RRAP REEF RESTORATION & ADAPTATION PROGRAM

Technical Report: Fouling control for aquaculture and deployment

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Reef Restoration and Adaptation Program – Fouling control for coral aquaculture and deployment

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Cover Images: Coral Reef, Credit: Gary Cranitch, Queensland Museum

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Acknowledgement

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The RRAP partners acknowledge Aboriginal and Torres Strait Islander Peoples as the first marine scientists and carers of Country. We acknowledge the Traditional Owners of the places where RRAP works, both on land and in sea Country. We pay our respects to elders; past, present, and future; and their continuing culture, knowledge, beliefs, and spiritual connections to land and sea Country.

We specifically acknowledge and thank the following Traditional Owners of sea Country that this report relates to:

Location	**Traditional Owner Group**
Davies Reef	Bindal
AIMS Townsville	Wulgurukaba
Keppel Islands	Woppaburra

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1 Summary

Early life stages of coral must overcome intense competition from benthic fouling organisms, which poses a major challenge for restoration efforts, particularly those relying on coral seeding devices susceptible to rapid colonisation. This project evaluated the potential of commercially available Fouling Release Coatings (FRCs) to reduce fouling and enhance coral survival on seeding devices. Specifically, we assessed: (1) the feasibility of applying FRCs to restoration substrates; (2) the degree of fouling reduction; (3) the impact of reduced fouling on the survival of coral microfragments and spat (settled coral larvae); (4) the influence of surrounding benthos on fouling pressure; and (5) how the proximity of FRC-treated surfaces to coral spat influenced protective outcomes. These questions were addressed through a series of sequential mesocosm and long-term field experiments, with earlier findings informing the design of subsequent trials. Results showed that FRC application reduced fouling by up to ~75% after 12 months, even in algal-dominated environments. Correspondingly, spat survival improved by between 10 to 100% at the device level, with the greatest gains observed in inshore reef habitats. These benefits were maintained until coral recruits exceeded 1 cm in diameter, a critical size threshold associated with lower mortality. While coating the device cores provided substantial protection, ongoing work is exploring whether applying FRCs directly to settlement tabs enhances this effect. This research not only demonstrates the value of FRCs in improving coral seeding outcomes but also establishes a foundation for the development of ecologically sustainable FRCs use in coral restoration. Future efforts will focus on optimising coating performance and surface design to support early-stage coral care, with the goal of delivering restoration-ready FRC formulations for broader use in reef restoration programs.

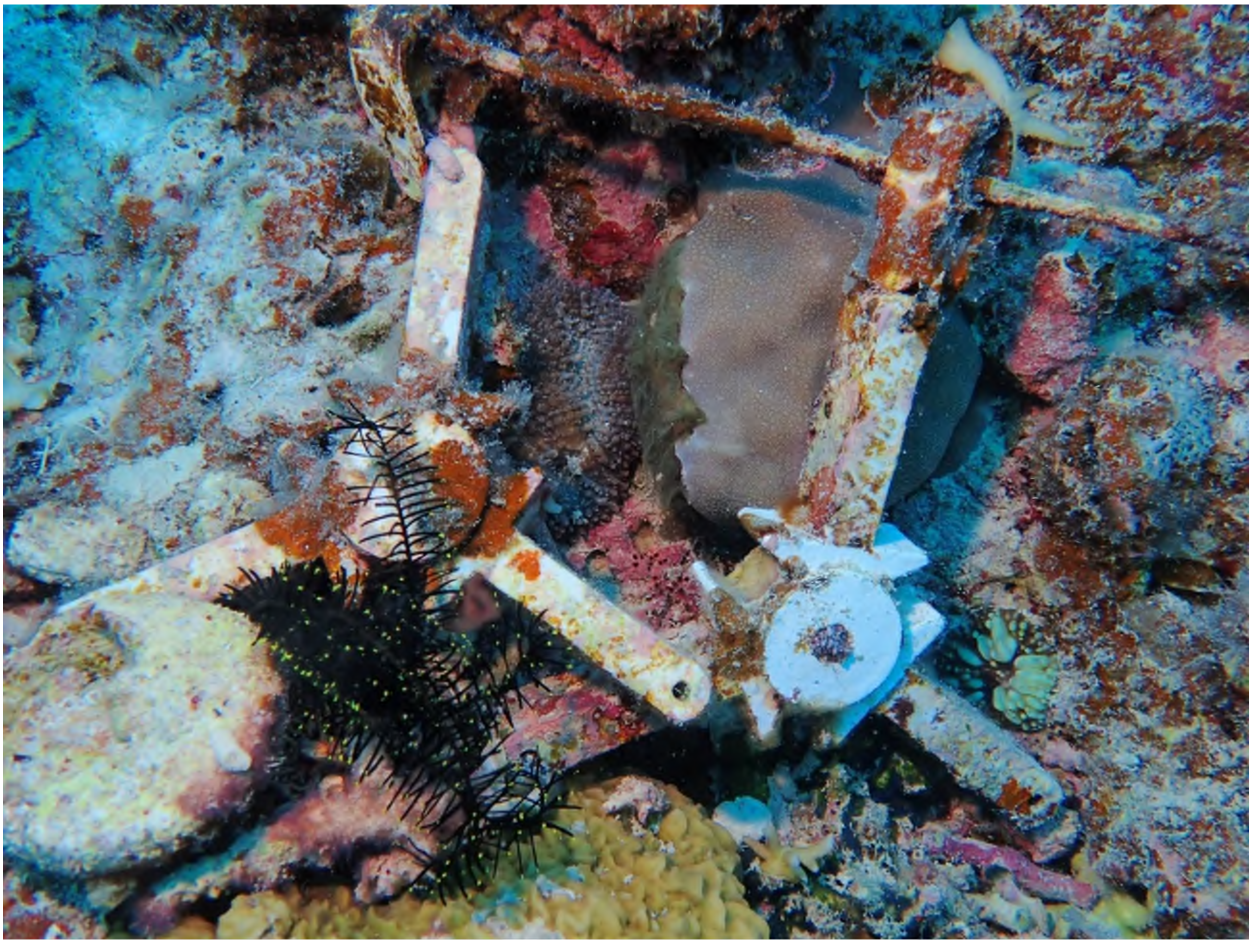


Image: Seeding devices on a reef after 46 weeks. The core of the right hand device is treated with a foul release coating to inhibit overgrowth of spat by benthic organisms. Image Jose Montalvo-Proano - AIMS.

2 Background

The global decline of coral reefs, driven by increasingly frequent and severe climate-induced bleaching events, has intensified interest in large-scale restoration solutions (Duarte et al., 2020; Fischer et al., 2021; Hagger et al., 2017). These efforts aim to restore damaged ecosystems by outplanting coral fragments or coral polyps (spat) produced through sexual reproduction (Fischer et al., 2021; Hughes et al., 2023; Randall et al., 2020; Rinkevich, 2021). For these programs to be effective, especially on vast reef systems like Australia's Great Barrier Reef (GBR), restoration strategies must not be only biologically viable but also scalable and cost-effective (Bayraktarov et al., 2019; Hughes et al., 2023; McLeod et al., 2022; Suggett et al., 2024). An emerging approach is the use of mass-produced coral seeding devices that can be deployed in large numbers from surface vessels (McLeod et al., 2022). While showing great promise, the success of coral seeding depends on coral survival during the early post-deployment stages (Randall et al., 2020; Rinkevich, 2021).

