

A Modular Calcium Carbonate-Based System for Scalable Coral Outplanting: Design and Theoretical Evaluation

Kevin Smulders
individual researcher

Abstract - Coral reef restoration is increasingly constrained by high labour costs and limited scalability of outplanting methods. This study presents the design and theoretical evaluation of a modular coral outplanting system comprising a stable base tray and sacrificial calcium carbonate (CaCO_3) inserts intended to support early stage coral attachment and subsequent biological integration. The system incorporates tapered plug-socket geometry, controlled spatial arrangement, and elevated placement to optimise hydrodynamic performance and sediment clearance. A conceptual and engineering based assessment was conducted to evaluate mechanical stability, sediment interaction, biological compatibility, and deployment efficiency. The design is predicted to increase deployment efficiency by up to an order of magnitude relative to conventional single fragment attachment methods, while reducing material costs per coral. Limitations include the absence of empirical validation and uncertainties regarding long-term ecological performance. This framework provides a scalable design for future experimental testing and potential application in coral reef restoration programs.

1. INTRODUCTION

Coral reefs are among the most biodiverse marine ecosystems, yet they are undergoing rapid global decline due to climate change, ocean warming, and local anthropogenic stressors (Hoegh-Guldberg et al., 2007; Hughes et al., 2017). Active restoration interventions, including coral gardening and direct outplanting, have been widely implemented to support reef recovery (Rinkevich, 2014). However, these approaches remain limited in spatial scale relative to the extent of reef degradation (Edwards & Gomez, 2007).

A primary constraint in restoration practice is the labour-intensive nature of coral outplanting. Conventional techniques typically involve attaching individual coral fragments to the substrate using epoxy, cement, or mechanical fasteners, requiring significant diver time per fragment (Boström-Einarsson et al., 2020). While effective at small scales, these methods are difficult to scale efficiently.

Recent advances have explored modular substrates, artificial reef units, and additive manufacturing approaches to improve restoration outcomes (Ng et al., 2017; Petersen et al., 2019). However, many of these systems involve complex structures, high production costs, or materials that do not readily integrate into natural reef frameworks. A key challenge remains the development of restoration systems that balance mechanical stability, biological compatibility, and operational scalability.

Coral growth occurs through calcification, whereby corals deposit calcium carbonate (CaCO_3) skeletons that form the structural foundation of reef ecosystems (Allemand et al., 2011). Substrate materials that align with this process may enhance early attachment and long-term integration. Accordingly, there is potential to develop restoration designs that combine engineering efficiency with biologically relevant materials.

This study presents a modular coral outplanting system designed to reduce deployment time, improve fragment stability, and utilise CaCO_3 -based substrates that can be incorporated into the reef over time. The system is evaluated through design analysis and theoretical performance assessment to determine its feasibility prior to empirical testing.

2. SYSTEM DESIGN

2.1 Overview

The proposed system consists of a stable base tray and a series of removable calcium carbonate inserts (hereafter “pods”), which together form a modular platform for coral outplanting (Fig. 1). The base tray provides structural stability and spatial organisation, while the pods function as sacrificial micro-substrates that support coral fragments during early attachment.

The modular configuration allows multiple coral fragments to be deployed simultaneously, improving efficiency relative to traditional single fragment methods. Over time, coral growth is expected to extend beyond the pods and integrate with the surrounding environment, reducing reliance on the artificial components.

