SUPPLEMENT

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Testing biodegradable mesh compositions to improve coral microfragmentation outcomes

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ABSTRACT

Introduction: Coral microfragmentation is a widely used technique in reef restoration, both *in situ* and in land-based nurseries. Typically, microfragments are individually attached to pedestals or artificial substrates, which requires substantial time and labor investment in the nursery and during field outplanting. An alternative approach involves the use of biodegradable meshes fixed to the substrate as a single unit supporting multiple microfragments. However, the optimal material combinations that provide the mechanical strength, stability, and adhesion necessary to maintain fragments in place after partial material degradation remain unknown. Therefore, experimental evaluation of biodegradable materials that optimize both stability and coral growth is a priority.

Objective: To evaluate whether two polymers (PCL and CAPA) combined with different concentrations of $CaCO_3$ influence coral growth rates and operational efficiency in both nursery and field conditions.

Methods: A controlled multifactorial experiment using a fully randomized block design was conducted over six months. The effect of mesh composition on cumulative growth in area and volume of *Montastraea cavernosa* was assessed using photogrammetry (Structure from Motion, SfM). Additionally, operational times in the nursery (handling, attachment, and cleaning) and during field outplanting were compared with and without mesh use.

Results: No statistically significant effects of mesh composition on growth rates were detected during the study period. Mean a real growth ranged from 0.5 to 0.8 mm^2, with a significant interaction among treatment, tank, and time, indicating low growth and high variability among tanks. Volumetric increase ranged from 0.25 to 0.62 cm^3, with no significant differences among treatments. However, mesh uses reduced nursery handling time by approximately 20 minutes per rack of 18 fragments.

Conclusions: Regardless of composition, biodegradable meshes represent a viable alternative to optimize asexual propagation through microfragmentation, improving operational efficiency without compromising coral growth.

Keywords: coral growth; biodegradable substrates; restoration; technological innovation.

RESUMEN

Pruebas de composiciones de malla biodegradables para mejorar los resultados de la microfragmentación de coral

Introducción: La microfragmentación de corales es una técnica ampliamente utilizada en restauración, tanto *in situ* como en viveros terrestres. Generalmente, los microfragmentos se fijan individualmente a pedestales o sustratos artificiales, lo que implica una elevada inversión de tiempo y mano de obra en el vivero y durante el trasplante en campo. Una alternativa consiste en emplear mallas biodegradables fijadas al sustrato como una unidad única que soporte múltiples microfragmentos. No obstante, aún se desconoce qué combinaciones de materiales ofrecen la resistencia mecánica, estabilidad y adhesión necesarias para mantener los fragmentos en su lugar tras la degradación parcial del material. Por ello, es prioritario evaluar experimentalmente materiales biodegradables que optimicen tanto la estabilidad como el crecimiento coralino.

Objetivo: Evaluar si dos polímeros (PCL y CAPA) combinados con distintas concentraciones de $CaCO_3$ influyen en las tasas de crecimiento coralino y en la eficiencia operativa en vivero y en campo.

Métodos: Se realizó un experimento multifactorial controlado con diseño de bloques completamente aleatorizado durante seis meses. Se evaluó el efecto de la composición de la malla sobre el crecimiento acumulado en área y volumen de *Montastraea cavernosa*, cuantificado mediante fotogrametría (Structure from Motion, SfM). Asimismo, se compararon los tiempos de operación en vivero (manejo, adhesión y limpieza) y durante el trasplante en campo, con y sin uso de mallas.

Resultados: No se detectaron efectos estadísticamente significativos de la composición de la malla sobre las tasas de crecimiento durante el período evaluado. El crecimiento promedio en área osciló entre 0.5 y 0.8 mm^2, con interacción significativa entre tratamiento, tanque y tiempo, evidenciando bajo crecimiento y alta variabilidad entre tanques. El incremento volumétrico varió entre 0.25 y 0.62 cm^3, sin diferencias significativas entre tratamientos. Sin embargo, el uso de mallas redujo el tiempo de manejo en vivero en aproximadamente 20 minutos por estantería de 18 fragmentos.

Conclusiones: Independientemente de su composición, las mallas biodegradables constituyen una alternativa viable para optimizar la propagación asexual mediante microfragmentación, mejorando la eficiencia operativa sin comprometer el crecimiento coralino.