Most devices are deployed just weeks after settlement, when coral spat are <1 mm in diameter. At this stage, spat are highly vulnerable, with mortality rates often exceeding 70–90% in the first year (Chamberland et al., 2017; Doropoulos et al., 2012; Edwards et al., 2015; Ricardo et al., 2017; Wilson and Harrison, 2005). To improve early survival, device design has increasingly incorporated physical refugia to shield spat from sedimentation, light extremes, and grazers (Whitman et al., 2024). However, one of the most persistent threats during this life stage is biofouling—rapid colonisation by benthic algae and sessile invertebrates. Fouling organisms like turf algae, bryozoans, and crustose coralline algae can quickly overgrow or smother juvenile corals, preventing them from reaching a critical 'escape' size of approximately 1 cm^2 after which survival improves (Box and Mumby, 2007; Doropoulos et al., 2012; Lirman, 2014; McCook et al., 2014; Vermeij, 2005). While manual algae removal can be effective in small-scale trials (Ceccarelli et al., 2018; Neilson et al., 2018; Smith et al., 2022), this approach is less feasible for large-scale restoration, highlighting the need for passive, scalable antifouling strategies.

In aquaculture and particularly shipping, fouling is often addressed using antifouling coatings (AFCs), which typically rely on biocides containing copper (Amara et al., 2018). While effective, AFCs are generally unsuitable for coral restoration due to their toxicity to non-target organisms, including corals (Negri et al., 2005; Negri and Heyward, 2001; Owen et al., 2002; Weber and Esmaeili, 2023). Biocide-free fouling release coatings (FRCs) present a more sustainable solution. These materials—typically composed of hydrophobic or amphiphilic silicones like polydimethylsiloxane (PDMS)—function by reducing surface energy, thereby lowering the adhesion strength of fouling organisms. Once settled, fouling organisms are more easily dislodged by water movement (Upadhyay et al., 2017; Zhang and Chiao, 2015).

Only one study has investigated the use of AFCs to enhance coral spat survival, applying paraffin wax adjacent to coral spat on terracotta tiles (Tebben et al., 2014). After 39 days in mesocosm conditions, wax-treated surfaces exhibited ~50% less algal fouling and nearly double the spat survival compared to uncoated controls. These results, though short-term, highlight the potential of FRCs in mitigating early-stage mortality in corals. Building on this, we conducted a series of proof-of-concept experiments, both in National Sea Simulator mesocosms and in the field, applying and testing commercially available biocide-free FRCs. Our goal was to assess the real-world efficacy of these coatings in reducing algal fouling and enhancing coral survival. We also examined how benthic environmental factors influenced fouling dynamics and whether coating placement relative to coral tissue affected outcomes. These findings offer new insights into the use of environmentally benign coatings to support coral survival at scale—an essential step toward practical, scalable reef restoration.

3 Preliminary studies on FRC performance in SeaSim mesocosms

A series of short-term (6 to 12 week) experiments were conducted in the National Sea Simulator (SeaSim), located at the Australian Institute of Marine Science (AIMS) in Townsville. These studies:

- Tested the application of five commercial AFs and FRCs and three innovative coatings (Table 1) on spat settlement surfaces (tabs) and deployment devices.
- Trialled the efficacy of these coatings to reduce fouling in mesocosm conditions over months-long durations.
- Assessed any positive or negative effects of the coatings on coral spat settlement and survival.
- Provided data to support the selection of FRCs for longer-term field deployments.

Table 1. Foul release coatings (FRCs) and antifoulant coatings (AF) applied in preliminary and/or field studies. The first five coatings are available commercially. The last three coatings were innovative coatings, not commercially available.

Coating	AF/FRC	Commercial	Mesocosm/field	Description
Hempaguard X7	AF	Yes	M and F	A silicone-based coating containing slow-release pyrithione biocide (Hempel, 2024a). Black colour.
Hempasil X3+	FRC	Yes	M	A hydrogel-based FRC (Hempel, 2024c). Black colour.
Hempasil 77300	FRC	Yes	M and F	A hydrophobic silicone foul release coating (Hempel, 2024b). White colour.
Intersleek 1001	FRC	Yes	M and F	An amphiphilic silicone fluoropolymer foul release coating, incorporating biorenewable long chain waxy sterols from lanolin (Akso Nobel, 2024). Red colour.
Wax	FRC	Yes	M and F	Food grade waxes (CoralCare) (Aqua Firma Services, 2024)
DCOIT	AF	No	M	Slow-release biocide dichlorooctylisothiazolinone (DCOIT) incorporated into adhesive coating (Roepke et al., 2022a)
Adhesive coating	FRC	No	M	Silica-based sol-gel based on n-octadecyl-trimethoxysilane (Roepke et al., 2022b)
NP	FRC	No	M	Cerium oxide nanoparticles (NPs) incorporated into adhesive coating (Roepke et al., 2022a)

3.1 Main findings from preliminary mesocosm experiments

3.1.1 Application of coatings

Most coatings could be effectively applied to smooth deployment and settlement device surfaces, including plastic (PVC) and alumina ceramic. Coatings were durable over the experimental periods, with most of the commercial coatings also requiring a *tie-coat* to bind the FRC or AF to surfaces. Effective application methods included hand painting or rolling and spraying (Abdul Wahab et al., 2022).

3.1.2 Proximity of coating to coral spat

Deployment devices were made of alumina ceramic each holding multiple 1.4 cm^2 concrete settlement tabs with spat or glued microfragments (0.8 cm). AFs and FRCs were applied on the device and/or the tab (Table 1). Each approach had advantages and disadvantages. Device coating was simpler, but protection from fouling was further from the spat (*far-field*), while tab coating provided closer protection (*near-field*), but required small gaps in the coating for larval settlement onto the tabs (tabs had to be *conditioned* to induce larval settlement). Both approaches were applied in SeaSim experiments and were found suitable for application in later field trials.

