

Automated Underwater Delivery System for Coral Probiotics

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Abstract

Coral reefs face global threats of functional extinction, largely due to anthropogenic impacts, especially climate change. Probiotic treatments using beneficial microorganisms for corals (BMCs) offer a promising solution to alleviate environmental impacts on corals, especially during heatwaves and disease outbreaks. However, the manual administration of these probiotics is not scalable. Here, we present the first automated probiotic delivery device that facilitates *in situ* delivery of BMCs. The device can deliver 2 L of probiotic solution at a maximum depth of 25 meters for a total duration of approximately 30 days. The device is equipped with a controller, probiotic cartridges with magnetic agitators, pumps, and a battery. The probiotic dosage and rate can be pre-programmed before deployment. The proposed technology contributes to the advancement of the deployment of microbial-based interventions beyond small-scale, manually intensive applications. It represents a step toward more efficient, scalable, and potentially cost-effective approaches for integrating microbial therapies into broader coral reef restoration and management efforts.

1. INTRODUCTION

Coral reefs play crucial ecological roles, delivering important ecosystem services, including fisheries, tourism, and coastal protection (Costanza et al., 1997, 2014). Despite their ecological importance, coral reef ecosystems are increasingly threatened with functional extinction as a result of multiple anthropogenic stressors, including climate change, ocean warming, pollution, and overfishing (Hughes et al., 2017). Globally, the general decline in coral coverage underscores the critical importance of coral restoration and rehabilitation initiatives (Voolstra et al., 2021). Multiple ecological intervention schemes have been proposed to restore or rehabilitate coral reefs (Peixoto et al., 2019; van Oppen et al., 2015; Voolstra et al., 2021). These strategies include coral transplantation, modification of reef substrate, and assisted coral recruitment (Ceccarelli et al., 2018).

The use of Beneficial Microorganisms for Corals (BMCs), or probiotics, has been proposed as a microbial-based strategy to rehabilitate coral reefs (Peixoto et al., 2017, 2019, 2021). Corals rely on their symbionts, including photosynthetic microalgae (Symbiodiniaceae) and their native microbiome, which play key functional roles, such as nutrient cycling, pathogen control, and detoxification. These beneficial microbes are usually lost and often replaced by pathogens when corals are exposed to stress (Peixoto & Voolstra, 2023). The application of these beneficial microorganisms, has therefore shown promising results in restructuring microbiomes, while improving coral growth, mitigate thermal stress and diseases in tank experiments (Rosado et al., 2019; Santoro et al., 2021; Ushijima et al., 2023; Zhang et al., 2021) and in the field (Delgadillo-Ordoñez et al., 2024; Pitts et al., 2025; Santoro et al., 2026). However, delivery optimization and scaling are among the main pressing challenges of the application of microbial-based restoration strategies in nature (Garcias-Bonet et al., 2024). To help overcome this limitation, we developed the first underwater automated device that can dispense BMCs to corals *in situ* reducing costs of microbial-based interventions associated with the rehabilitation of coral reefs. To validate the performance of the Automated Underwater Delivery system, a variety of lab and field tests were

conducted to assess the limits of operation concerning the depth, dispensation accuracy, and energy consumption.

2. MATERIALS AND METHODS

2.1. Automated Delivery System Design. The automated delivery system was designed using an off-the-shelf enclosure as the base (model WTE6-ASM-R1-VP, Blue Robotics, Fig. 1). The external braces and brackets were designed and manufactured in-house using PVC and acrylic sheets. Polypropylene 500 mL syringes from Guangzhou Shell Medical Technology Co. were chosen to store the BMCs during deployment. The nozzles of the syringes are fitted with LuerLok valve (MTLL105-10 JU Plasfitting Co. Ltd, China) to seal the contents of the syringe during transport and installation. The connection between the output of the syringes and the corals is made using 7 mm polyethylene tubes (Chinadrip Irrigation Equipment, China). Hydraulic dampers were installed in the output of the pumps to provide better dosage accuracy. The dampers are made of a 10 mL syringe (Becton Dickinson, USA). The stirring mechanism was designed in-house and vacuum molded from polycarbonate (ABCRapid, China) and uses magnetic coupling for the agitation. The magnets used are neodymium magnets with a thickness of 2.5 mm and a diameter of 10 mm (Dongguan Song Sun Magnet Co. Ltd., China).

