REEF RESTORATION & ADAPTATION PROGRAM

Approaches to Stabilisation (RS-02)

Final Report June 2025

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Cover Page: Coral reef, Credit: Gary Cranitch, Queensland Museum

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This report summarises work undertaken under *Approaches to Stabilisation (RS-02)* in accordance with the Reef Restoration and Adaptation Program's *Rubble Stabilisation* Project Agreements. It provides a summarised, point-in-time synopsis of activities, methods, findings and outcomes completed in accordance with the approved project scope up to 30 June 2025.

All information reflects project scope and outcomes as of May-June 2025. Subsequent updates, analyses, or scientific developments are not included. This report should be read alongside any associated and publicly available technical reports, datasets, and publications for full detail. This report does not provide scientific inferences, policy guidance or operational instructions beyond the project's defined scope and duration.

Acknowledgement

This work was undertaken for the Reef Restoration and Adaptation Program (RRAP). Funded by the partnership between the Australian Government's Reef Trust and the Great Barrier Reef Foundation, partners include: the Australian Institute of Marine Science, CSIRO, the Great Barrier Reef Foundation, Southern Cross University, the University of Queensland, Queensland University of Technology and James Cook University.

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
Whitsundays	Ngaro
Whitsundays	Gia
Lodestone Reef	Girramay Bandjin
John Brewer Reef	Manbarra

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1 Executive Summary

Reef recovery to disturbances is challenged by poor substrate quality or limited substrate availability and is a particular problem for coral restoration efforts. Poor substrate quality and availability, as exemplified by fields of rubble, can develop quickly after disturbances such as tropical cyclones, boat groundings or blast fishing in overseas locations, but can also develop over the longer term because of bleaching, Crown-of-thorns starfish (COTS) invasions and pollution. The strategies available at present to stabilise rubble and increase substrate availability and/or stability can be prohibitively expensive if implemented at scale, are labour intensive, and polluting from having high carbon footprints through introducing large amounts of foreign materials to the reef (e.g. plastics, metal, concrete). The efficacy of stabilisation methods is variable and, in some cases, poorly documented. Scope therefore exists to develop new and more scalable and eco-friendly methods for substrate stabilisation that enables restoration to be smarter and better through integration with other existing intervention methods. Having stable substrates is critical for the future success of the Reef Restoration and Adaptation Program (RRAP) as the Program begins progressing coral seeding-based interventions into the Pilot Deployments Program and where between 10-100 million corals per year are planned to be produced for out-planting – the success of these restoration approaches will be maximised where there is stabilised and quality substrate for coral recruitment and survival.

This Project therefore had two main objectives: 1) to critically review existing methods and through field deployment, evaluate specific stabilisation methods (sub-project 2.1), and 2) develop a new method for rubble stabilisation (underwater bioadhesives) that has the potential to alleviate or overcome limitations of existing stabilisation methods (sub-project 2.2). Specifically, this project evaluated the efficacy of metal frames/reef bags for rubble stabilisation on the Great Barrier Reef (GBR), and how bioadhesives can be used in rubble stabilisation. These sub-projects then provided inputs into the RRAP Synthesis and Tools (RS-03) Project, Rubble Stabilisation Guidelines. (Figure 1).

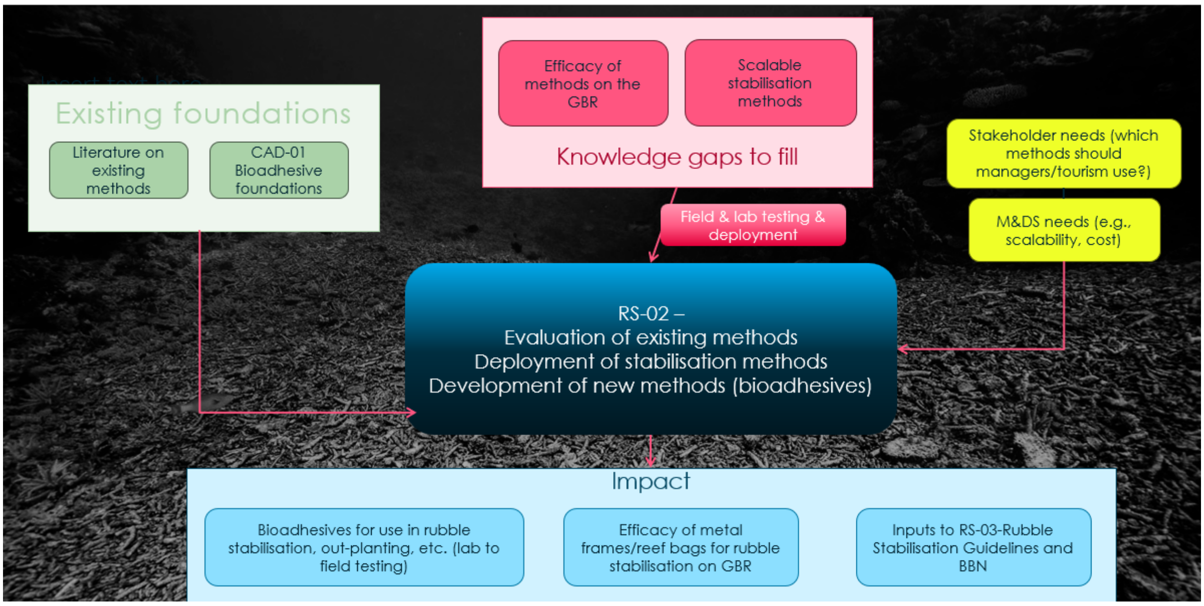

Figure 1: Summary of the RRAP Approaches to Stabilisation (RS-02) Project objectives, impact and connectivity with other RRAP projects.