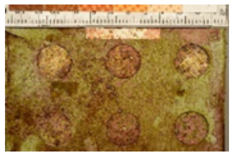
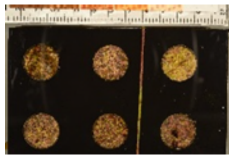
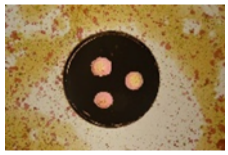
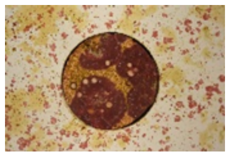
3.1.3 Comparative effectiveness of coatings to reduce fouling

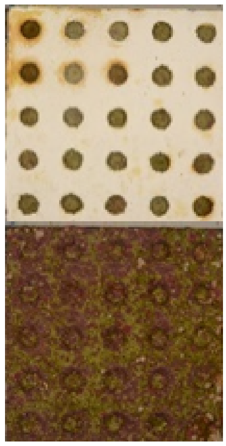
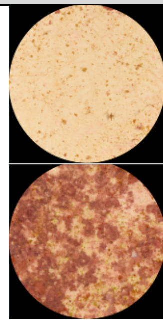
Experiments consistently demonstrated that the silicone-based FRCs Hempasil X3+, Hempasil 77300 and Intersleek 1001 were as effective as the copper-based AF (Hempaguard X7) in reducing fouling. All prevented more than 70% fouling over 6 – 12 weeks on a variety of surfaces, in comparison to uncoated surfaces that were almost 100% fouled over that same period (Table 2). The wax coating had an intermediate effectiveness in reducing fouling – 15% to 60% reduction compared to controls. The innovative antiadhesive FRCs, with and without cerium oxide nanoparticles, were only moderately effective (15% reduction) in reducing fouling over a 6-week period.

3.1.4 Effect of coatings on coral settlement and survival

There were no negative effects of any of the FRCs on coral larval settlement or spat survival. Indeed, settlement was sometimes higher on FRC treatments, such as Hempasil X3+ and Intersleek 1001, with larvae attaching to the FRC coatings themselves (Table 2). Coral larval settlement is very sensitive to a range of contaminants, including AF biocides (Negri and Heyward, 2001); therefore, this observation is a strong indication that the FRCs applied are not toxic to corals. While the FRCs tested were not harmful to coral larvae and spat, the inhibition of fouling did not result in an increase in spat survival over these short-term experimental periods (Table 2). Longer field trials are required to assess the potential benefits of FRC coatings on spat survival.

Table 2. Summary of experiments conducted in the National Sea Simulator (SS) and an overview of results.

<table>
<tr><td colspan="4">Experiment SS1:
Hypothesis: Biocide-free FRCs are as efficient as copper-based antifoulants (AF) in reducing fouling on treated PVC devices, improving coral spat survival on adjacent aragonite plugs. Device treatments: Control (no coating), Wax (FRC), Intersleek 1001 (FRC), Hempasil X3+ (FRC), Hempaguard X7 (AF).</td></tr>
<tr><td>Coatings: Distance to coral ~ 10 mm. Spat settled on aragonite plugs which were placed in PVC trays coated with FRC, AF or uncoated (control). The trays mimicked deployment devices and were placed in an outdoor mesocosm.</td><td>Fouling results:
Fouling reduction after 12 weeks:
~95% by Hempasil X3+ (FRC), bottom image) and Hempaguard X7 (AF)
~85% by Intersleek 1001 (FRC)
~15% by Wax (FRC)
0% by Control (no coating, top image)</td><td>Spat survival at 12 weeks:
Very low survival (0-5%) observed across treatments.
Survival at 6 weeks did not differ significantly between treatments:
~48% control
~30% wax
~22% Intersleek 1001
~30% Hempasil X3+
~35% Hempaguard X7
For more details: see (Abdul Wahab et al., 2022)</td><td>
</td></tr>
<tr><td colspan="4">Outcome and insights: Strong performance in reducing fouling among all commercial FRCs and AF coatings over wax, with the uncoated surface most heavily fouled after 12 weeks. Non-toxic FRCs (Intersleek 1001 and Hempasil X3+) were as effective at reducing fouling as copper-containing AF Hempaguard X7. Survival of spat not statistically different among treatments. Consider applying FRCs closer to spat to improve protection from fouling.</td></tr>
<tr><td colspan="4">Experiment SS2:
Hypothesis: Biocide-free FRC are as efficient as copper-based antifoulants (AF) in reducing fouling on treated ceramic plugs, without causing negative effects to coral spat survival due to their proximity. Device treatments: Control (no coating), Wax (FRC), Intersleek 1001 (FRC), Hempasil X3+ (FRC), Hempaguard X7 (AF).</td></tr>
<tr><td>Coatings: Distance to coral ~ 4 mm. Spat (Acropora digitifera) settled on ceramic plugs coated with FRC, AF or uncoated (control) and placed on clean PVC trays. The trays mimicked deployment devices and were placed in an outdoor mesocosm.</td><td>Fouling results:
Similar findings on fouling reduction after 12 weeks as per SS1:
~95% by Hempasil X3+ (FRC, top image) and Hempaguard X7
~85% by Intersleek 1001 (FRC)
~15% by Wax (FRC)
0% by Control (no coating, bottom image)</td><td>Larval settlement:
Settlement on conditioned plugs was 0.09 spat/cm^2.
The greatest settlement was on FRC plugs Hempasil X3+ > Intersleek 1001 > wax.
Unexpectedly, the greatest settlement was directly on the FRC rather than the bare ceramic circles.
Spat survival:
Not assessed due to low settlement across treatments.
For more details: see (Abdul Wahab et al., 2022)</td><td>
</td></tr>
<tr><td colspan="4">Outcome and insights: Durable attachment of AF and FRC coatings onto ceramic surfaces, which suggest applicability on seeding devices. Consistent performance in reducing fouling among all commercial FRCs and AF coatings over wax, with the uncoated surface most heavily fouled after 12 weeks. Non-toxic FRCs (Intersleek 1001 and Hempasil X3+) were as effective at reducing fouling as copper-containing AF Hempaguard X7. Survival not affected despite spat being in very close proximity to coatings and was not statistically significant among treatments. Consider applying FRCs on concrete settlement surfaces used by other RRAP groups.</td></tr>
</table>