Palabras clave: crecimiento coralino; sustratos biodegradables; restauración; innovación tecnológica.

INTRODUCTION

Climate change and local stressors are driving rapid changes on coral reefs ecosystems at local, regional and global scales (Pandolfi et al., 2003; Perry & Alvarez-Filip, 2019). Ocean warming, diseases, coastal development, and uncontrolled use of reef resources is leading to extensive coral mortality across different bioregions (Alvarez-Filip et al., 2011; Reverter et al., 2024; Williams et al., 2019). Currently, corals are the taxa facing the greatest chances of extinction; and in the Western Atlantic region, about 40 % of coral reef builders have been recently classified as threatened species according to the IUCN criteria (Gutierrez et al., 2024). In the Dominican Republic, the status of coral reefs is critical, as coral diseases and bleaching have triggered extensive mortalities on reef-building corals (Croquer et al., 2024). Thus, finding scalable solutions to repopulate coral populations must be a priority.

Coral restoration has become an increasingly popular strategy to confront the coral reefs crisis (Rinkevich, 2005; Vardi et al., 2021). Over the past two decades, coral restoration projects have expanded as restoration practitioners from NGOs and academic institutions continuously engage in these efforts. Sexual and asexual propagation of corals, substrate

enhancement and ecosystem-based approaches, such as the introduction of herbivores, are common approaches for coral restoration (Boström-Einarsson et al., 2020). Despite recent advances in coral reef restoration being undisputable, there are still different bottlenecks to overcome, particularly finding more cost-effective and scalable solutions. In fact, intervention scalability and coral restoration costs are perhaps the most challenging operational problems waiting for feasible solutions (Mulà et al., 2025).

For years, the development of new technologies such as substrates with different forms and chemical composition has played a al., 2020; Foo & Asner, 2019; Suggett et al., 2023). central role in leading and guiding coral restoration efforts (Boström-Einarsson etEcologists, biologists, scientists and engineers, have made significant investments to develop coral culture techniques, monitoring devices, artificial reefs/substrates and molecular tools to identify more resistant corals (Schmidt- Roach et al., 2025). Our ability to culture corals through assisted coral reproduction (Edwards et al., 2024; Randall & Szmant, 2009; Sellares-Blasco et al., 2021) and microfragmentation (Forsman et al., 2015; Knapp et al., 2022) has improved as the result of cumulative knowledge on coral reproductive biology and ecology. Our capacity to outplant corals has also increased with the advent of drone technology to spread out propagules, and Structure from Motion (SfM) combined with remote sensing tools to select outplanting sites (Foo & Asner, 2019; Schill et al., 2021) and to monitor the outcomes of interventions (Koch et al., 2021). However, coral restoration practitioners still face challenges to fulfill and scale up cost-effective solutions for their coral restoration goals as thousands of sexual and asexual propagules/outplanting units are often handled individually.

Amongst various techniques, microfragmentation is one of the most used by restoration practitioners (Boström-Einarsson et al., 2020; Page et al., 2018), particularly in the Caribbean where land-based facilities have expanded (Bayraktarov et al., 2020; Young et al., 2012). The rationale of the technique is to promote faster growth as a physiological response of a colony when it is cut down into small (1–4 cm) pieces (Forsman et al., 2015). While this technology has clear advantages as it is affordable and easy to implement, the process of microfragmentation is stressful for the corals and injured animals require individual attention. In addition, individual handling and cleaning of each coral microfragment is time demanding.

Over the last 15 years, Fundacion Puntacana (FPC) has led coral restoration based on asexual propagation of corals in the Dominican Republic. The Center of Marine Innovation (CIM 1.0) land-based facility is currently producing 500–600 coral microfragments per tank/quarter and the projected capacity at CIM 2.0 will increase by 2.5-fold. As established production expands, FPC's coral restoration program requires developing more cost-effective and efficient strategies to outplant corals to keep up with coral production schemes. One potential solution is to reduce time of handling during the outplanting phase with meshes that maximize coral growth and survivorship.