To pump the BMCs from the syringe reservoir, diaphragm pumps from ET-PUMP (model R27-02-12) were used. These pumps were selected due to their capacity to handle higher pressures while being small in dimensions (7.5x2.7x2.4 cm). The pumps have been modified to provide feedback to the microcontroller. This was done by fixing a small neodymium magnet (D8x1mm, ShengCiTong') to the rotor shaft and placing a magnetic reed switch (model 59170-1-S-00-D, Littelfuse Inc.) within the pump housing. This allows for the digital encoding of the pump motor turns and, by extension, for the microcontroller to estimate the volume discharge.

Furthermore, a fifth pump is used to flush the delivery tubes from any residual BMCs solution using surrounding seawater. This feature prevents agglomeration and blockage of the probiotic solution in the pump line, small-diameter hoses and nozzles (**Figures S3 and S4** in SI show the hydraulic circuit and diagram control of all pumps). Each pump output is fitted with a dampener, a hydraulic accumulator, which absorbs pressure spikes and reduces the pressure in the delivery tube. The dampener is made from a syringe which was modified by sealing the rear end and shortening the plunger to create a compressible volume of air that absorbs the pressure spikes (**Figure S5a**). The comparison of continuous undamped pumping in comparison to damped intermittent bursts with the pump motor turning 3 revolutions and resting for 250 ms (**Figure S5b**). These intermittent pump bursts reduce the variation in dispensation volume due to the back pressure caused by the tube length and constriction of the nozzle orifice.

The motor used for agitation is a brushed DC motor (RS-555sh-4033, Ningbo Leison Motor Co. Ltd.). This motor was selected due to its profile and torque output. The motors are connected to the main enclosure with a waterproof connector (18AWG, YETOR). The motors and the pumps are driven using N-channel

MOSFETs (IRFF540, Vishay Siliconix) as drivers. The rotor is coupled to a magnetic driver with embedded magnets. The agitation impeller assembly is fitted inside the syringe cartridges and is comprised of an acrylic frame with an o-ring (46x50x2 mm, Uxcell). The impeller is supported by a zirconium oxide ceramic bearing (SL 18 3044 10x26x8 mm, Zhongxingao Slewing Bearings). The agitation control and slip and stall information are presented in the Agitation Section in Supplementary Information (SI). To power the dispenser, a 12 V 12 Ah lead acid battery (model WP12-12A, LNG power) was used. This battery was selected due to its capacity to power the device for 1 month on a single charge. The power estimation for the device is presented in the Power Consumption Section at SI.

1. **2.2. Electronic Circuit and Firmware.** As an electronic controller for the dispenser, an ESP32 microcontroller from Espressif Systems (model ESP32-WROOM-32) was chosen due to its embedded Bluetooth Low Energy (BLE) system, versatility, and low-power features. A real-time clock device (DS3231, Maxim Integrated) was added to the system to provide real-time feedback to the dispenser and provide precise control of when to pump the BMCs or agitate the reservoir. A reed switch (Littelfuse Inc. model 59170-1-S-00-D) was added to provide control of the sleeping/working mode of the system.
2. **2.3. Settings.** The microcontroller was programmed in C++ using Arduino integrated development environment (IDE) software. The mobile application to control the parameters of the device was developed using Flutter and Dart language with Android Studio as an IDE. Flutter was used for developing the graphical user interface and Dart was used for developing the back-end operation of the application. The main BLE functionality was performed using the Flutter Blue+ library and the data transmission was achieved using characteristics and services. More information about the BLE and its layout is presented at the Mobile Application Section in the SI.
3. **2.4. System Calibration and Test at Laboratory Setup.** The BMC dispensation pump is affected by the underwater pressure, as the seawater opposes the outgoing flow from the reservoirs. The hydrostatic pressure experiment was performed by constructing a closed hydraulic loop system where the pressure of the circuit was increased in 0.25 bar steps with a manual intra-aortic balloon pump until the BMC dispensation pump was no longer able to pump any volume. The circuit pressure was measured using a commercial pressure sensor (MS5837, TE connectivity). The same pressure sensor was used for a general leak test, in which the device was submerged in a hydrostatic pressure testing vessel filled with Ethylene Glycol. The pressure of the testing vessel was then increased in 0.5 bar steps up to 8 bar, equivalent to around 80 meters in depth.