<table>
<tr><td colspan="4">Experiment SS3:
Hypothesis: Biocide-free FRC applied to concrete surfaces featuring indentations can reduce fouling more effectively than other methods of controlling initial biofilm growth (e.g., concrete with dried crustose coralline algae (CCA) biofilms). The addition of indentations can attract larval settlement despite FRC on its surroundings. Control tiles with no coatings feature live or dead (dried) biofilms. Treatments: Control (no coating), Wax (FRC), Intersleek 1001 (FRC), Hempasil 77300 (FRC), and variation of control surfaces (e.g., live vs dead biofilm conditioning).</td></tr>
<tr><td>Coatings: This experiment used white Hempasil 77300 (FRC) as the colour better matches that of bare alumna ceramic of the control devices. Distance to coral ~ 4 mm. Spat settled on indented 5 × 5 cm tiles coated with FRC or left as controls. Indents in the FRC tiles had dead biofilm, while the control tiles had live or dead biofilm.</td><td>Fouling results at 6 weeks:
FRC treated surfaces were effective in reducing fouling relative to all controls.
~75% Hempasil 77300 (FRC, top image)
~85% Intersleek 1001 (FRC)
~60% Wax
0% by Control (no coating, bottom image)</td><td>Settlement by choice:
Higher in live conditioned surfaces (~35%) relative to FRC treated tiles (~15%).
Survival at 6 weeks:
~90% for FRC treatments, including wax
~80% for controls
~30% observed for unconditioned concrete
For more details: see (Abdul Wahab et al., 2022)</td><td></td></tr>
<tr><td colspan="4">Outcome and insights: Significant reduction of fouling on FRC-treated surfaces relative to controls; however, there was no clear benefit of FRC treatment on spat survival. The exposure time was relatively short in mesocosm conditions. FRC may provide more benefits under greater fouling pressure – i.e., longer deployments in reef conditions. Consider applying Hempasil 77300 to ceramic seeding devices under reef conditions. Indent depth could be reduced or shape improved to avoid sediment deposition.</td></tr>
<tr><td colspan="4">Experiment SS4:
Hypothesis: Innovative biocide-free FRCs are as efficient as biocide-containing antifoulants (AF) in reducing fouling on PVC treated ceramic surfaces, and do not affect the settlement of coral larvae on treated plugs. Treatments: Control (no coating), cerium oxide nanoparticles (FRC), silicone antiadhesive (FRC) and DCOIT biocide (AF).</td></tr>
<tr><td>Coatings: Coated ceramic plugs were placed in 3 replicate outdoor mesocosms for 37 d. Larvae were then settled on the coated plugs which featured small uncoated areas.</td><td>Fouling results:
Fouling after 37 days:
~40% on DCOIT (AF, top image)
~85% antiadhesive and nanoparticles (FRCs)
~5% control (no coating, bottom image)</td><td>Settlement of coral larvae:
No statistical difference between settlement on AF and FRC plugs. Larvae avoided settling directly on DCOIT (AF).</td><td></td></tr>
<tr><td colspan="4">Outcome and insights: The alternative AF and FRC coatings reduced fouling on coral settlement surfaces and there was little effect of FRCs on larval settlement, which indicates negligible toxicity to this very sensitive process in coral recruitment. More development of these coatings is required to match the performance of commercial FRCs applied in SS1-SS3. These results were published in: (Roepke et al., 2022a; Roepke et al., 2022b).</td></tr>
</table>

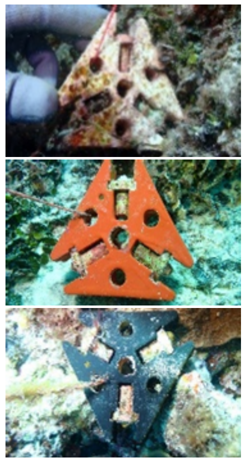
4 Efficacy of FRC to reduce and improve spat survival in long-term field deployments

A series of long-term (36 to 48 week) experiments were conducted on midshelf and nearshore reefs of the GBR. These studies:

- Tested the efficacy of four commercial FRCs (Table 1) to reduce fouling in field conditions over durations of almost a year – when recruits reach ~1 cm diameter.
- Assessed any positive or negative effects of the coatings on coral spat settlement and survival and microfragment survival, including the protection by the coatings, reduced fouling and benthic habitat.

Table 3 summarises these experiments, providing information on the hypothesis tested, and main results and insights. Select experiments are presented in more detail below the table.

*Table 3. Summary of field deployment experiments (D) conducted and an overview of results. *Experiments explained in more detail in sections below.*

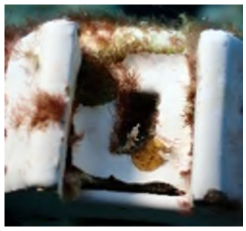
<table>
<tr><td colspan="4">Experiment D1:
Hypothesis: The efficacy of the FRCs to reduce fouling and improve microfragment survival observed in aquaria (Exp. SS1) can be sustained for 36 weeks under reef conditions, when ceramic devices are fully coated. Device treatments: Control (no coating), Wax (FRC), Intersleek 1001 (FRC), Hempasil X3+ (FRC). Location: Davies Reef.</td></tr>
<tr><td>Coatings: Distance to coral ~ 10 mm. Microfragments (Acropora millepora) glued to ceramic plugs and fitted into triangle alumina device.</td><td>Fouling results:
Fouling reduction after 36 weeks:
~92% by Hempasil X3+ (FRC, bottom image)
~89%% by Intersleek 1001 (FRC, middle image)
~63% by Wax (FRC, top image)
~23% by Control (no coating)</td><td>Microfragment survival at 36 weeks:
~53% on Hempasil X3+
~58% on Intersleek 1001
~51% Wax
~46% Control</td><td></td></tr>
<tr><td colspan="4">Outcome and insights: Strong performance in reducing fouling among all commercial FRCs over wax, with the uncoated surface most heavily fouled after 36 weeks. Survival of microfragments was slightly higher on FRC devices relative to control. Consider reducing the area of FRC treatment on devices as only areas around the coral require protection. Some surfaces of wax “crystalised” and fell after 13 weeks (first assessment).</td></tr>
</table>

<table>
<tr><td colspan="4">Experiment D2*:
Hypothesis: The efficacy of the FRCs observed in aquaria (Exp. SS3) can be sustained under reef conditions, for 46 weeks, when only the cores of ceramic devices are coated. Device included coral microfragments and the following treatments: Control (no coating), Wax (FRC), Intersleek 1001 (FRC), Hempasil 77300 (FRC, new formulation). Location: Davies Reef.</td></tr>
<tr><td>Coatings: Distance to coral ~10 mm.
Microfragments (A. millepora) glued to concrete tabs and fitted into 3-arm star alumina device.</td><td>Fouling results:
Similar findings on fouling reduction after 46 weeks as per D1:
~50-75% by Hempasil 77300 (FRC, bottom image)
~40-50% by Intersleek 1001 (FRC, middle image)
~5-15% by Wax (FRC, top image)
0% by Control (no coating)</td><td>Microfragment survival:
Survival was not influenced by FRC coatings, and high variation occurred due to donor colony effects.
However, there was no negative effect on coral health and normal tissue growth was observed on top of FRC coatings.

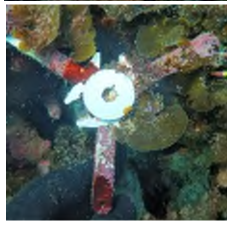
(more details in section 4.1.1 below and in Montalvo-Proano et al. (2025))</td><td>

</td></tr>
<tr><td colspan="4">Outcome and insights: Fouling protection on device cores was consistently sustained over time despite the reduced coating area (50%, relative to exp. D1). Suggest deploying spat to increase genetic diversity and increasing statistical power to detect FRC influence on survival. Arms of devices were heavily fouled in all devices after 13 weeks, despite FRC treatments on cores. Clear evidence that FRC did not affect tissue growth as some cores were found almost entirely covered by coral by 46 weeks. This experiment was published in Montalvo-Proano et al. (2025).</td></tr>
<tr><td colspan="4">Experiment D3*:
Hypothesis: FRC treatment of device cores against fouling and increase spat survival under reef conditions after 46 weeks post deployment. Treatments: Control (no coating), Hempasil 77300 (FRC). Location: Davies Reef.</td></tr>
<tr><td>Coatings: Distance to coral ~10 mm.
Spat (Acropora loripes) were settled on concrete tabs and fitted into a 3-arm star alumina device with or without FRC protection of device cores.</td><td>Fouling results:
FRC treated surfaces were consistently effective in reducing fouling relative to controls over 46 weeks.
~75% Hempasil 77300 (FRC, bottom image)
0% by Control (no coating, top image)</td><td>Spat survival:
Survival was influenced by the proportion of device fouling, time of exposure as well as the abundance of coral or CCA cover on its surrounding benthos.
Survival was 10% higher on FRC devices relative to controls after 46 weeks.