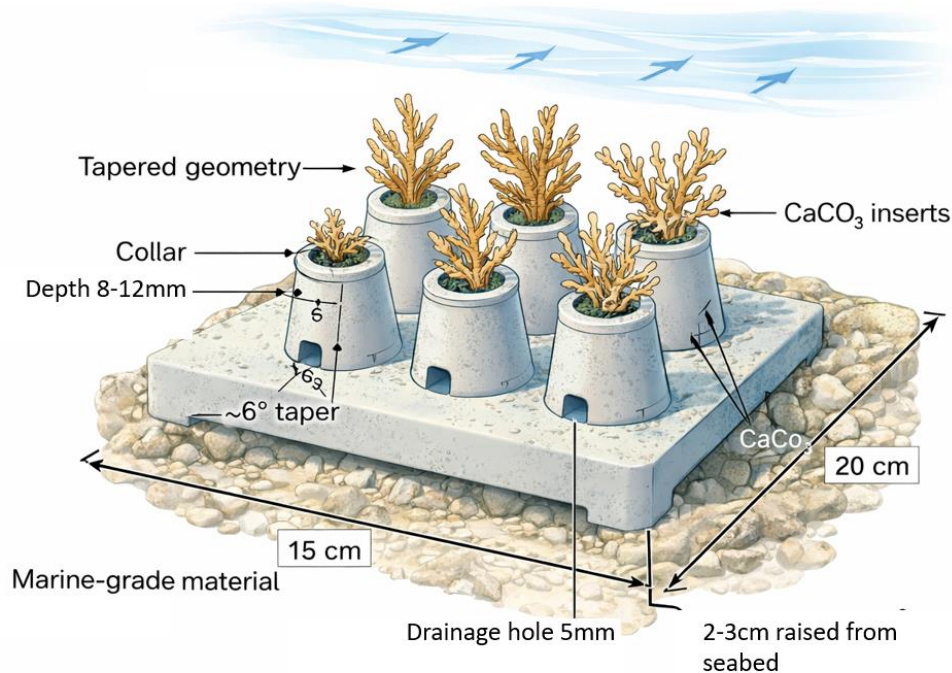


Figure 1 Conceptual rendering of the assembled modular coral outplanting system, showing a stable base tray populated with calcium carbonate (CaCO_3) inserts containing coral fragments. The elevated design (3cm above sea bed) promotes water flow and reduces sediment accumulation.

2.2 Base Tray Design

The base tray is constructed from marine-grade concrete or ceramic materials commonly used in artificial reef applications due to their durability and ecological compatibility (Baine, 2001). The tray measures approximately 20 cm by 15 cm with a height of 3–4 cm and is elevated 2–3 cm above the substrate creating a clearance sufficient to promote flow and reduce sediment accumulation, through integrated feet or ribbing.

This elevation is intended to promote water flow beneath the structure and reduce sediment accumulation, which is a key factor influencing coral survival (Rogers, 1990). The tray contains between six sockets arranged in a grid pattern, each designed to receive an individual pod. Socket depth is limited to approximately 10–15 mm to minimise sediment retention while maintaining sufficient mechanical stability.

2.3 Calcium Carbonate Inserts

The inserts are composed of CaCO_3 -based composites and are designed to mimic natural reef substrate (Fig. 2). Each pod incorporates a tapered cylindrical geometry with an approximate taper of 5–7°, enabling a secure but removable fit within the corresponding socket.

A shallow concave collar at the top of each pod provides lateral stability for the coral fragment, while a central socket accommodates the fragment itself. For branching corals, this socket typically measures 6–8 mm in diameter and 8–12

mm in depth. A small drainage aperture, approximately 3mm in diameter and offset from the centre, allows water exchange and reduces sediment accumulation within the pod.

Surface roughness on the order of 1–3mm is incorporated to promote microbial biofilm formation and enhance early stage coral attachment, as microtopography has been shown to influence settlement and growth (Nozawa, 2008; Webster et al., 2004).

The geometric parameters of the system were selected to balance mechanical stability, hydrodynamic performance, and ease of deployment. Elevation of the base tray by approximately 2–3cm above the substrate was chosen to enhance water flow beneath the structure and reduce sediment accumulation, which is known to negatively affect coral survival (Rogers, 1990). The tapered plug socket interface, set at approximately 6°, provides a compromise between secure seating and ease of insertion; shallower angles may result in excessive friction and difficulty during deployment, while steeper angles increase the likelihood of instability and lateral movement. A drainage aperture of approximately 5mm diameter was incorporated into each insert to facilitate water exchange and prevent sediment retention within the socket. This size is sufficient to allow flushing under moderate flow conditions while minimising the risk of clogging or structural weakening of the insert. Collectively, these parameters were selected to ensure short-term mechanical stability while supporting the transition to biological attachment and long-term integration.



Figure 2 Exploded view of the system components, illustrating the base tray and individual CaCO_3 inserts. Key features include tapered geometry for secure seating, a central socket for coral fragment placement, and a drainage aperture to facilitate water exchange.

