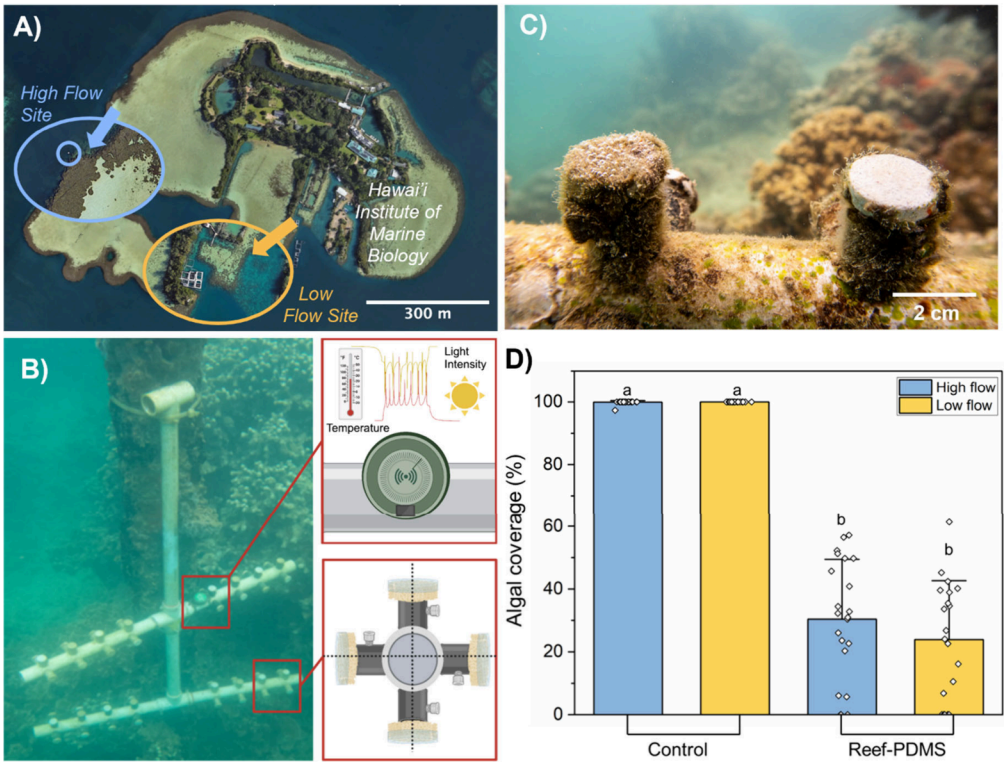


**Figure 3.** Long-term *in situ* study of fouling-prevention coatings on a coral reef in Hawai'i. (A) High-flow and low-flow study sites at Moku o Lo'e, O'ahu, Hawai'i (Areal image obtained from Google Earth) (B) Example image of an experimental tree (Created with BioRender.com). (C) Image of algal-covered control plug (left) and reef-PDMS (right) after 12 weeks postdeployment. (D) Percentage of algal coverage (means ± SD) on experimental substrates 13 weeks postdeployment ($n$ = 20−27). Statistical results are indicated (Means that do not share a letter are statistically significant, $p < 0.001$).

that algal coverage on reef-PDMS samples were highly effective in reducing competitive turf algae cover (Figure 3C−D). After 13 weeks of deployment, the surfaces of the control plugs were entirely covered with filamentous turf algae and other algal biofilms, while reef-PDMS showed a mean algal coverage of about 30% (±29% SD) and 24% (±19% SD) at low and high-flow sites, respectively (ANOVA, Tukey HSD post hoc, $p < 0.001$, Figure 3D). Reef-PDMS were effective in reducing algal coverage, independent of directional exposure (Figure S4) and thus small-scale variations in irradiance and local hydrodynamics. Analysis during earlier time points show that after about 3−5 weeks most of the control surfaces are fully covered with algae (Figure S5).

Together, these results suggest that reef-PDMS could be an ideal solution to reduce unwanted competitors, such as rapidly growing turf algae, in reef restoration and engineering projects, especially in the early stages of postdeployment. Rapidly growing turf algae can negatively impact ecosystem engineering approaches by producing chemicals and metabolites that deter coral settlement[46] and increase the labile pool of dissolved organic carbon,[47] thereby promoting reef microbialization,[48] potentially leading to unfavorable microbial activity and reef hypoxia.[44] Thus, reef-PDMS coatings could provide a means to affect the temporal dynamics of reef succession in artificial or hybrid reef projects, given corals a more beneficial macroenvironment as well as biochemical and microbial landscape.