Sub-project 2.1 Evaluation of Existing (Engineered) Methods for Rubble Stabilisation

This project was undertaken in two stages. Stage one was a desktop exercise to evaluate the degree to which current methods stabilise rubble. The review involved internal team workshops and meetings coordinated between the rubble stabilisation field team and experts working in rubble stabilisation (. It also included limited field inspection of sites with stabilisation methods, such as the reef bags previously deployed at Bait

Reef and Pinnacles in the Whitsundays, to assess their effectiveness and the degree of ecosystem recovery (Figure 2). To date, monitoring of these initial trials has occurred over a four-year period. For the reef bags, most coir remained intact during the first 12 months but had completely biodegraded after two years, leaving behind the experimental rubble mounds (Kenyon et al. 2025). After approximately two years, fish abundance was higher above mounds compared to surrounding rubble. Rubble stability and binding were also higher, after approximately three years, in rubble mounds than in surrounding rubble at Pinnacle Bay, but not at Bait Reef (although binding did increase in Bait Reef mounds over this time). The increased stability and binding did not, however, translate to significantly higher coral recruitment on rubble mounds in either location. The placement of these reef bags in terms of depth, reef zone, sediment load and competition appears crucial. Off the back of this first trial of reef bags, a second trial was developed whereby the layers of coir mesh were reduced from two to one, the mesh hole size was increased, and reef bags were compared to 'pile only' treatments (rubble piled but not covered by a reef bag; Figure 2). Monitoring of the second trial of reef bags at Bait Reef indicates that the number of corals is promisingly higher on pile only treatments, and on reef bags, compared to 'control' rubble sites. This second round of deployment included higher replication in a proximal location, all at one depth, and will be monitored again in June 2025.

Stage two involved choosing another stabilisation method, rebar structures, to also trial at Bait Reef to assess whether they had any appreciable effect on rubble mobilisation, binding rates, and coral recruitment. Three rebar structure designs were developed, after consultation with rubble stabilisation experts and review of the existing literature as part of the desktop exercise of stage one. A key element of stage two was to field test a widespread or common method. The Mars Assisted Reef Restoration System (MARRS) Reef Stars were identified as an extensively used and increasingly popular method being deployed for rubble stabilisation (Nunez et al. 2024). The three designs of rebar structure included one that was similar to a reef star (open-based pyramid), together with a flat mesh reported to be effective by Raymundo et al. (2007) and a flat mesh combined with a pyramid to provide vertical relief (Figure 3). Deployment of the rebar stabilisation structures commenced in May 2022 with a two-year field trial conducted to measure the success or failure of the deployed method in rubble stabilisation, with monitoring of the stabilisation structures undertaken in 2023 and 2024 (Figure 4). Structures were found to be effective in terms of limiting rubble movement and increasing rates of binding. However, the effect of structures on coral recruitment onto the stabilised rubble is still in question. Coral surveys will be repeated in June 2025 on both the rubble *and* on the structures themselves which have been previously unsurveyed.

A component of this sub-project included collaboration with: 1) the RRAP Moving Coral Sub-program to evaluate whether the combined use of rubble stabilisation and enhanced larval supply can have a synergistic benefit on recruitment; and 2) the RRAP Coral Aquaculture and Deployment (CAD) Sub-program to test deployment devices including their mobility under different hydrodynamic conditions and their ability to aid in rubble stabilisation and coral recovery. This led to discussions with the RRAP CAD Sub-program team from early 2021, and into 2023. In early 2022, the decision was made to put on hold deployment of the RRAP deployment devices until the CAD team had narrowed down the design of their devices. In early 2023, the deployment of RRAP devices at Bait Reef became untenable. The RRAP deployment devices were sent to the University of Queensland (UQ) engineering team to test their mobility under laboratory hydrodynamic conditions.

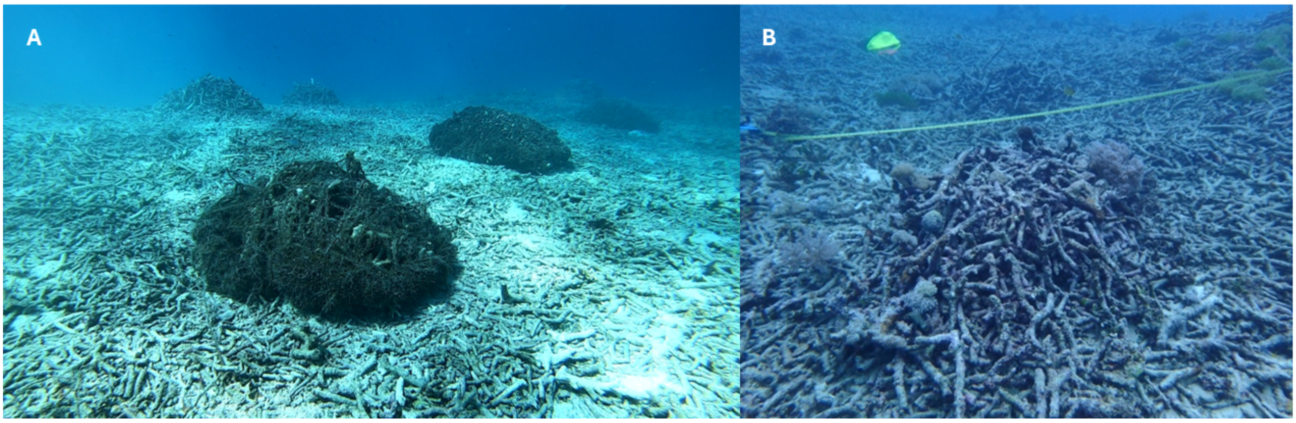

Figure 2: Reef bag trials at Bait Reef. A) Overview of coir reef bag dimensions and spacing on the rubble field. B) Closeup of second trial which included reef bags as well as mounds of rubble without an enclosing reef bag.