(more details in section 4.1.2 below)</td><td>
</td></tr>
<tr><td colspan="4">Outcome and insights: Paired design (FRC + control) allowed direct comparison of treatment relative to core fouling reduction, survival and influence of surrounding benthos. Significant reduction of fouling on FRC surfaces relative to controls. Clear beneficial role of FRC to reduce core fouling and increase spat survival compared to controls, despite sharing similar benthic community. Areas with higher coral cover had a negative effect on survival, followed by CCA and then turf. Consider application of FRC on tabs to increase survival yields.</td></tr>
</table>

<table>
<tr><td colspan="4">Experiment D4:
Hypothesis: Fouling can be reduced and spat survival enhanced by application of FRC to both the device cores and the upper surfaces of concrete settlement tiles. Tab treatments: Hempasil 77300 (FRC) and control (no coating). Device treatments: 77300 (FRC) on the cores and control (no coating). Location: Davies Reef.</td></tr>
<tr><td>Coatings: Distance to coral ~10 mm (device) and ~4mm (tab).
Spat (A. loripes) were settled on concrete tabs and fitted into a 3-arm star alumina device with or without FRC protection. Tab treatment: Hempasil 77300 (FRC), live and dry biofilm to induce larval settlement.</td><td>Fouling results:
Similar device fouling on cores as per Exp. D3.
However, this experiment was affected by cyclone activity before the first census.
Treatments were affected and FRC tabs damaged.
FRC tabs (top image) were more likely to have survivors post cyclone relative to live or dry biofilm tabs (bottom image).</td><td>Survival:
Could not be accurately assessed due to the loss of tab-FRC treatment effects but was significantly lower than similar experimental timeframes.
Post cyclone, strong abundance of bryozoans was observed overgrowing spat on concrete tabs, an observation not seen in previous experiments, despite sharing similar locations.</td><td>
</td></tr>
<tr><td colspan="4">Outcome and insights: The attachment of FRC to concrete tabs was affected by the manipulation on the assembly of devices (tabs were split post-coating, which left uncoated edges). Strong water velocity due to cyclone activity also impacted the experiment. Bryozoans grew aggressively on concrete surfaces post-cyclone which diminished the statistical power to assess treatment effects over survival. Nevertheless, competition was diminished by the FRC tab treatment for devices not affected by the cyclone. Consider developing alternative surfaces that reduce indent depth, damage to coatings during assembly and improve the adhesion of coatings to the concrete tab. This experiment is detailed in (Montalvo-Proano et al., in prep)</td></tr>
<tr><td colspan="4">Experiment D5*:
Hypothesis: The addition of FRC protection to printed ceramic tabs fitted into FRC-treated devices can enhance the spat survival in comparison to that observed in Exp. D3. Device treatments: Control (no coating), Hempasil 77300 (FRC). Location: Davies Reef.</td></tr>
<tr><td>Coatings: Distance to coral ~10 mm (device) and ~4mm (tab).
Spat (A. loripes) were settled on ceramic tabs and fitted into a 3-arm star alumina device with or without FRC protection. Tab treatment: Hempasil 77300 (FRC), live and dry biofilm to induce settlement.</td><td>Fouling results:
TBA (1st census April 2025)</td><td>Survival:
TBA (1st census April 2025)</td><td>

</td></tr>
<tr><td colspan="4">Outcome and insights: More rapid conditioning was observed on the ceramic tabs than concrete tabs used in previous experiments. Larvae were observed to settle more homogeneously across ceramic surfaces in comparison to concrete. Channel design on tabs promoted settlement as individual spat (less spat clumping). Strong FRC attachment to smooth ceramic tabs, and less damage was observed when sliding tabs into device. Fouling and survival assessments are underway with the first census occurring in mid-April 2025.</td></tr>
</table>

<table>
<tr><td colspan="4">Experiment K1*:
Hypothesis: FRC coating of device cores can protect against fouling and increase spat survival over 48 weeks deployment at algal-dominated inshore reef sites. Device treatments: Control (no coating), Hempasil 77300 (FRC). Location: North Keppel Island.</td></tr>
<tr><td>Coatings: Distance to coral ~10 mm.
Spat (A. millepora) were settled on concrete tabs using live biofilms to induce settlement. Tabs were fitted into a 3-arm star alumina device with or without FRC protection on the core areas.</td><td>Fouling results:
FRC substantially reduced device fouling after 48 weeks despite a very challenging algal dominated environment.</td><td>Survival:
Spat survival doubled on FRC-treated devices, in comparison to controls at both the device and tab levels.
(more details in section 4.1.4 below)</td><td>
</td></tr>
<tr><td colspan="4">Outcomes and insights: Survival was increased by the presence of FRC-treated surfaces, despite strong competition on the tab due to fouling. FRC treated surfaces reduced macroalgal attachment and interrupted overgrowth of the devices. Tab fouling was abundant and played an important role in spat survival. The reef benthic community was also found to influence survival.</td></tr>
</table>

4.1.1 Experiment D2 – Coral microfragments deployed at Davies Reef on FRC-treated seeding devices

Long field deployments present more challenges to FRC performance in comparison to aquarium conditions. In experiment D2 the cores of coral deployment devices were individually coated with three types of commercial FRC – Intersleek 1001 (FRC1), Hempasil 77300 (FRC2) and Coral Care (Wax). The arms of the devices were left uncoated to allow fouling to aid retention on the reef. Coral microfragments (8 × 8 mm *Acropora millepora*) were glued onto three concrete tabs (14 × 14 mm) which then slotted into the device core. Devices were then deployed at three different locations at Davies Reef (GBR). The experiment was monitored quarterly over a total of 46 weeks, with microfragment survival, device fouling and benthic community surrounding each device recorded at each of the four census points. These traits were monitored in a non-intrusive approach via underwater photography (for more details: (Montalvo-Proano et al., 2025).

All FRCs significantly reduced fouling, with FRC2 as the best performer, followed by FRC1 then wax (Figure 1). The field performance of the FRCs was similar to their mesocosm performance (e.g., experiments SS1-SS3). The control (untreated) cores were almost completely fouled by the end of the 46-week deployment. At this point, FRC2 reduced fouling on the device core by an impressive 75%, while FRC1 and wax reduced fouling by 50% and 15%, respectively. The device arms were >95% fouled in the first 8 weeks of exposure, without significant differences among treatments (i.e., adjacent coating did not affect rapid fouling of the uncoated device arms).