**3.2. Mitigation of Algal Competition via Coral-Guards.** A core challenge in coral restoration projects, is the intense direct space competition of algae with asexually generated coral fragments in coral nurseries and when outplanted onto a degraded reef.[49,50] Given the successful results of reef-PDMS in reducing competitive algal cover, we hypothesized that this mechanism could be leveraged to reduce immediate competition of coral fragments used in coral outplanting efforts. Often, such asexually generated coral fragments are attached to coral plugs and maintained in underwater coral nurseries. Nursery cleaning requires a considerable allocation of the time and resources invested in restoration projects.[49,50] We hypothesized that by creating a protective nontoxic slippery ring surrounding the coral branch, we could create a competition-free environment and reduce maintenance efforts. Further, we hypothesized that corals would be able to overgrow the slippery coatings given the firm attachment of the central branch, facilitating successive growth over fouling-prevention coatings. Lab experiments with the developed prototype coral-guards, revealed that corals were indeed able to encrust and overgrow the slippery surfaces (Figure 4A-D). OCT and $\mu$CT imaging revealed skeletal deposition directly onto the PDMS-based coating without signs of penetration through the PDMS network (Figure 4C−D). Yet, corals appeared firmly attached to the coral-guards and we could not detect any visual detachment during our 90-day flow-through experiments. This finding demonstrates that despite characteristics such as low wettability and inertness, which make adhesion to i-PDMS based SLIPS unfavorable, coral-guards can support coral tissue growth. This suggests an interesting mechanism by which coral cells could attach and grow on top of a slippery surface,[51] eventually giving them a competitive advantage over opportunistic settlers that are


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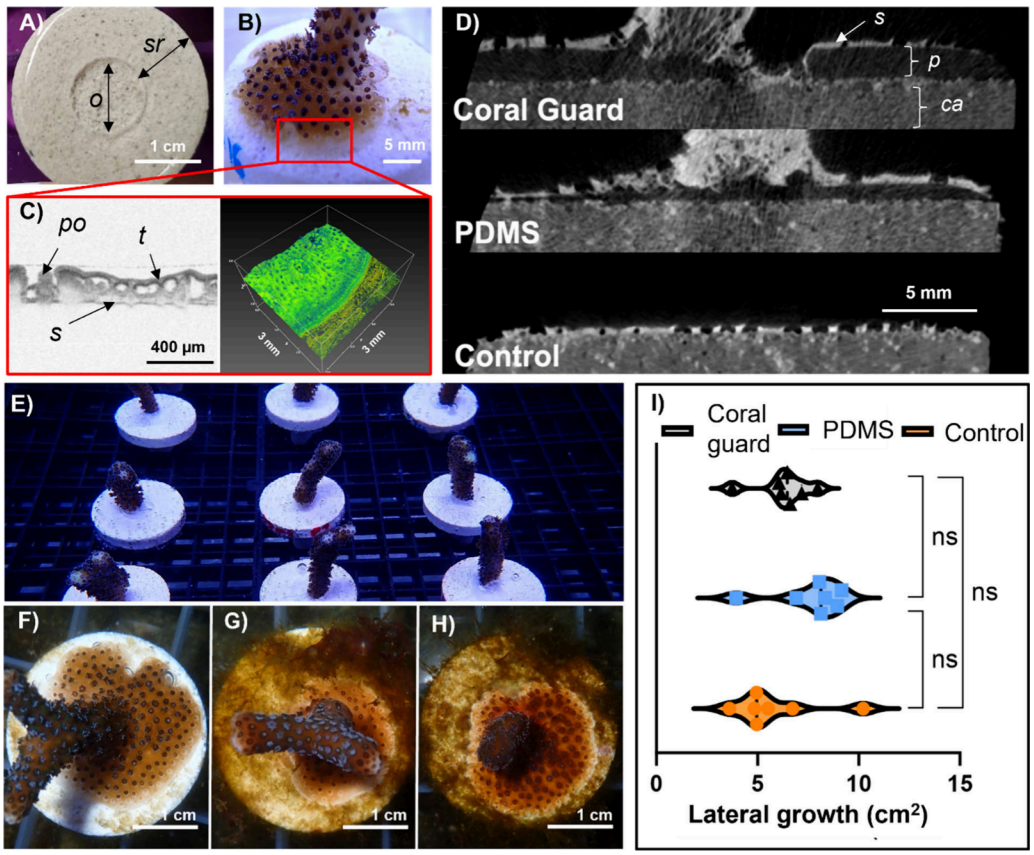