Since BMC solutions can have different viscosity that can influence fine dosage control, a viscosity experiment was conducted by filling a syringe cartridge with mixtures of glycerin and distilled water at various concentrations to achieve a range of dynamic viscosities. To determine the viscosities that the device can accommodate, the test was performed on a fully assembled system. In contrast, to assess the magnetic coupling relationship with distance, the device was modified by securing the magnetic driver without its enclosure at varying distances from the impeller and agitating distilled water.

The Power consumption test was performed by recording the current consumed by various operating cycles using a current meter (INA219, Adafruit) and powering with a constant voltage of 12 V from a voltage supply (E3633A, Keysight Technologies). The complete power estimation results are presented in the Power Consumption Section at the SI.

2.5. BMCs viability tests.

To ensure the viability of BMCs once incorporated in the syringe cartridges, we assessed the number of viable cells over a period of 15 days, by plating an aliquot of the concentrated initial BMC suspension on marine agar media plates and using a flow cytometer. For cell counting, samples were stained using Sybr® green I nucleic acid stain, incubated for 15 min in dark conditions. The percentage of alive cells was analyzed using a double stain with Sybr® green I and propidium iodide (PI) and analyzed with a BD Accuri™ C6 flow cytometer in low flow rate.

2.6. *In situ* underwater tests

Several *in situ* deployments were carried out at the Coral Probiotics Village, an underwater laboratory located in Al Fahal reef, a midshore reef in the central Red Sea (22° 18' 18.4" N; 38° 57' 52.5" E, (Garcias-Bonet et al., 2025)) to test the correct underwater functioning of the magnetic stirrers, pumps, accuracy of dosage (frequency and volume), and battery life. The tests were performed by deploying the automated delivery system at 9 m deep in August - September 2022, November - December 2022 and March 2023. The daily *in situ* mean seawater temperature ranged from 32.73°C in August 2022 to 25.83°C in March 2023 and average salinity of 39 PSU.

3. RESULTS

3.1. System Calibration in Laboratory

To sustain operation while deployed underwater, multiple pressure tests were conducted. The absolute pressure in the enclosure is approximately one atmosphere, with small variations due to temperature. When submerged, there is a pressure differential between the inside and outside of the enclosure. The leak test showed that the device housing can withstand up to 7 bar of pressure, corresponding to around 70 meters depth (Fig. 2a). However, the pump system stopped working at around 2.5 bar of pressure, around 25 meters depth (Fig. 2b and c). The length of delivery tubes also affected the throughput of the pumps. The volume rate that can be dispensed up to a 6-meter radio is shown in Fig. 2d.

The magnetic agitators successfully prevented the precipitation of cells in the suspension, avoiding the subsequent agglomeration problem in the reservoirs. The agitation time for all reservoirs was pre-programmed with the dispensation time before deployment. The complete agitation control methodology and tests are presented in the Agitation Section in the SI.

3.2. BMCs Cell Viability and In Situ Deployment Tests

The cell viability of the BMCs solution was approximately $t \sim 1 \times 10^7$ cells/ml after two weeks of maintaining the solution in the syringes in an incubator at 26°C. The same concentration of viable cells was counted after two weeks of field deployment at ~ 26 °C.

A total of three in situ deployment tests were successfully performed covering the natural range of seawater temperature in the central Red Sea (Fig. 3). Throughout these field tests, the device's functioning, including proper stirring, pumping, timing, and dosage accuracy, was visually confirmed by divers.

4. DISCUSSION

The developed Automated Underwater Delivery System represents an important advancement toward the scaling and automation of microbial-based interventions for coral reef restoration. Current approaches that rely on manual delivery by SCUBA divers are time-consuming, labor-intensive, and associated with substantial operational costs. Moreover, diver-based deployment limits the spatial coverage, frequency, and overall capacity of intervention efforts, particularly when treatments need to be applied repeatedly or across dispersed reef areas. By automating the delivery process, the proposed system has the potential to overcome several of these logistical constraints and facilitate the broader implementation of microbial-based restoration strategies. The dispenser can reduce reliance on intensive manual operations while improving the efficiency, consistency, and scalability of intervention deployment. Such automation may enable treatments to be delivered more systematically and at a greater spatial scale, supporting repeated applications where required and reducing the resources needed for large-scale restoration activities.