Device coatings did not influence the survival of microfragments for the duration of the experiment (Figure 2a). Similarly, survival estimates were not necessarily affected by the combination of both location and time, suggesting that the loss of microfragment replicates was not influenced by specific sites over time. In this experiment, survivorship was more related to donor colony effects (i.e., genetic background limited to just one representative per tab). This outcome suggested the need to explore a similar approach with coral spat (i.e., more genetic variation per tab) to avoid biased mortality, as well as increased replication, improving the ability to detect treatment effects on survival. Importantly, this experiment confirmed that the applied FRCs had no negative effects on coral survival or growth. In some instances, microfragments grew more rapidly on FRC surfaces relative to controls, potentially due to the lack of competition. Furthermore, macro images did not reveal any abnormal growth near FRC coatings (Figure 2b).

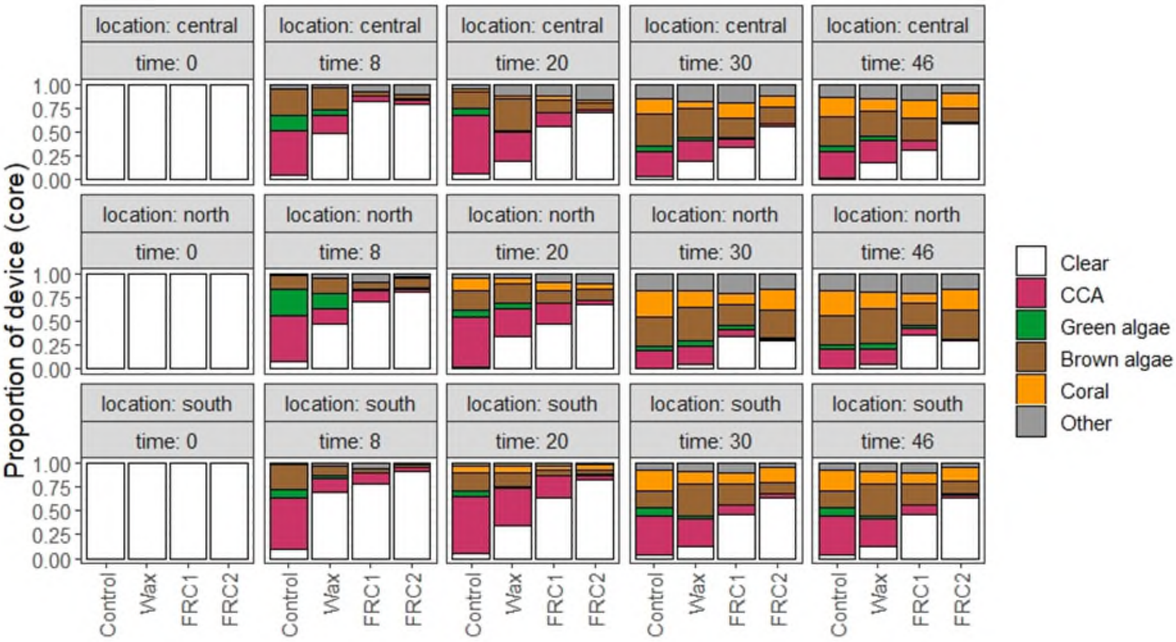


Figure 1. Proportion of fouling (CCA, green algae, brown algae, coral and other) on device core in relation to time, treatment and location over a 46-week deployment. 'Clear' denotes no fouling observed.

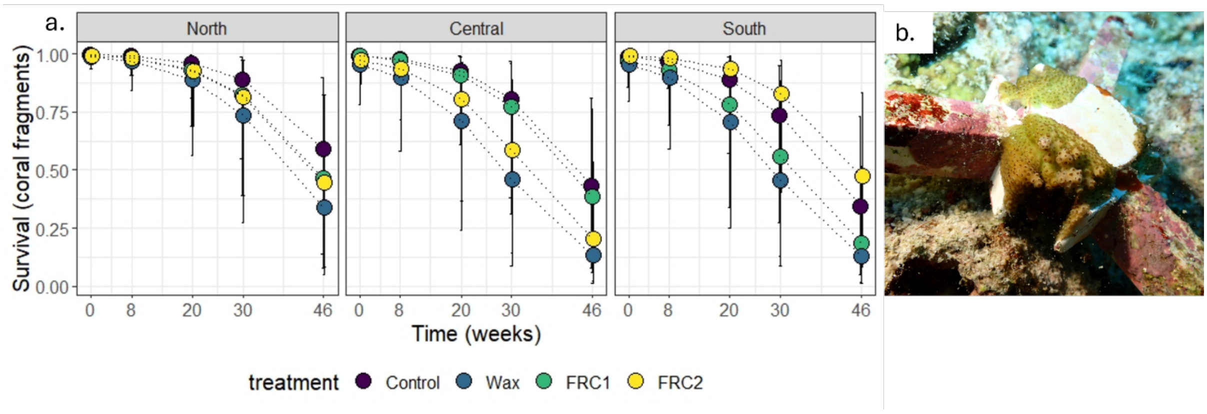


Figure 2. (a) Survival of coral fragments deployed at three different locations (North, Central, South) at Davies Reef. Colours represent the four different treatments. (b) Example image displaying tissue growth on FRC2 surface on seeding device at 46 weeks.

4.1.2 Experiment D3 – Coral spat deployed at Davies Reef on FRC-treated seeding devices

In this experiment, half the seeding device cores were coated with the best performing FRC from experiment D2–Hempasil 77300 (FRC2). In brief, coral colonies (*A. loripes*) were collected from Davies Reef and spawned at SeaSim. Larvae were reared for ~7 days and settled onto large, live-conditioned concrete tiles. Tiles were split into individual 14 × 14 mm tabs, and those with 5-10 recruits were selected for deployment. Tabs were haphazardly allocated across all devices (three per device). Deployment of devices in treated and untreated pairs exposed both device treatments to the same immediate benthos. Devices (n=24) were deployed along each of three transects at three locations and remained on the reef for 46 weeks with quarterly assessments (e.g., survival, device fouling, benthic community). NOTE: more details can be found in (Montalvo-Proano et al., *in prep*).

The FRC was very effective in reducing fouling on device cores. By 13 weeks post-deployment, FRC devices had only 20% fouling compared to 90% on uncoated devices (Figure 3). After 46 weeks, the FRC continued to reduce fouling on device by up to 75%. The fouling taxa were dominated by CCA and green algae on the cores of both FRC and control devices. However, colonisation of brown/red algae was much less evident on FRC devices in comparison to controls.

Figure 3. Proportion of fouling observed over time on core of control (left) and FRC2 (right) devices. Fouling categories included CCA, green and brown algae, and others. Fouling reduction was evident for every censusing timepoint (middle image).

Spat survival was consistently higher on FRC-treated devices in comparison to uncoated controls (Figure 4). Analysis clearly demonstrated the influence of device fouling on coral survival and showed that reducing competition through FRC application can translate into measurable gains in survivorship. By 46 weeks, average survival remained higher on FRC devices (67%) relative to controls (58%). The most pronounced difference occurred at six months, when survival on FRC-treated surfaces exceeded that of controls by 20%.