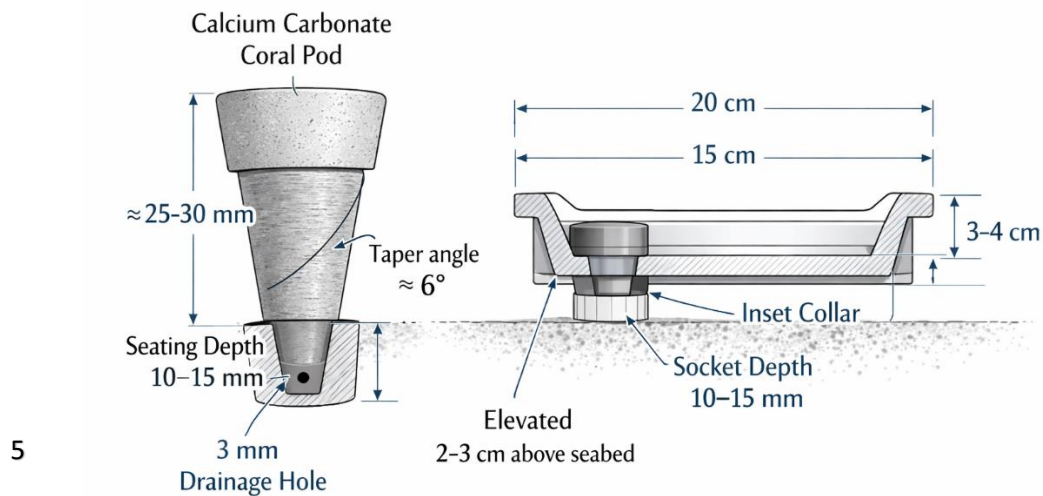


Figure 3 Technical schematic of the CaCO_3 insert geometry, showing taper angle 6° , collar dimensions, frag hole depth, drainage hole placement, and seating depth within the base tray.

2.4 Material Rationale

The use of marine concrete or ceramic for the base tray provides long-term structural integrity, while the CaCO_3 -based inserts offer a biologically compatible substrate aligned with coral calcification processes (Allemand et al., 2011). Over time, coral growth and bioerosion are expected to reduce the functional importance of the inserts, allowing the system to transition from artificial support to biologically integrated structure.

3. THEORETICAL PERFORMANCE EVALUATION

3.1 Mechanical Stability

The low profile design of the tray reduces hydrodynamic drag, while the distributed mass enhances stability under moderate flow conditions. Similar design principles are widely applied in artificial reef structures to minimise displacement (Baine, 2001). The tapered interface between pods and sockets further reduces lateral movement and enables secure placement without reliance on adhesives.

3.2 Hydrodynamics and Sediment Interaction

Sedimentation is a major driver of coral mortality, particularly in restoration contexts (Rogers, 1990). The elevated design of the tray facilitates water flow beneath the structure, reducing the likelihood of sediment accumulation. The inclusion of drainage apertures and shallow socket depths further minimises the formation of low flow zones that could otherwise trap sediments.

3.3 Biological Compatibility

Successful coral attachment depends on substrate characteristics and the process of calcification (Allemand et al., 2011). The use of CaCO_3 -based materials provides a chemically suitable substrate, while surface roughness promotes microbial colonisation and early attachment (Webster et al., 2004). These features collectively support the transition from mechanical stabilisation to biological integration.

3.4 Integration and Long-Term Behaviour

The inserts are designed to become progressively incorporated into the reef through coral overgrowth and encrustation. Bioerosion processes may further reduce their structural role over time. This approach aligns with restoration strategies that seek to minimise long-term artificial material presence while supporting natural reef development (Ng et al., 2017).

4. DEPLOYMENT WORKFLOW AND EFFICIENCY

The modular system enables a streamlined deployment process in which base trays are first positioned on the substrate and stabilised where necessary, followed by insertion of pre-prepared coral pods. This approach reduces the need for individual fragment attachment underwater.

Estimated deployment times of 1.5–2.5 minutes per tray suggest that a single diver could deploy between 90 and 225 coral fragments per dive, depending on conditions, depth of deployment and experience. In contrast, conventional methods typically require several minutes per fragment (Boström-Einarsson et al., 2020). The proposed system therefore has the potential to significantly increase restoration efficiency and scalability. Assuming a conservative deployment time of 2 minutes per tray containing six fragments, this corresponds to approximately 3 fragments per minute, compared to approximately 0.3–0.5 fragments per minute using conventional single-fragment attachment methods.