Restoration often demands the use of nonbiodegradable artificial substrates as stabilizers of sessile fauna such as oysters and corals (Boström-Einarsson et al., 2020; Comba et al., 2023). Plastics have been widely used to provide a stable frame for nurseries, but there are concerns about their potential threat to marine biodiversity (Walters et al., 2022). Thus, efforts to move from nonbiodegradable-plastic restoration to biodegradable or plastic-free approaches have been identified as a priority (Comba et al., 2023; Walters et al., 2022), particularly in coral restoration projects (Leonard et al., 2022; Lott et al., 2020). Two common biodegradable polymers used are PCL-50 (Polycaprolactone, semicrystalline polyester) and CAPA-6800 (Caprolactone-based polymer). They are both biodegradable polycaprolactones, but PCL-50T degrades faster in seawater and yields smoother surfaces, while CAPA-6800's higher molecular weight provides greater hydrolytic stability, toughness, and durability, resulting in slower

seawater degradation and slightly rougher processed surfaces (Table 1).

Recently, Seafoundry introduced the idea of using biodegradable meshes made of a mix of biodegradable plastic and calcium carbonate ($CaCO_3$) to facilitate the outplanting phase. Increasing calcium carbonate makes both polymers stiffer and less ductile, with PCL-50T losing toughness faster while CAPA-6800 retains more durability (Table 2). However, finding the best combination and/or proportion of materials that are rough and stable, enhance coral growth and dissolve quicker in the reef is an important step to better assess the feasibility of this solution. In this paper, we aimed at testing two plastics mixed with different concentrations of CaCO3 to determine if this technology represents a solution to decrease operation time and costs in an expanding land-based coral nursery.

MATERIALS AND METHODS

Experimental design: We conducted a multifactorial controlled experiment using a fully randomized block design (i.e., each treatment is present in each of the replicated blocks) to test the effect of mesh composition on coral growth using *Montastraea cavernosa* as a model system (Fig. 1). The experiment included three factors: (1) material type (fixed factor with seven levels of treatments): (a) 100 % CAPA-6800 + 0 % CaCO3, (b) 100 % PCL-50T + 0 % CaCO3, (c) 80 % CAPA-6800 + 20 % CaCO3, (d) 80 % PCL-50T + 20 % CaCO3, (e) 90 % CAPA-6800 + 10 % CaCO3, (f) 90 % PCL-50T + 10 % CaCO3 and (g) ceramic plugs as controls. (2) Time (fixed factor with 6 monitoring times): T1 (November 2023), T2 (December 2023), T3, (January 2024), T4 (February 2024), T5 (March 2024), T6 (April 2024) and (3) Block (random factor with three levels): tank 1, tank 2 and tank 3. The design had a total of eight different sources of interpretable variation including main effects, random variability, interactions between factors and the residual (Table 3).

All treatments were repeated in each block (i.e. independent tanks) to control potential

Table 1
Contrasting physicochemical properties of PCL-50 and CAPA-6800 polymers. The COCa3 concentrations were set to maximize contrasting properties.

Properties	PCL-50T	CAPA-6800
Polymer Type	High–molecular-weight polycaprolactone (>10,000), supplied as 2–3 mm pellets.	High-molecular-weight PCL (~80,000), granular 3 mm pellets.
General Biodegradability	Biodegradable PCL is used in medical, film, adhesive, and composite applications.	Biodegradable, compostable (EN13432), used in adhesives and bioplastics.
Biodegradation in Seawater (Expected Behavior)	Faster degradation is likely due to lower molecular weight; PCL shows measurable weight loss (~10 wt. % in blends) under seawater exposure.	Slower degradation is expected because of higher molecular weight and enhanced stability, still biodegradable but less rapidly in seawater.
Surface Roughness After Processing	Smoother surfaces are expected because lower viscosity allows more uniform flow.	May show slight roughness from occasional high-viscosity inclusions during processing.
Hydrolytic Stability	Standard PCL: moderate hydrolytic stability.	High hydrolytic stability: low moisture absorption, no pre-drying needed.
Thermal Stability	Typical PCL behavior; low melting point ~60 °C.	Melting point 58–60 °C; stable when stored below ~50 °C.
Mechanical Durability	Moderate durability; lower tensile properties vs. CAPA-6800.	Very high elongation (~800 %); excellent flexibility, tear and impact resistance.
Best Use-Case Fit	Applications prioritizing biodegradation rate, lower viscosity processing, and surface smoothness.	Applications require high toughness, flexibility, long-term stability, and slower degradation.

Information extracted from Engler et al. (2023), JinJiang Shengjin Technology CO. (2023), Perstorp Holding AB. (nd), Special Chem (2026), and TRiiSO (2018).