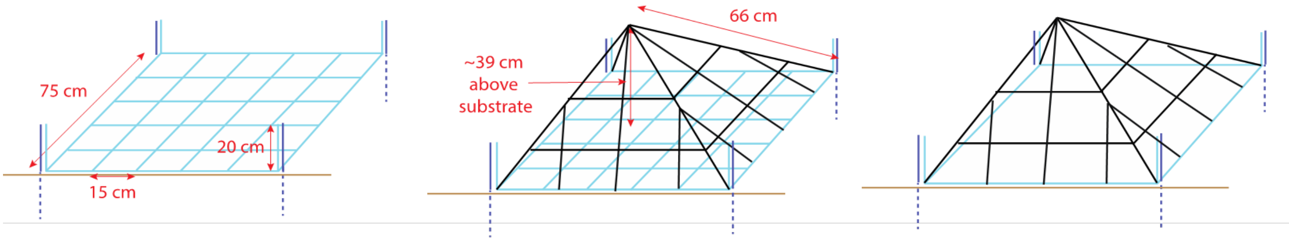

Figure 3: Chosen designs and dimensions of rebar structures deployed in field trials at Bait Reef to assess the efficacy of structures in directly (pinning) and indirectly (trapping) stabilising rubble.

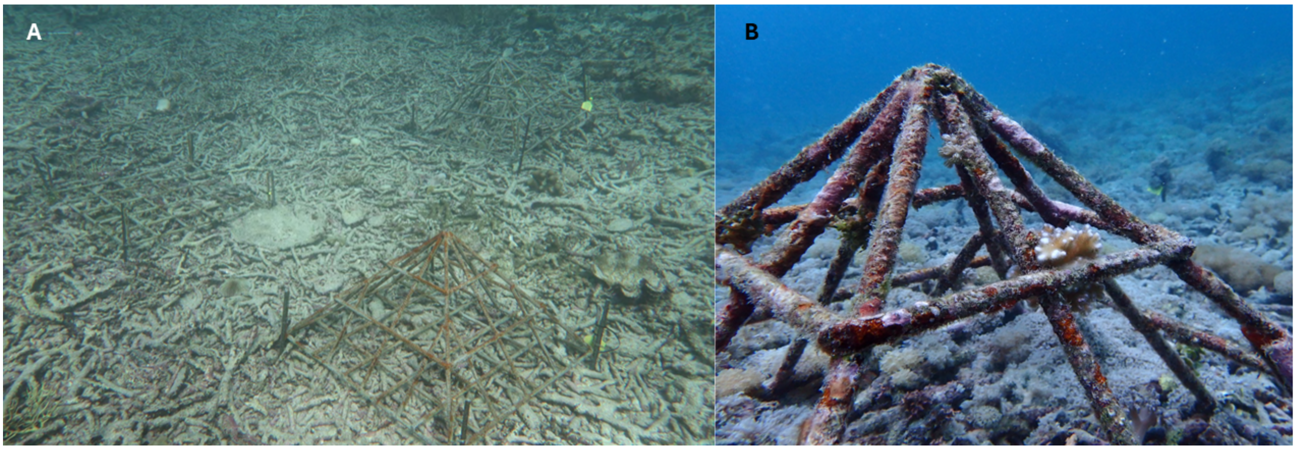

Figure 4: Rebar structure field trial at Bait Reef. A) Overview of deployment site with flat grid, open pyramid and closed pyramid rebar structure. B) Closeup of pyramid rebar structure showing natural coral recruitment.

Project 2.2: Evaluating Biogeochemical Methods for Rubble Stabilisation

Project 2.2 focused on developing the underwater bioadhesives as a novel, scalable and more environmentally friendly stabilisation method. Underwater bioadhesive materials have the potential to be used in many different coral reef intervention strategies and for restoration in different marine ecosystems. We are unaware of any other existing or emerging technology that can have such wide application in marine ecosystem restoration. The technical challenges for underwater bioadhesives, however, are many: the adhesive needs to be applied underwater to wet surfaces and needs to exclude water from the bonding surfaces, provide strong adherence and durability over time, as well as be scalable, adaptable and sustainable.

The primary objectives therefore were to advance the Queensland University of Technology (QUT)-developed underwater bioadhesives initially developed for the RRAP Coral Aquaculture and Deployment

(CAD) Sub-program for rubble stabilisation applications, where the bioadhesives would bio-mimic and help accelerate natural binding and stabilisation processes.

This was achieved through desktop and small-scale laboratory testing to develop bioadhesive formulas and assess performance such as cohesion, adhesion, durability, and ecotoxicity. The underwater bioadhesives have now been established as a proof-of-concept with RRAP funding, reaching a Technology Readiness Level (TRL) of 5 (Figure 5). This is based on an extensive review of existing literature/patents and adhesive reproduction (TRL1 and 2); design and experimentation of new bioadhesive materials (TRL3); laboratory testing of bioadhesive material properties (e.g. strength, toxicity, adhesion, cohesion, binding different materials) quantifying bioadhesive performance and threshold requirements (TRL4); and the first field trials on the Great Barrier Reef (GBR) integrating the bioadhesives as part of coral attachment devices through the RRAP CAD Sub-program as part of an integrated system (TRL5). Several generations of underwater bioadhesive were developed including a base formulation that allows the adhesive to be tuneable for different requirements. Laboratory testing included wave flume experiments measuring bioadhesive bonding strength under simulated wave and current conditions. This laboratory testing has demonstrated that binding strengths of some of the bioadhesives can significantly exceed 250 kilopascals (kPa). This is benchmarked to rubble mobilisation thresholds of greater than 30 kPa as determined in the RRAP Rubble Location, Prediction and Sub-program Management (RS-01) Project. Flume tank testing has also shown bioadhesive-treated rubble resists current flows of greater than 1.24 m s^{-1}.