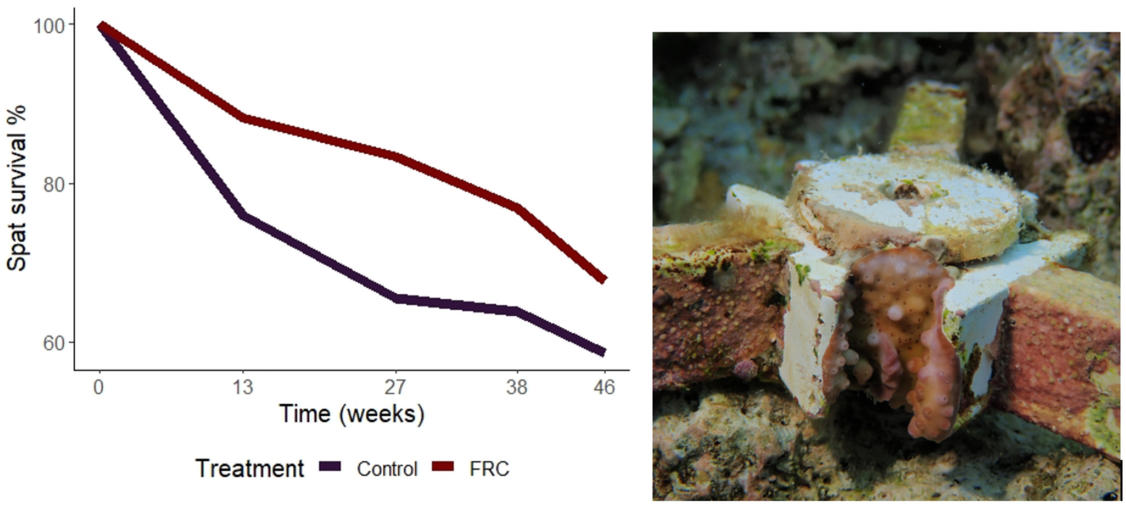


Figure 4. Mean spat survival relative to device treatment over 46 weeks. Image shows durable fouling protection by the FRC (white core) in comparison to the fully fouled device arms at 46 weeks. This coral recruit reached escape threshold of > 1 cm diameter, growing directly over the FRC.

This *in-situ* study provides proof of concept that non-biocidal FRC coatings can effectively reduce potentially competitive algal fouling and enhance spat survival on seeding devices used for coral reef restoration. Further evaluation at sites with higher macroalgal densities, where coral recruitment is more strongly suppressed, would enhance understanding of their broader applicability and effectiveness.

4.1.3 Experiment D5 – Coral spat deployed at Davies Reef on FRC-treated seeding devices

This experiment was deployed in December 2024 and is scheduled to run for 12 months. Experiment D5 investigates the use of 3-D printed ceramic tabs, featuring settlement channels (Figure 5a), designed to direct larval settlement and enable application of FRC to the raised surface, immediately adjacent to larvae that settle in the channel. To date, the adhesion of FRC (Hempasil 77300) to ceramic has proven effective and durable. Moreover, this tab material has shown faster and more uniform biofilm conditioning relative to the traditional concrete tab material used in previous experiments, resulting in a more homogenous settlement across larger settlement surfaces before separation into individual tabs (Figure 5a).

This experiment also tested the most recent prototype for facilitating both larval settlement and natural Symbiodiniaceae infection of coral spat, without compromising donor fragment health or requiring artificial inoculation (Figure 5b). Previous designs relied on larger recirculating water volumes; however, in this version, symbiont infection was performed by passive circulation between donor and recruit tanks within two weeks. This prototype has strong potential for scale-up, particularly for use with coral spat that cannot be inoculated with cultured symbionts due to permitting restrictions.

Fouling and survival assessments are underway with the first census occurring in mid-April 2025.

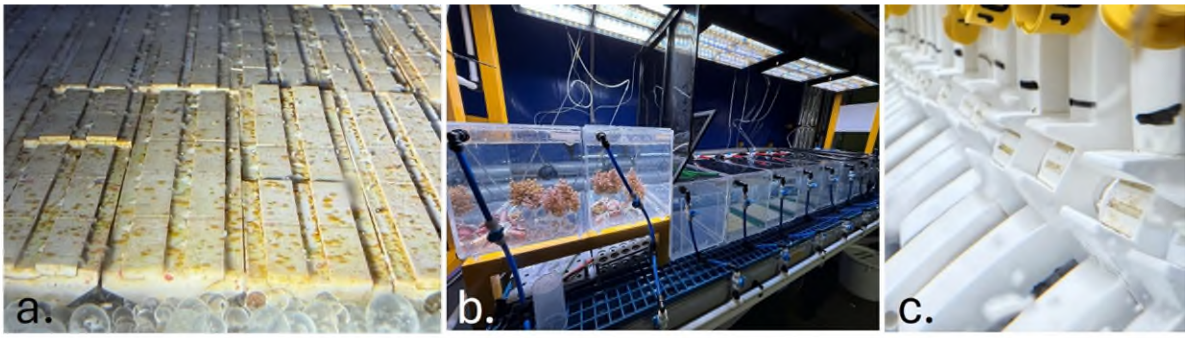


Figure 5. Examples images displaying (a) larval settlement on ceramic tabs with channels, (b) the set up for the natural infection of symbionts from donor fragments, and (c) FRC tabs assembled in devices prior to deployment.

4.1.4 Experiment K1 – Coral spat deployed on FRC-treated seeding devices across an algal gradient at the Keppel Islands

The benefits of FRC treatments observed on seeding devices deployed at midshelf reef sites, such as Davies Reef (experiments D2 and D3), prompted further investigation into their performance under more challenging conditions. Experiment K1 extended this evaluation to the inshore reefs of the Keppel Islands in the southern GBR, which are characterised by high abundances of fleshy macroalgae. The experimental design was similar to that of experiment D3, with *Acropora millepora* spat settled on concrete tabs within device cores coated with Hempasil 77300 (FRC2) or left uncoated as controls. Performance of the FRC to inhibit fouling and improve spat survival was assessed after 48 weeks. The six study sites exhibited differences in benthic community structure, ranging from high *Sargassum* or *Caulerpa* abundance to sites dominated by fast growing encrusting coral species.

Overall, device cores treated with FRC2 exhibited substantially reduced fouling after 48 weeks of exposure (Figure 6a). On average FRC device cores had 37% fouling coverage, compared to 75% on uncoated controls. Fouling on both control and FRC devices was primarily composed of CCA and brown/red algae, occurring on both cores and arms of devices (Figure 6b). Notably, the FRC-treated surface also appeared to act as a physical barrier, limiting the lateral growth of competitive encrusting coral species across the device cores.