Table 2

Expected changes on physicochemical properties of PCL-50 and CAPA-6800 polymers when mixed with low (1–10 %), intermediate (10–30 %) and high (30–60 %) concentrations of Calcium Carbonate.

Category	PCL-50T	CAPA-6800
Low $CaCO_3$ Loading (1–10 %)	Slight stiffness increases; noticeable loss of ductility.	Slight stiffness increases; minimal loss of ductility due to high native flexibility.
Medium Loading (10–30 %)	Much stiffer; more brittle; rougher surfaces due to particle exposure.	Stiffer but retains better toughness; minor roughness increase; still more durable than PCL-50T.
High Loading (30–60 %)	Strong brittleness; significant loss of flexibility; processing difficulty increases.	High rigidity but retains some toughness; viscosity increases substantially during processing.
Surface Roughness	Roughness increases significantly as $CaCO_3$ rises; smoother at baseline.	Roughness also increases; baseline may show slight inclusions already.
Hydrolytic Stability	Moderate stability: $CaCO_3$ slightly slows water diffusion but overall, still degrades faster.	High hydrolytic stability maintained; $CaCO_3$ further reduces water ingress.
Biodegradation (including seawater)	Degradation slows with filler but remains faster than CAPA-6800.	Degradation slows further due to higher MW and reduced water penetration.
Processing Behavior	Handles low–moderate filler well; viscosity climbs at high loadings.	Already high viscosity: $CaCO_3$ increases shear demands more strongly.
Durability	Durability drops quickly with filler; becomes brittle at moderate–high loadings.	Remains more durable at all filler levels due to inherent strength and elongation.

The COCa3 concentrations are set to increase contrasting effects on these properties for both polymers (information extracted from TRiiSO (2019).

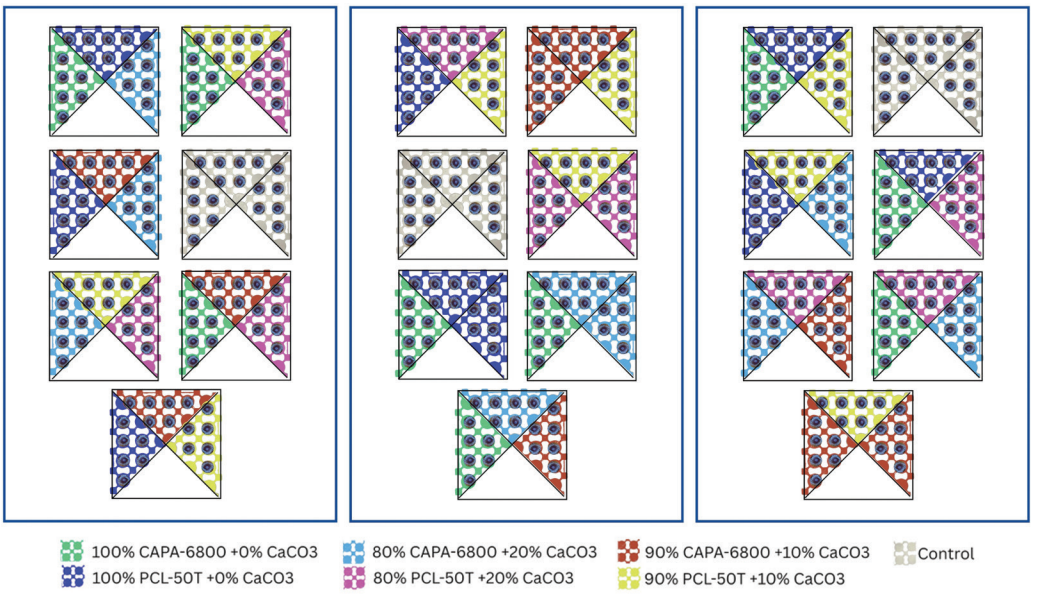

Fig. 1. Layout of experimental design. Tanks S1, S2 and S3 contain 7 treatments in triplicates randomly assigned into each replicated pyramid and tank (block). Each color represents a treatment that repeats within each block. Each treatment had six *Montastraea cavernosa* microfragments (i.e., operation units or observations).

Table 3
Multivariate permutation analysis of variance (Permanova) based on Euclidean distance for cumulative growth (area and volume) of *Montastraea cavernosa* microfragments over six months.