The first use of bioadhesives with small coral fragments indicated oxidation-based crosslinking was occurring that resulted in coral micro-fragment contact mortality. That is, the bioadhesive interaction with water was generating locally anoxic conditions. This oxidation temporally decreased the dissolved oxygen in the water to significant levels at the bioadhesive-coral interface in the first one to two days affecting coral tissues at the microscale. However, the bioadhesive does not affect the surrounding body of water at reef scale and is non-toxic to the environment in water volumes greater than one litre. The effect of the adhesive on a coral fragment depends on fragment size, coral taxa, and application methods. Increasing the size of the fragment, and separation from the tissues when applying the bioadhesive greatly improved survival rates. The RRAP CAD Sub-program led a nine-month field trial involving coral larval tiles or tabs inserted into devices with bioadhesive, showing that coral survival and growth was very high and was not negatively influenced by the bioadhesives.

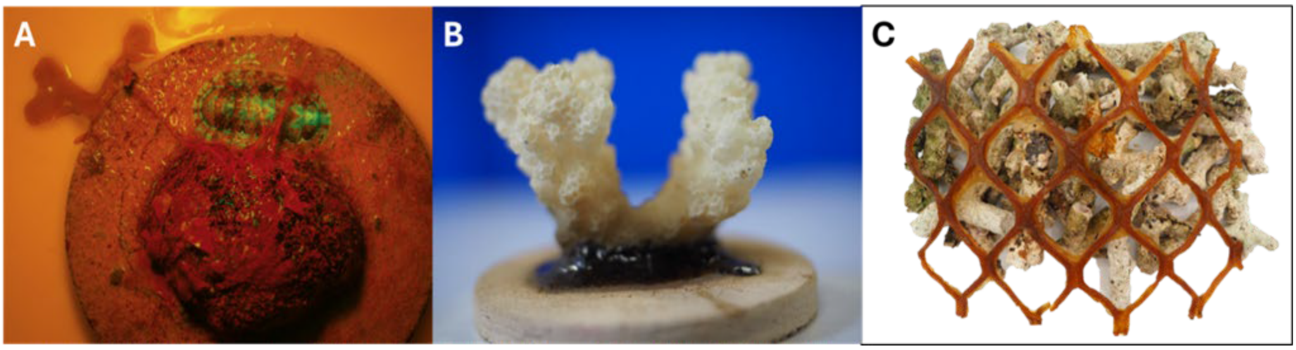

Figure 5: Bioadhesive tests and applications. A) 90-day ecological and microtoxicity trial at the Australian Institute of Marine Science (AIMS) National Sea Simulator (SeaSim). Five cm diameter ceramic tile with bioadhesive is fouled with fibrous and fleshy algae, and crustose coralline algae; a chiton is adjacent at top. Image taken in UV light. B) Example of bioadhesive used for coral fragment attachment test. C) Plan view of bioadhesive moulded mesh for direct substrate stabilisation.

An opportunistic trial to assess some environmental aspects of the bioadhesives was able to be completed using the ReefHQ aquarium in Townsville before its final closure. The aquarium offered a controlled environment and accessibility — advantages over isolated coral reefs, which often demand significant time and resources and lack full-time observation. Before the ReefHQ aquarium closure, the Coral Reef Exhibit represented a 1-million-litre system and had 130 coral species and 120 fish species along with hundreds of species of sea stars, sea urchins, sea cucumbers, brittle stars, feather stars, snails, worms and sponges. We examined, for the first time, the potential attraction of grazers to the bioadhesives to consume the bioadhesive materials and therefore affect bioadhesive performance on the reef as well as cause harm to fish or other grazers. Approximately 60 hours of footage was acquired during the experiments. Fish and invertebrates' proximity counts indicated no attraction or toxicity effect on the fish or invertebrate community. No direct grazing or ingestion of the bioadhesive during the experiments was observed. In summary, environmental toxicity assessments completed utilising small-scale laboratory tests, a three-month AIMS SeaSim trial, a RRAP CAD Sub-program led field trial and a one-month ReefHQ trial in partnership with the Great Barrier Reef Marine Park Authority (GBRMPA) have collectively demonstrated the bioadhesives are non-toxic in marine environments.

2 Background and Justification for the Research

Natural and man-made disturbances on coral reefs can result in extensive damage to functioning and diverse coral reefs which, in some cases, can be partly or fully reduced to fields of rubble. Rubble, an unstable and mobile substrate, can strongly inhibit the ability of young corals to recruit back onto reefs. Stabilising the coral rubble substrate is an important beneficial strategy to foster coral settlement, growth and reef recovery. One strategy to improve overall coral cover and reef health is through restoring rubble-dominated areas on reefs. However, rubble stabilisation is presently in its infancy in terms of operational restoration methods for coral reefs.