Overall, the proposed automated underwater dispenser provides a technological foundation for advancing the deployment of microbial-based interventions beyond small-scale, manually intensive applications. Its development represents a step toward more efficient, scalable, and potentially cost-effective approaches for integrating microbial therapies into broader coral reef restoration and management efforts.

Declarations

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Conflict of Interest

The authors declare no conflict of interest.

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Figures

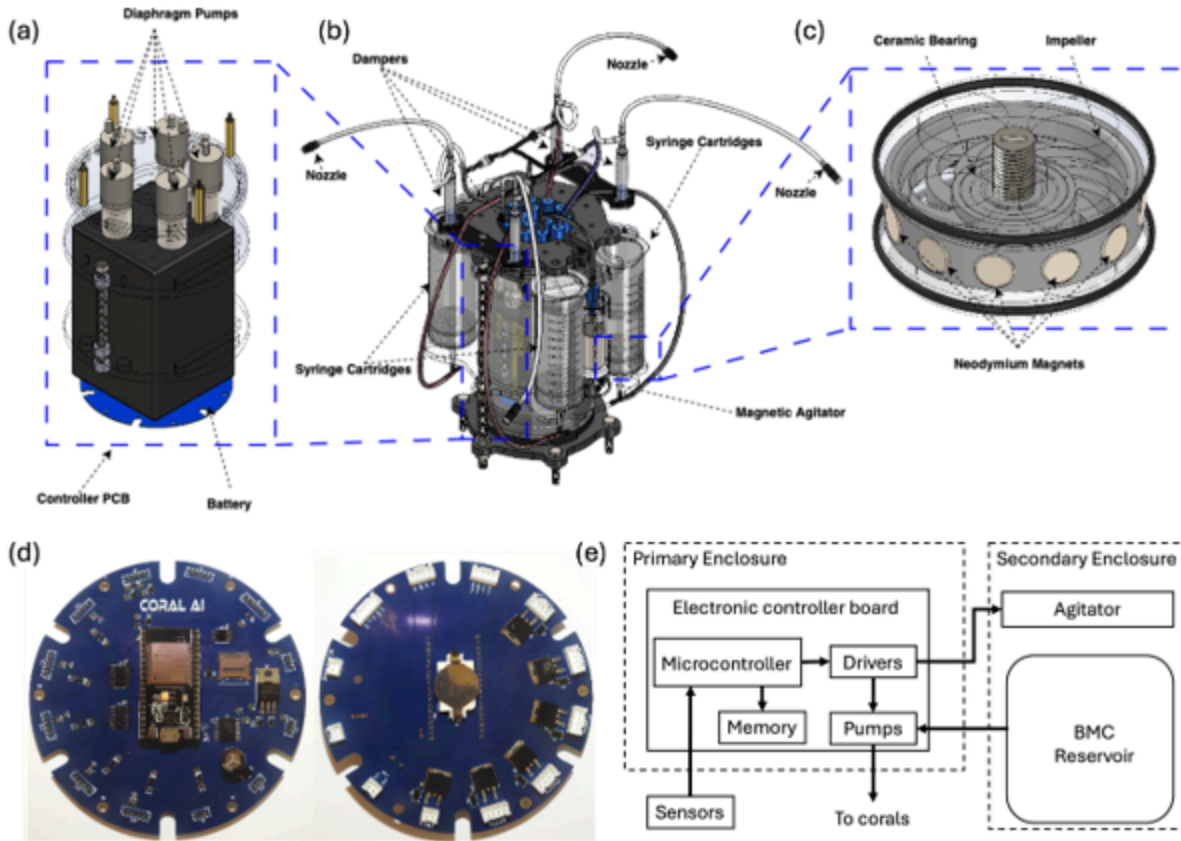


Figure 1

Schematic drawings of the system and operating flow. (a) The core components of the system, include the battery, the pumps, and the controller board. (b) The replaceable components of the system (c) the cartridge impeller used for the agitation of BMCs. (d) Images of the controller board. (e) System block diagram.