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms
Ta	**2**	**5.5292**	**2.7646**	**5.0057**	**0.016**	**999**
Tr	6	25.069	4.1782	0.98271	0.448	998
Ti	**5**	**30.977**	**6.1954**	**8.8502**	**0.002**	**998**
TaxTr	**12**	**50.411**	**4.201**	**7.6065**	**0.001**	**999**
TaxTi	10	7.1582	0.71582	1.2961	0.23	999
TrxTi	30	38.611	1.287	1.1805	0.303	999
TaxTrxTi**	**46**	**50.264**	**1.0927**	**1.9785**	**0.005**	**998**
Res	1560	861.57	0.55229			
Total	1671	1082.8				

** Term has one or more empty cells. / Tank, Time, tank-Time interaction and tank-treatment-time interactions shown as significantly different (in bold).

environmental variability. For each of the seven treatments (mesh composition) we had 7 meshes per tank (21 mesh total) with six microfragments (n = 126 observation/replication units) per mesh (Fig. 1). Coral microfragments were randomly assigned to meshes and then each mesh was randomly assigned to each tank to minimize potential uncontrolled effects within each block (e.g. coral genotype and environmental variation among tanks).

Coral microfragments were obtained from two different colonies (genets/unknow genotypes) using standard microfragmentation procedures (Page et al., 2018). Microfrags were plugged with instantaneous super glue into each of the replicated meshes and monitored for six months.

Dependent variables: Coral growth rate is a key variable for establishing the performance of microfragmentation land-based facilities (Koch et al., 2021). In our experiment we estimated growth rates by measuring cumulative changes in area and volume for a six-month interval (Equation 1 and Equation 2). Rather than estimating individual growth rates for each microfragment, we determine the performance of the population of microfragments (hereafter referred to as cohort) for each treatment. Cumulative growth rate is an additive function standardized by the initial mean size of the microfragment, so that average change in size and/or volume can be compared among fragments that do not have the same initial size. Contrary to the growth rate slope which can take negative values, cumulative growth is easier to interpret as it is always a positive function quoted by the average initial size of the cohort of microfragments (Equation 1 and Equation 2).

(Equation 1)

$$CGa = \mu + \frac{At - At'}{Ao}$$

where C_{Ga} = cumulative growth expressed as area, μ = Cohort average area of microfragments, AT = average estimate area in a specific period, Ao = average estimate area when the experiment began, AT' = average estimate area at the end of experiment

(Equation 2)

$$CGv = \mu + \frac{Vt - Vt'}{Vo}$$

where C_{Gv} = cumulative growth expressed as volume, μ = Cohort average volume of

microfragments, Vo = average estimate volume when the experiment began, VT = average estimate volume in a specific period, VT' = average estimate volume at the end of experiment

Instead of following individual growth for each microfragment, average estimated size and volumes of the cohort of microfragments were calculated using standard procedures on SfM techniques, allowing precise tracking of cumulative growth over time using 3D models. Briefly, 3D models were built from videos of coral microfragments recorded each month. Following the protocol outlined by Agudo-Adriani et al. (2016) and Agudo-Adriani et al. (2019) videos captured with a GoPro 10 (8k resolution) were first cut into frames, then stitched using overlapping matching points to build sparse and dense meshes using Agisoft Metashape Professional version 1.8.5 (Agisoft LLC, 2022). For each mesh one tag was used to align and calibrate repeated models over time. From these 3D models, orthomosaics were created and from these we extracted accurate measurements of coral surface area and volumetric changes monthly (Fig. 2).

In addition, we recorded several environmental variables in each tank (i.e., salinity, temperature, alkalinity, Calcium and Magnesium) every morning for five months. Salinity and temperature were measured with a waterproof sensor (H198319), whereas alkalinity and minerals were measured with colorimetric water quality kits (Salifert). Photosynthetic Active Radiation (PAR) every day in the morning (8–10:30 h) and in the afternoon (14:30–17:30 h) using a quantum meter device (Apogee instrument, MQ-510).