This project is one of three themes within the RRAP Rubble Stabilisation Sub-program and is focused on **methods of rubble stabilisation**. An initial Rubble Stabilisation report and R&D program was developed in 2019 (Mead et al. 2019), which involved four-stages of advancement over the first five years to arrive at a position of proof-of-concept testing and deployment development in a full 10-year program. A subsequent evaluation of existing methods for rubble stabilisation was undertaken (Gibbs et al., 2019) and highlighted two key issues: 1) that existing engineered methods (e.g. reef spiders, reef hubs, rubble removal) were relatively costly, and 2) lacked scalability for the Great Barrier Reef. Existing methods often have a negative environmental footprint through introducing artificial materials to damaged reefs. Given approximate deployment costs are now known for existing methods of stabilisation, their costs can be factored into any future intervention programs. However, no engineered methods have been used for rubble stabilisation on the Great Barrier Reef, nor properly assessed in terms of their ability to stabilise rubble (as opposed to creating three-dimensional structure) and under different hydrodynamic and environmental conditions experienced across the length and breadth of the Great Barrier Reef.

The RRAP Approaches to Rubble Stabilisation (RS-02) Project objective was to run an evaluation of the efficacy of at least one existing methodology under a range of reef physical conditions on the Great Barrier Reef, with innovative research undertaken to explore the potential of novel binding methods as a future prospect for rubble stabilisation at larger scales than are currently economically feasible. As part of the project, we assessed reef bags, rebar stabilisation structures of three different designs, and aluminium meshesand advanced the development of underwater bioadhesives for rubble stabilisation and other coral restoration needs.

3 Research Objectives and Key Findings

A current list of project outputs are listed on the RRAP website: gbrrestoration.org. Key research objectives and findings are detailed below.

Table 1: Key findings of the Project aligned to the overarching and specific research questions for each sub-project.

Objective		Key Findings and/or Outcomes
2.1 Evaluation of Existing (Engineered) Methods for Rubble Stabilisation		
2.1 (a)	Desktop exercise to evaluate the degree to which current methods stabilise rubble. This will include field inspection at preexisting sites to deliver a unique four-year dataset on binding rates, calcification and ecological responses, at both an inshore and offshore site.	In the early stages of RS-02, we developed a summary of what did and did not work in the field of rubble stabilisation by conducting literature reviews, internal team workshops, and meetings coordinated between the rubble stabilisation field team and experts working in rubble stabilisation Information was collected on the array of methods available, and the proportion of projects which had quantitative versus qualitative data, or no post-deployment observations at all. These preliminary concepts were used to feed into this project in terms of which method would be tested. Field inspections at pre-existing sites were also undertaken and assesssed the first trial deployment of reef bags at Bait Reef (offshore) and Pinnacle Bay (inshore). These were deployed in early 2019, and monitored in 2020, 2022 and 2023, generating a four-year dataset on the reef bags. We found that coir mesh bags stabilised rubble into 3D mounds for one-year, biodegrading afterwards. Fish abundance was higher above the rubble mounds compared to surrounding rubble, and binding increased in rubble mounds but not in surrounding rubble. It was proposed that coral recruitment may have been hindered by thick mesh with small holes. This led to the second design of reef bags, which comprised only a single layer of coir mesh instead of two, with larger holes.
2.1 (b)	Deploy the most successful method identified from (a) during a two-to-three-year field trial to measure the effect of that method for rubble stabilisation, as well as in aiding coral growth and ecological recovery.	Based on the review in 2021, three methods of rubble stabilisation were identified for deployment at Bait Reef in mid-2022, in the central Great Barrier Reef. These were flat mesh (pins rubble, no vertical relief), flat mesh with pyramid (pins rubble, traps rubble, provides vertical relief) and open-based pyramid (traps rubble, provides vertical relief). In addition to these structures, the second iteration of reef bags was also deployed in late 2021. The three structure designs, as well as reef bags were monitored in 2023 and 2024, and will be re-surveyed (corals only) in mid-2025 by GBRMPA (with assistance from the RRAP Rubble

Objective		Key Findings and/or Outcomes
		Stabilisation team). We found that the stabilisation structures restricted rubble movement and increased the probability of binding between rubble fragments, but coral outcomes remain unclear. On reef bags, the number of corals was found to be higher on piles and reef bags, compared to control rubble. This method shows promise for restoration of rubble areas, without the need to introduce any foreign material into the environment. For the stabilisation structures, coral surveys were only carried out on the rubble substrate beneath structures, while several corals were noted to have begun growing on the structures. In June 2025, the abundance of corals growing on the structures will be monitored as well as on the rubble substrate.
2.1 (c)	Test the method in 2.1 (b) across a range of physical environments, and measure efficacy to increase natural coral recruitment in combination with enhanced larval supply (with the RRAP Moving Corals (MC) Sub-program) and with deployment devices (with the RRAP Coral Aquaculture and Deployment (CAD) Sub-program).	Owing to the small field team of the RRAP Rubble Stabilisation Sub-program, and logistics of manufacturing and transporting the stabilisation structures to other locations, the stabilisation structures were only tested at Bait Reef. However, the reef bags were tested at both Bait Reef and Pinnacle Bay. Furthermore, aluminium flat meshes, like the rebar flat meshes tested at Bait Reef, were also tested at Moore Reef (northern Great Barrier Reef). These were deployed in 2023 and monitored at four, eight and 12 months. Preliminary analyses indicate greater binding of rubble stabilised by the mesh compared to control rubble. We did not test the efficacy of RRAP deployment devices due to mismatched timelines with finalisation of device design . However, we did track the movement of rubble pieces under each of the three stabilisation structure designs, in comparison to control, unstabilised rubble. Over approximately two months, tagged rubble pieces moved the most in control plots, and the least under the 'flat mesh with pyramid' design. Tagged rubble also moved very little under both other structure designs. We suspect that the movement of RRAP deployment devices would be similarly impeded by the rubble stabilising structures.
2.2 Evaluating Biogeochemical Methods for Rubble Stabilisation		
2.2 (a)	Scoping study to evaluate the potential for biogeochemical rubble stabilisation (including bio-cement and bio-rock), in particular: the potential for upscaling; critical bottlenecks in deployment that would preclude utilisation at scale; best-practice methods for rubble stabilisation; synergy with other RRAP interventions to achieve deployment at scale.	An extensive literature review was completed on existing approaches to rubble stabilisation that focused on: 1) whether the method was synergistic with other approaches to generate improved or more accelerated outcomes; 2) ecological benefits (e.g. adding 3D complexity, beneficial to fish, coral recruitment); 3) overall environmental impact (e.g. addition of foreign materials, permanency on the reef); 4) cost; and 5) efficacy. The range of stabilisation approaches examined were: 1) sponge transplantation; 2) rubble vacuuming; 3) mesh