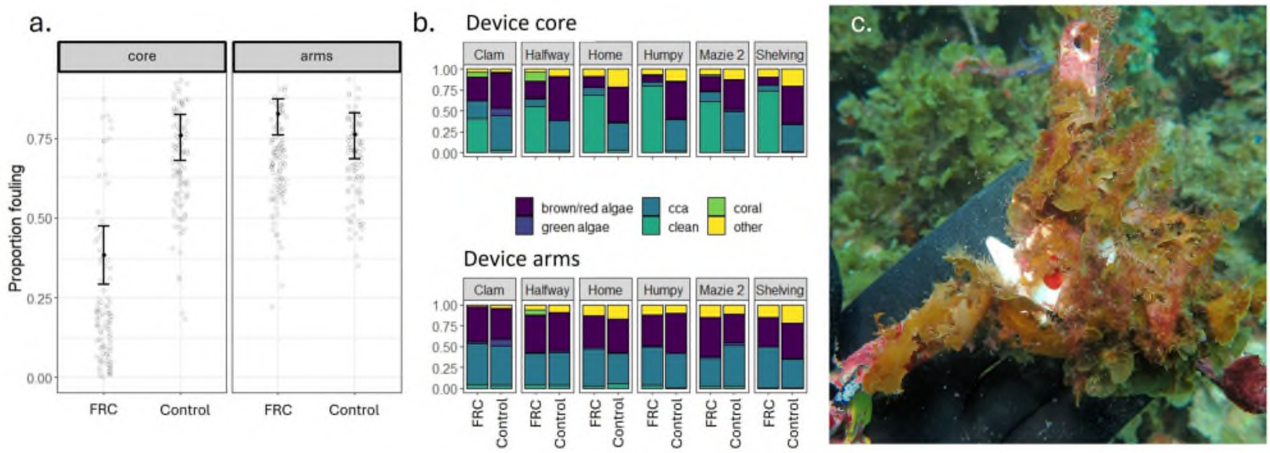


Figure 6. (a) Proportion of fouling on cores and arms of FRC and control devices over 48 weeks. (b) Bar plots representing the abundance of each type of fouling category on the device. (c) Example image of a deployment device with FRC-coating on the core facing strong fouling pressure from macroalgae.

Spat survival was, on average, twice as high on FRC-treated devices compared to controls at the device level (Figure 7). A similar trend was observed at the tab level, where survival in FRC treated devices was also double that of controls. This reduction in survival likely reflects additional competition from fouling organisms on the tab surface. Multiple factors appear to have contributed to the observed survival patterns, and we are currently evaluating the most effective modelling approaches to explain these trends. For instance, differences in macroalgal type, the extent and composition of tab fouling, and whether the device was partially buried at the time of retrieval may all influence coral survival outcomes.

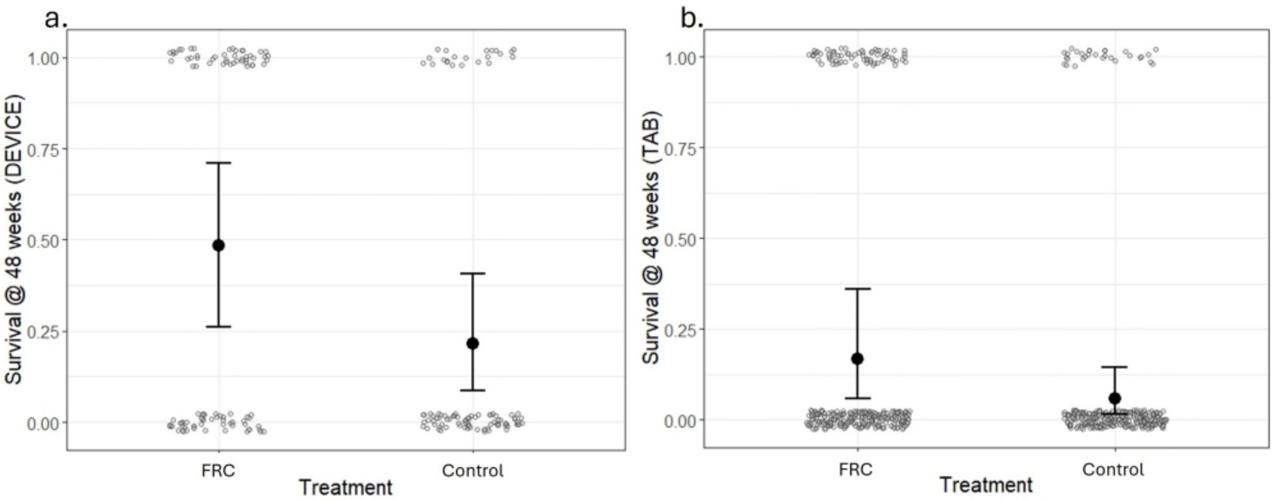


Figure 7. Spat survival according to treatment at 48 weeks of exposure encompassing devices across all sites. (a) Survival is displayed as more general device level as well as (b) at the replicate tabs within each device.

5 Conclusion

This project implemented a comprehensive series of proof-of-concept mesocosm and field experiments, supported by detailed data analysis to evaluate the application and suitability of commercial FRCs for improving coal seeding outcomes using deployment devices. The research was guided by targeted questions addressing key knowledge gaps in the use of FRCs in coral restoration, with the aim of systematically assessing their benefits and limitations. The experiments demonstrated that FRC treatments consistently, safely, and significantly reduced fouling on device surfaces, resulting in improved coral spat survival. This protective effect was sustained even after long-term exposure to reef environments, with benefits maintained until coral recruits exceeded 1 cm in diameter—a threshold beyond which mortality rates typically decline markedly. The indirect benefit of FRC treatments on coral survival was found to depend on fouling pressure, which varies with benthic ecosystem type, with the greatest improvement—doubling spat survival—observed at inshore reef habitats. While substantial protection from algal overgrowth was achieved by coating the core components of devices, the final experiment is expected to determine whether applying FRCs directly to the settlement tabs offers additional benefits. Building on these results, we aim to explore sustainable FRC alternatives with equivalent or enhanced performance. Future efforts should focus on optimising FRC use in restoration by improving both coating efficacy and the design of settlement surfaces and *early-care* platforms for coral recruits. Our overarching goal is to develop a restoration-ready FRC formulation that can be adopted globally to reduce post-deployment fouling and improve coral restoration outcomes.

6 Abbreviations

AIMS	Australian Institute of Marine Science (AIMS)
AF	Antifoulant coating – contains biocides
CCA	Crustose coralline algae
FRC	Foul release coating – biocide-free
FRC1	Intersleek 1001
FRC2	Hempasil 77300
GBR	Great Barrier Reef
Hempasil X3+	Hempasil X3+, Hydrogel-based Fouling Release Coating
Hempaguard X7	A silicone-based coating containing slow-release copper biocide
Hempasil 77300	A hydrophobic silicone foul release coating
Intersleek 1001	An amphiphilic silicone fluoropolymer foul release coating
NP	Nanoparticles
PDMS	Polydimethylsiloxane – a silicone-based polymer (solid substrate) or oil
PVC	Polyvinyl chloride – a polymer
SeaSim	National Sea Simulator, AIMS
Wax	Food grade wax foul release coating (CoralCare)

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