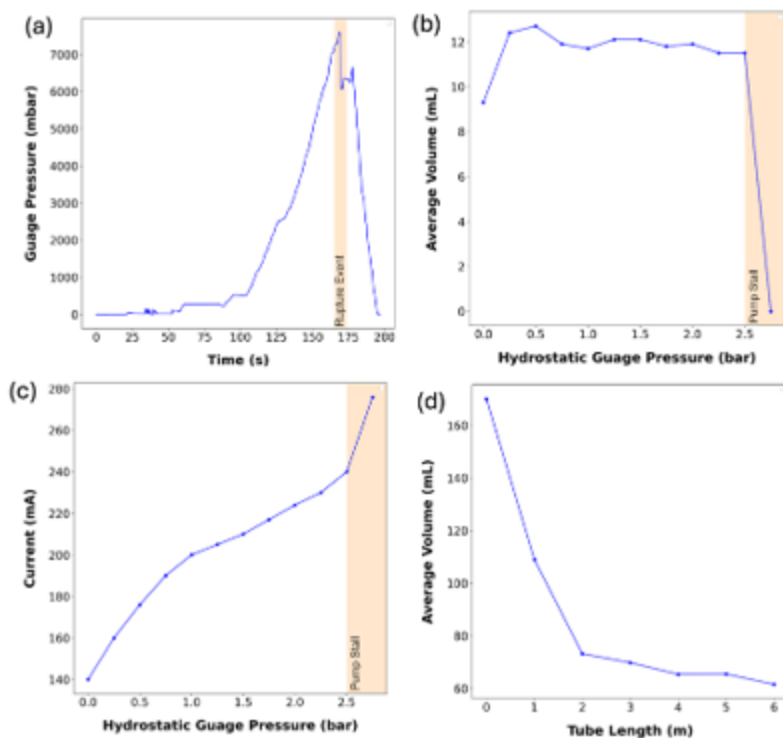


Figure 2

Pressure and leak tests. (a) The maximum pressure that can be sustained by the proposed device. (b) The dispensation volume with respect to hydrostatic pressure. (c) Pump motor current with respect to hydrostatic pressure. (d) Relationship of the delivery tube length and actual dispensed volume.

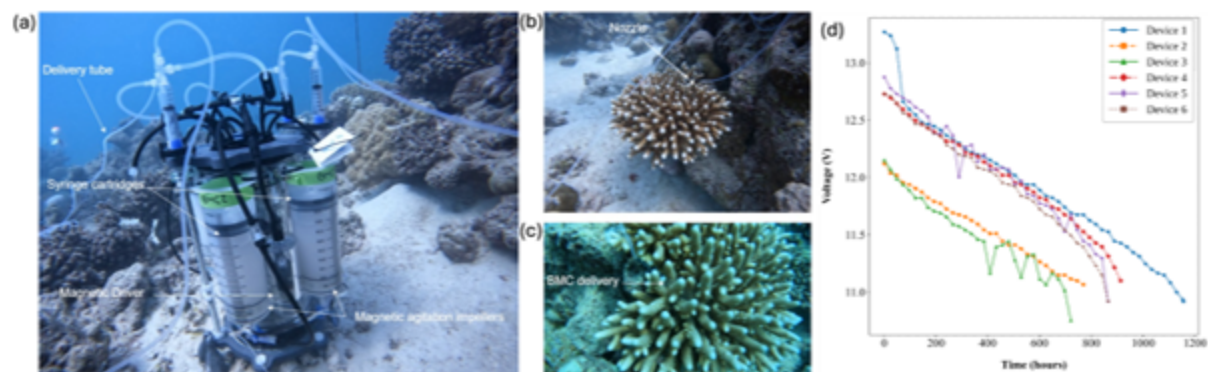


Figure 3

In situ deployment of an underwater dispenser in the Red Sea. (a) The device deployed at 9 m deep with BMC cartridges with four delivering nozzles. (b and c) Coral colonies receiving BMCs solution. (d) The operating voltage log of six devices deployed showing over 700 hours of continuous operation.

Supplementary Files

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