Objective		Key Findings and/or Outcomes
		stabilisation; 4) grouting/cement; 5) geofluid pumping; 6) Biorock; 7) Reef Stars; and 8) reef balls/bags. While some of these methods have been trialled or undergoing trials on the Great Barrier Reef (e.g. reef bags – see sub-project 2.1, Reef Stars) or implemented as a result of a ship grounding due to rubble and substrate contamination (vacuuming; Douglas Shoals, see Neale and Boylson, 2019), the efficacy and success was poorly documented and in the case of Biorock solutions, lacked peer-reviewed literature and independently reviewed outcomes. While some solutions have been successful overseas (e.g. Reef Stars, Lange et al. 2024), such approaches do not directly stabilise rubble – it is generally concealed by the Reef Star; and is a strategy that will be much more costly and likely prohibitive to implement at large scales on the Great Barrier Reef. To date, it is an approach that has been suited to small-scale restoration and led by tourist operators. The main outcome of the review is the recognition that novel approaches are needed to meet the potential challenges for restoration at scale on the Great Barrier Reef in the future. This scoping study thus led to defining objectives for Objective 2.2(c) and a focus on novel, scalable and more environmentally friendly stabilisation methods: 1) To advance the QUT-developed underwater bioadhesives in the RRAP CAD Sub-program for Rubble Stabilisation applications where the bioadhesives can mimic natural binding and stabilisation processes; and 2) Complete desktop and small-scale laboratory testing to assess bioadhesive formulas and performance – cohesion, adhesion, durability, and ecotoxicity as the foundation for future funding to support field trials.
2.2 (b)	Undertake preliminary sponge and microbialite seeding experiments under laboratory conditions to identify best species and rates of binding. This can include electrical stimulation experiments and rates of precipitation (Biorock).	As part of the experiment tracking binding rates and strengths over time, we determined which organisms were most effective for binding. The strongest groups of binders were vermetid snails, serpulid worms, bivalves, tunicates (solitary ascidians), crustose coralline algae, and hard corals themselves. Of these, tunicates and serpulid worms began to appear first, at four months, while vermetids and bivalves did not successfully recruit and bind until the eight-month mark. Deoxyribonucleic acid (DNA) analyses have been undertaken to determine the lowest identifiable taxonomic level for key binders identified in this experiment. Following the reviews in 2.2 (a) Biorock methods (electrical stimulation) and biogeochemical microbial/sponge binding methods were not pursued in this project because the reviews highlighted concerns on these approaches not being economic or feasible, would poorly scale, and electrical stimulation methods were also unproven. As a result, the body of work related to this objective was included in Objective 2.2 (c).

Objective		Key Findings and/or Outcomes
2.2 (c)	Build on outcomes of preliminary biomimetic glue development and trials as part of the RRAP Coral Aquaculture and Deployment (CAD) Sub-program.	Substantial progress has been made since 2023 in developing underwater bioadhesives for rubble stabilisation and other reef restoration applications. Importantly, the underwater bioadhesives represent a novel technology developed exclusively within RRAP, and did not exist before RRAP commenced. Furthermore, the use of underwater bioadhesives for rubble stabilisation had not previously been considered and is a novel concept developed in RRAP. This approach is now quickly gaining global interest and attention. Key outcomes are: 1) a suite of underwater bioadhesive materials that meet the following criteria: a. The bioadhesives are environmentally friendly/sustainable, using plant-based, non-toxic materials that are 75% biodegradable and 25% degradable. b. The use of bioadhesives to bind rubble is technically feasible in that the bioadhesives undergo a crosslinking attachment process as opposed to chemical reactions to adhere materials/surfaces, and strength testing has demonstrated strong binding (see below). c. The bioadhesives are ecologically effective demonstrating the potential for wider applications in reef restoration beyond rubble stabilisation, such as for coral fragment attachment and out-planting (Figure 2), as a coating material (e.g. to replace more toxic and environmentally unfriendly resins used to coat Reef Stars and as a coating of filaments used to connect coral attachment devices), and as a cement to replace plastic cable ties used to secure Reef Stars and other structures on the sea bed. For rubble stabilisation, the bioadhesive materials have been developed through this and other projects in two forms: 1) as moulded mesh (up to 1 x 1 m sheets) for surface stabilisation, and 2) as a polyfilla-type material with lowered viscosity to facilitate deeper penetration of the rubble substrate and greatly increase binding and stability. Critically, the multiple uses of the bioadhesive materials enhance its scalability. d. Through rapid development and testing and advancing its technology readiness level, the bioadhesive as a restoration solution or application is shown to have economic viability. Preliminary commercial production costs using small-scale pilot plant facilities are <$100/kg. The multiple uses of the bioadhesives as summarised above will also help contribute to reducing the cost of production. 2. The underwater bioadhesives have been advanced from TRL0 to TRL5 in two years with RRAP funding, and the underwater bioadhesives are now achieving TRL6 (the bioadhesives are being tested in a relevant environment or operational environment) with the support of external funding.