**Figure 4.** Coral growth characterization in coral-guard experiments. (A) Top-view image of a coral-guard, showing the slippery transparent ring (*sr*) and open center (*o*) for coral fragment attachment. (B) Lateral tissue growth of *Stylophora pistilla* on the coral guard. (C) OCT imaging of section shown in panel (B). Cross-sectional OCT image (left) shows the coral tissue (*t*), the skeleton (*s*), and a contracted polyp (*po*). The 3D rendering (right) visualizes the tissue growth front encrusting the coral-guard substrate. (D) Cross-sectional $\mu$CT images visualizing the skeletal layer (*s*), the PDMS layer (*p*), and the underlying calcium carbonate layer of the coral plug (*ca*) for the three different sample types (coral-guard, PDMS, control). (E–I) Growth experiments showing attached coral fragments at day 1 of the experiment (E) and after 90 days of cultivation for coral guards (F), PDMS (G), and control substrates (H). Violin plot of estimated lateral tissue growth ($cm^2$) after 90 days of cultivation (I) (ns= nonsignificant).

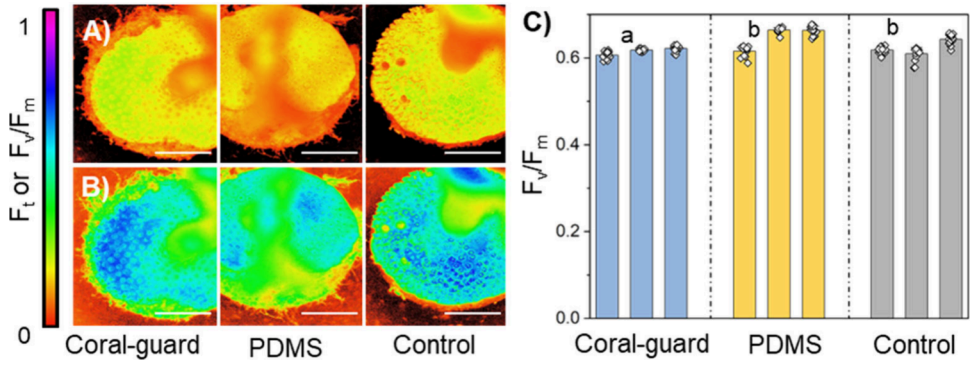


**Figure 5.** Effects of coral-guards coral photophysiology. (A) Typical images of the transient fluorescence ($F_t$) and (B) the maximum quantum yield of PS II ($F_v/F_m$). Imaging was performed such that the laterally growing tissue was in focus. Scale bars = 1 cm. (C) Bar plots of $F_v/F_m$ values generated from 15 areas of interest for each of three coral fragments per substrate type.

deterred from the substrate (Figure 4 B–F), warranting further investigations.

Although previous studies support the nontoxic nature of i-PDMS,[37,52,53] we aimed to explore whether there are any potential negative effects on coral growth and tissue healthiness. Our results revealed no negative effects on average tissue growth rates on coral guards (5.8 $cm^2$ ± 2.15 SD) compared to PDMS only (7.6 $cm^2$ ± 1.78 SD) and control plugs (6.3 $cm^2$ ± 1.31 SD ANOVA, Tukey HSD post hoc, p= 0.17, Figure 4A-F).

Likewise, $F_v/F_m$ values suggested that all corals were healthy, irrespective of treatment and $F_v/F_m$ values were on average >0.6 (Figure 5A-C). We found no significant difference between coral-guards (0.62 ± 0.01 SD) compared to coral plug controls (0.62 ± 0.02 SD) (Figure 5A-C, ANOVA, Tukey HSD post hoc p = 0.10), while there was a small difference



https://doi.org/10.1021/acssuschemeng.4c07508
ACS Sustainable Chem. Eng. 2025, 13, 5808–5817

(mean $F_v/F_m$ difference = 0.03) between coral guards and PDMS (0.65 ± 0.02 SD, ANOVA, Tukey HSD post hoc, $p < 0.01$, Figure 5c). However, such minor differences in $F_v/F_m$ should not be overinterpreted, due to the susceptibility of the imaging-PAM to suffer from optical artifacts (Wangpraseurt et al., 2019) Overall, these results demonstrate that lubricant infusion and PDMS do not adversely impact coral growth and coral healthiness[54,55] relative to controls within the scope of our experiments. Therefore, our developed coral-guards provide a nontoxic solution to reducing direct space competition with adjacent benthos (Figure 4A-F).