5. COST CONSIDERATIONS

Cost is a major limiting factor in large-scale restoration (Edwards & Gomez, 2007). The proposed system uses relatively low-cost materials and reusable moulds, with estimated production costs of approximately \$7–13 per tray. This corresponds to a hardware cost of approximately \$1–2 per coral fragment, excluding labour. These estimates compare favourably with reported restoration costs, which can exceed \$10 per coral when labour is included (Boström-Einarsson et al., 2020).

6. LIMITATIONS

This study is based on theoretical evaluation and does not include empirical validation. As such, several uncertainties remain, including coral survival rates, long-term structural performance, and ecological interactions such as grazing and competition. The system's performance under high energy conditions also requires investigation. These limitations highlight the need for controlled laboratory and field based testing.

7. FUTURE WORK

Future research should focus on experimental validation of the system through laboratory flume studies and pilot field deployments. Comparative assessments with existing outplanting methods would provide valuable insight into performance across different environmental conditions and coral species.

8. CONCLUSION

The modular CaCO₃-based coral outplanting system presented here offers a potentially scalable and cost effective alternative to conventional restoration methods. By integrating mechanical design with biological compatibility, the system addresses key constraints in current practices. While further validation is required, the design provides a strong foundation for future research and application in coral reef restoration. No new empirical data were generated for this study. All information presented is derived from design analysis and existing literature.

REFERENCE

- [1] Allemand, D., Ferrier-Pagès, C., Furla, P., Houlbrèque, F., Puverel, S., Reynaud, S., Tambutté, É., Tambutté, S. and Zoccola, D. (2011) Coral calcification, cells to reefs. *Comptes Rendus Palevol*, 10(5–6), pp. 453–470.
- [2] Baine, M. (2001) Artificial reefs: a review. *Ocean & Coastal Management*, 44(3–4), pp. 241–259.
- [3] Boström-Einarsson, L., Babcock, R.C., Bayraktarov, E., Ceccarelli, D., Cook, N., Ferse, S.C.A., Hancock, B., Harrison, P., Hein, M., Shaver, E. and Smith, A. (2020) Coral restoration – A systematic review. *Biological Conservation*, 246, 108557.
- [4] Edwards, A.J. and Gomez, E.D. (2007) *Reef restoration concepts and guidelines: making sensible management choices in the face of uncertainty*. St Lucia, Australia: Coral Reef Targeted Research & Capacity Building for Management Program.
- [5] Hoegh-Guldberg, O., Mumby, P.J., Hooten, A.J., Steneck, R.S., Greenfield, P., Gomez, E., Harvell, C.D., Sale, P.F., Edwards, A.J., Caldeira, K. and Knowlton, N. (2007) Coral reefs under rapid climate change and ocean acidification. *Science*, 318(5857), pp. 1737–1742.
- [6] Hughes, T.P., Kerry, J.T., Álvarez-Noriega, M., Álvarez-Romero, J.G., Anderson, K.D., Baird, A.H., Babcock, R.C., Beger, M., Bellwood, D.R. and Berkelmans, R. (2017) Global warming and recurrent mass bleaching of corals. *Nature*, 543(7645), pp. 373–377.
- [7] Ng, C.S.L., Lim, S.C., Ong, J.Y., Teo, L.M.S., Chou, L.M., Chua, K.E. and Tan, K.S. (2017) Enhancing the biodiversity of degraded coral reefs: coral recruitment on engineered substrates. *Marine Ecology Progress Series*, 581, pp. 1–14.
- [8] Nozawa, Y. (2008) Micro-topography influences recruitment of corals. *Marine Biology*, 155(1), pp. 71–79.
- [9] Petersen, D., Laterveer, M., Schuhmacher, H. and Osinga, R. (2019) Innovative substrate tiles to spatially control coral reef communities. *Rapid Prototyping Journal*, 25(3), pp. 567–580.
- [10] Rinkevich, B. (2014) Rebuilding coral reefs: does active reef restoration lead to sustainable reefs? *Aquatic Conservation: Marine and Freshwater Ecosystems*, 24(1), pp. 1–13.
- [11] Rogers, C.S. (1990) Responses of coral reefs and reef organisms to sedimentation. *Marine Ecology Progress Series*, 62, pp. 185–202.
- [12] Webster, N.S., Smith, L.D., Heyward, A.J., Watts, J.E.M., Webb, R.I., Blackall, L.L. and Negri, A.P. (2004) Metamorphosis of a scleractinian coral in response to microbial biofilms. *Applied and Environmental Microbiology*, 70(2), pp. 121–131.