Objective		Key Findings and/or Outcomes
		3.The underwater bioadhesive is highly tuneable, and it can be chemically adapted to suit different purposes, environments and surfaces. This has allowed us to utilise the bioadhesive materials in different ways as summarised under Key Finding 1c above. 4. Environmental toxicity assessments have been completed utilising small-scale laboratory tests, a three-month AIMS SeaSim trial and a one-month ReefHQ trial in partnership with the Great Barrier Reef Marine Park Authority. Field trials of coral attachment devices using the bioadhesive have also provided invaluable information on the potential toxicity of the bioadhesive materials to corals and other benthic organisms. 5. Through continued development and new formulations of the underwater bioadhesives, binding strengths greater than 250 kPa have been achieved. This is benchmarked to rubble mobilisation thresholds of greater than 30 kPa as determined in RRAP Project Rubble Location, Prediction and Sub-program Management (RS-01). Flume tank testing has also shown bioadhesive-treated rubble resists current flows of greater than 1.24 m s^{-1}. 6. This Project has demonstrated how invaluable cross-program linkages and dependencies in RRAP can be, in this case between the RRAP CAD Sub-program and the RRAP RS Sub-programs. The underwater bioadhesive was initially developed for a RRAP CAD specific challenge – fastening coral larval tiles to devices. The challenges were inherently the same for rubble stabilisation, and the opportunity was taken to apply this new technology to rubble stabilisation. Both Sub-programs have greatly benefited by the R&D in each program that have greatly accelerated development of the underwater bioadhesives.
2.2 (d)	Co-involvement in other field studies (including the RRAP EcoRRAP Sub-program) establishing baselines study of natural stabilisation and recovery rates for reefs.	Principal involvement has been with the RRAP CAD Sub-program and in two field trials: 1) a coral attachment device trial using bioadhesives to secure coral larval tiles (9 months, 2023-2024); and 2) a linking filament trial (2024-2025) where three types of filaments are being trialled to link and connect coral attachment devices to minimise movement and loss. In the first field trial, coral larval tiles or tabs were inserted into devices, with (+) and without (-) bioadhesive. They were distributed onto the reef and subjected to two tropical cyclones of differing intensity (Tropical Cyclone Jasper and Tropical Cyclone Kirrily). The devices were recovered from the rubble and analysed for tile retention and survivability. These realistic conditions were chosen to simulate the increasing climate devastation expected when these devices are deployed. Key outcomes were: 1) the underwater bioadhesive retained the tiles on the seeding devices, i.e. there was 100% retention; and 2) coral survival and growth were very high and were not negatively influenced by the bioadhesives. In the second linking filament trial which is still ongoing, devices were deployed at John Brewer and Lodestone Reefs without coral recruits as the aims were two-fold: 1) to compare the

Objective		Key Findings and/or Outcomes
		movement of individual devices to those linked in groups of three; and 2) to evaluate how different filament types affect movement and determine which filament material will be most effective in future deployments to reduce movement. Three different filaments were used – a biodegradable monofilament fishing line, cotton thread, and cotton thread coated with bioadhesive material. Devices were deployed at four sites across two reefs, with 180 devices deployed at each site. Following surveying between April 7-17, 2025, the bioadhesive coated filaments have outperformed uncoated cotton and fishing line in linking devices. Throughout the project, the RRAP Rubble Stabilisation team also liaised with representatives from Mars Incorporated, regarding rubble monitoring methods to assess Reef Star installations. Methods developed by the team were shared with the Mars Incorporated team and several surveys at Reef Star sites on the Great Barrier Reef were undertaken, to gain an insight into consolidation and recovery on rubble areas under the Reef Stars in comparison to nearby, unstabilised rubble.

Adjustments to key research objectives

Table 2: Variation in the Project over time.

Initial Research Question	Explain when, how and why the research question changed
Test the method in 2.1 (b) across a range of physical environments, and measure efficacy to increase natural coral recruitment in combination with enhanced larval supply (with the RRAP Moving Corals (MC) Sub-program) and with deployment devices (with the RRAP Coral Aquaculture and Deployment (CAD) Sub-program).	To attempt to address research component one, there were discussions with the RRAP CAD Sub-program team from early 2021, and into 2023. In early 2022, a conversation between the RRAP Rubble Stabilisation and RRAP CAD teams led to the decision to put on hold deployment of the RRAP deployment devices until the RRAP CAD team had narrowed down the design of their devices (from six options). In early 2023, the deployment of RRAP devices at Bait Reef became untenable. The RRAP deployment devices were sent to the UQ engineering team to test their mobility under laboratory hydrodynamic conditions, consistent with component two.
Laboratory controlled binding experiments using sponges, microbialites and electrical stimulation (i.e. Biorock)	We did not pursue biogeochemical binding methods (microbial and sponge cementation) and Biorock methods (electrical stimulation) as the desktop reviews highlighted several concerns with these approaches including that that they are not economic/feasible, not scalable, would likely result in binding rates too slow (biogeochemical methods) and existing work indicated the method was unproven and its efficacy questionable (Biorock). Consequently, sub-project 2.2 principally focused on underwater bioadhesive development.

4 Future Research Recommendations

Evaluation of Existing (Engineered) Methods for Rubble Stabilisation

Regarding the rubble stabilisation structures (rebar) at Bait Reef, coral surveys have so far only been carried out on the rubble substrate beneath structures, while several corals were noted to have settled on the structures. In June 2025, the abundance of corals growing on the structures will be monitored as well as on the rubble substrate. While all 3 designs have proven to restrict rubble movement in comparison to control rubble, we suspect that the designs with vertical relief (i.e. open-based pyramid and flat mesh with pyramid) may prove ultimately more effective for coral recruitment by providing structure above the level of the rubble substrate. This was a key finding of the rubble stabilisation workshop held in Bali in 2023, i.e. that solely pinning rubble can be effective but generally only in areas with low deposited sediment, low cover of competitors such as macroalgae, and good water quality. A high cover of soft corals has been observed at Bait Reef, and levels of deposited sediment also appeared to be high. During the June 2025 surveys, the percentage cover of soft corals in each structure will also be assessed in comparison to control rubble.