**3.3. Applications of Reef-PDMS and Coral-Guards in Restoration and Hybrid Reef Engineering.** Global reef degradation urgently calls for innovative, scalable solutions to support current reef restoration and engineering efforts. A major challenge is the rapid settlement and growth of unwanted fouling organisms, such as epiphytic turf algae, which limit coral growth and recruitment. Current leading solutions include mechanical removal of turf algae and the addition of grazers and herbivores. Recently, a few studies have explored the use of fouling control materials either in proximity to or in contact with coral tissue or adjacent substrate.[56,57] These first studies highlight the potential for antifouling coatings and material science innovations in coral reef restoration. However, many industrial antifouling materials have previously shown adverse effects on corals, such as irgarol disrupting symbiont photosynthesis.[58]

Here, we applied the bioinspired SLIPS principle to develop reef-PDMS and coral-guards (Figure 1), which effectively reduce macroalgal cover on reef restoration substrates. These solutions can be easily produced from readily available and well-characterized materials like PDMS.[34,37] Recent studies have also developed sprayable[59] and UV-curable[60] slippery PDMS formulations, enhancing the scalability of this approach while retaining excellent fouling prevention properties. We therefore envision reef-PDMS as a sustainable and scalable coating solution for mitigating competitive interactions between corals and macroalgal competitors. Coral-guards were highly effective in reducing competition pressure and facilitating the growth of the branching coral *Stylophora pistillata* (Figure 4). This proof-of-concept should now be expanded to explore its suitability for other reef-building corals with different growth patterns (e.g., mounding, encrusting). The ability to easily modulate the slippery coating facilitates rational pattern design and engineering to enhance coral growth versus competitive algal growth. Likewise, such approaches could be applied to coral recruits[57] or micropropagates[61] that are easily overgrown by adjacent benthos and suffer from low survival rates.[62] For example, materials are being developed that encapsulate settlement-inducing microbes as a coating on restoration substrates.[63] These materials could be spatially patterned with reef-PDMS to create selective zones for settlement induction and fouling reduction, thereby enhancing postsettlement survival—a critical bottleneck in reef restoration. Furthermore, the potential of these materials to support the growth of other essential ecosystem engineers, such as crustose coralline algae, remains an important area for future research.

In conclusion, the development and application of reef-PDMS and coral-guards represent a promising advance in the field of coral restoration. By addressing the issue of unwanted fouling organisms and promoting coral growth, these materials offer a practical solution to support the resilience and recovery of coral reefs in the face of global degradation. We envision that coral-guards will find wide applications in *ex situ* or *in situ* coral nurseries, as they can be easily integrated by reef practitioners as part of their maintenance routines to aid in coral growth and survival during outplanting. Further research and field studies will be essential to optimize these technologies for ecological applications and explore their full potential across diverse reef ecosystems.

## ■ ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acssuschemeng.4c07508.

Schematic drawing and images of experimental setup, additional graphs representing data from Reef-PDMS analyzed at different time points, and conditions (PDF)

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Designed the study: ZK, DW. Performed the experiments: ZK, IF, StK, EW, LB, SaK, NL, DBB, JL, DS, DW. Analyzed and interpreted the data: ZK, IF, StK, SaK, EW, LB, DBB, JA, DW. Contributed reagents/materials/tools: DW. Wrote the manuscript: ZK, DW, StK with editorial contributions from all authors.

### Funding

This material is based upon work supported by the Defense Advanced Research Projects Agency under the Reefense Program, BAA HR001121S0012 to D.W., and by the Office of Naval Research under award number N000142512127 to D.W. and J.A.

### Notes

The views, opinions and/or findings expressed are those of the author and should not be interpreted as representing the official views or policies of the Department of Defense or the US Government.

The authors declare the following competing financial interest(s): D.W. is founder of Hybrid Reef Solutions, a mission driven startup company that aims to restore and create coral reefs. D.W. and Z.K. are coinventors on a provisional patent application related to this work filed by the University of California, San Diego (no. 63/692,633).

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## ACKNOWLEDGMENTS

Justin Chen and Vanessa De La Garza are thanked for help with field work and illustrations. The R3D Consortium is an association of academic and industry partners who are involved in developing coastal resilience solutions. The consortium is focused on nature-inspired breakwaters; settlement, growth and survival technologies for coral-reef-ecosystem species; and advancing the science of adaptive biology for coral species in the face of warmer oceans. In support of these efforts, the consortium supports fund raising efforts, project management, site assessments and surveys, data management, experimental design and permitting support for experimental campaigns to test and prove these nascent technologies.

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