There may be limitations to coral recruitment at Bait Reef that trump the issue of mobility and limit the effectiveness of the rubble stabilisation structures without additional control measures such as larval replenishment and/or soft coral removal. Furthermore, there was a bleaching event in 2022 that affected some corals at Bait Reef and could have dampened recruitment. Having said this, recruitment onto the nearby reef bags and piles at Bait Reef appears to be higher than on the control rubble. Thus, there may be site-specificity within Bait Reef, leading to different outcomes for the stabilisation structures compared to the second trial of reef bags.

Nevertheless, the capacity of the rubble stabilisation field team to test the stabilisation structures in other environments was limited, due to the small RRAP RS-02 diving team (2 people) and competing objectives within the project and other RRAP rubble stabilisation streams. In future, it would be pertinent to build upon collaborations with Mars Incorporated, who has deployed Reef Stars at Bait Reef as well as at many other locations worldwide. By forming an understanding of how Reef Stars perform at Bait Reef, in comparison to other locations, insights could be made into the expected effectiveness of our *stabilisation structures* in other locations. Reef Stars have also been deployed at Moore Reef, where the aluminium meshes were deployed.

As revealed through the development of the Bayesian Belief Network (BBN) and Rubble Stabilisation Guidelines (the Guidelines) in the RRAP Synthesis, Intervention Tool and Guidelines (RS-03) Project, the number of correctly monitored rubble stabilisation projects is limited and skewed toward certain environments. We hope that the release of the Guidelines will improve the quality of attempted rubble stabilisation efforts and lead to greater reporting of findings in terms of reports and/or publications. This will ensure that a higher number of environments is represented in terms of stabilisation projects.

As RRAP continues, it would be pertinent for the RRAP deployment devices and larval replenishment projects to be carried out on some areas of rubble substrate with and without rubble stabilisation methods. This could be easily achieved in areas where Mars Reef Stars are already deployed and in new deployment areas. Reef bags or piles may be another good option, as they do not involve the introduction of non-biodegradable material into the environment. Rubble will continue to increase on reefs as disturbances increase in intensity and frequency. Thus, it is likely that restoration of rubble areas will be necessary in some cases, particularly where the reefs in question are of high tourism value and/or are high value in terms of larval connectivity. In those cases, rubble stabilisation should be conducted prior to the deployment of RRAP deployment devices and/or the supply of larval slicks. Without it, the effectiveness of the applied replenishment could be severely dampened, particularly if periods of rough weather are experienced soon after.

Evaluating Biogeochemical Methods for Rubble Stabilisation

Bioadhesive development has been rapid, and the outcomes outlined here have been achieved within three years despite funding being limited to laboratory testing. Future research efforts are focused on two key aspects: 1) taking the bioadhesives out of the laboratory and onto the reef (Figure 5), and 2) scaling up bioadhesives to be a cheap and viable intervention method to support restoration efforts.

Figure 6: First bioadhesive mesh deployment, Hope Reef, April 2025 as part of a Mars Sustainable Solutions-supported field trial.

Field verification trials (Figure 6) are an important step to advance the bioadhesive materials along a technology readiness level pathway to reach Level 9 and beyond. Longer-term field trials are required to evaluate bioadhesive effectiveness in rubble stabilisation as a substrate improvement method, for direct coral out-planting, and its longevity in reef environmental conditions. Field trials are also required to evaluate how bioadhesive materials can be integrated with other restoration practices (e.g. Reef Stars). Field trials can be done globally evaluating performance in different environmental conditions (e.g. water temperature, depths, reef zones) as well as for location-specific challenges (e.g. blast fishing damaged reefs in Asia).

Scaling up bioadhesive utilisation requires several approaches. To date, the bioadhesives have been fabricated in a research laboratory, which imposes two limitations: 1) the amount of bioadhesive than can be made, and 2) cost of production. To resolve this bottleneck, production needs to be outsourced to commercial manufacturers to ensure larger quantities can be produced at much cheaper unit cost. Commercial manufacturers will also be able to assist with containerisation and different dispensing methods for the bioadhesive materials so it can be shipped globally, safely stored and then dispensed depending on the application.

Identifying and developing multiple applications for the bioadhesives will also promote wider use, greater demand and therefore continue to help lower production cost. The R&D completed to date has identified at least four different uses of bioadhesive materials in reef restoration:

1) As an **adhesive/cement** for coral fragment or 3D structure attachment.

2) As a **'Polyfilla'** type material with low viscosity that allows deep penetration of substrates that will greatly improve rates of rubble stabilisation.

3) As **moulded structures** or mesh for surficial stabilisation of substrates.

4) As a **coating material** to replace more environmentally unfriendly materials (e.g. resin coatings of reef stars) or as a protective material (e.g. linking filaments for coral attachment devices).

The bioadhesives are an emerging intervention method created by the RRAP. Bioadhesive materials have the potential to be used in different intervention strategies for restoration in different marine ecosystems. The following marine ecosystems are identified as having substantial opportunity for bioadhesive utilisation:

1) Coral reefs including cold water corals

2) Giant kelp forests

3) Shellfish reefs

4) Seagrass.

Consequently, this RRAP novel intervention method has the potential to benefit other, and highly valuable marine ecosystems in Australia.

5 References

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