Statistical Analysis: A permutational multivariate analysis of variance (PERMANOVA; Anderson, 2005) based on Euclidean Distance was used to test significant effects of treatment, time, and block on coral growth. This method was chosen due to its robustness in handling complex ecological datasets and its ability to account for both fixed effects and random variation within the experimental design (Anderson & Walsh, 2013). Furthermore, the test is more flexible than others (e.g. Mantel test) for normality and homogeneity of dispersion (Anderson & Walsh, 2013). However, before running the PERMANOVA we checked for homogeneity of dispersions for each of the main factors and interactions using the PERMDISP test (PERMANOVA; Anderson, 2005). In order to visualize if there were patterns for the cumulative growth rates (area and volume)

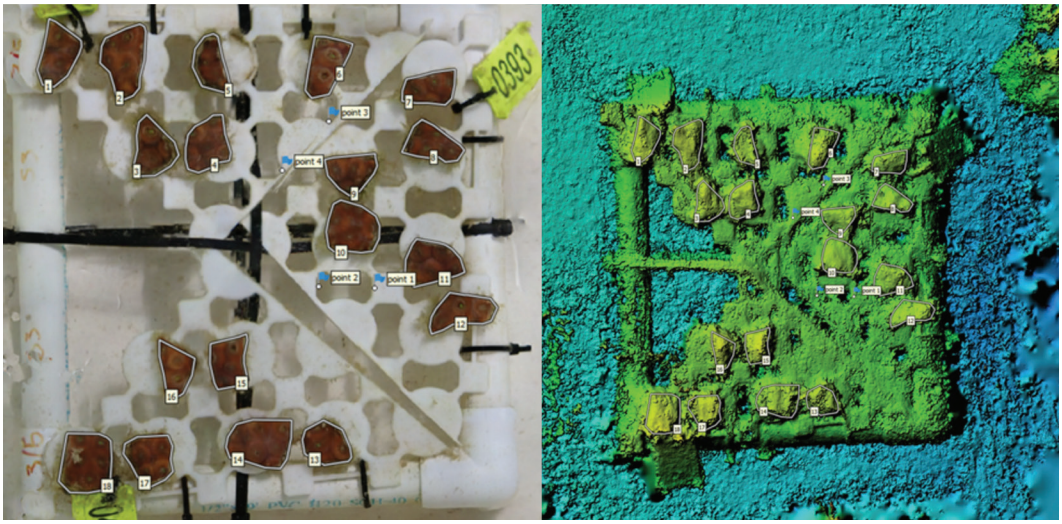

Fig. 2. 3D models of M*ontastraea cavernosa* microfragments derived from SfM to estimate cumulative growth expressed as surface and volume.

between treatments, a metric multidimensional scaling (MDS) based on Euclidean distance was used computed from a z-score normalized matrix (z = value of each cell – mean of the column/standard deviation) because both variables are expressed in different units (Clarke & Gorley, 2005). Centroids and 95 % confidence intervals of each treatment were estimated and represented in the metric ordination space using bootstrapping (100 simulations). Finally, to avoid pseudoreplication individual fragments were nested within each mesh. All statistical analyses were conducted using PRIMER 7 with PERMANOVA+ (Anderson, 2008).

RESULTS

We observed no mortality on any of the 126 coral microfragments monitored during five months in each of the three tanks and seven treatments. The area and volume of coral microfragments were positive but moderately correlated (Fig. 3). After 5 months, average growth for the microfragment cohort of *M. cavernosa* varied from 0.5 to 0.8 mm^2 (Fig. 4A). In terms of area, the lowest cumulative growth was recorded for CAPA-6800 80 % and 90 %, whereas the largest was observed for 80 % PCL-50T (Fig 4A). The volumetric cumulative growth ranged from 0.25 to 0.62 cm^3, with highest averages being recorded for 80 % PLC 50T (Fig. 4B). Cumulative growth expressed as area and volume was extremely variable in time within and between treatments with initial sizes varying from 2.5 to 3.3 cm^2 and 0.5 to 1.25 cm^3, respectively (Fig. 5A, Fig. 5b). While microfragments never stopped growing, for some treatment growth slowed down during the experiment (Fig. 5A, Fig. 5b).

The analysis of variance based on permutations (PERMANOVA) showed no significant effects of the treatments (pseudo-F = 0.98, df =6, p =0.48) on area and volume (Table 1). Instead, we found a significant interaction between time-treatment-tank (pseudo-F = 1.98, df = 46, P = 0.005) (Table 1), further indicating that coral microfragment cumulative growth for each of the treatments followed a different temporal trajectory in each tank. We found little variation in salinity, temperature, alkalinity, Calcium and Magnesium concentrations; however PAR recorded during the morning, and the afternoon was more variable among tanks (Table 4).

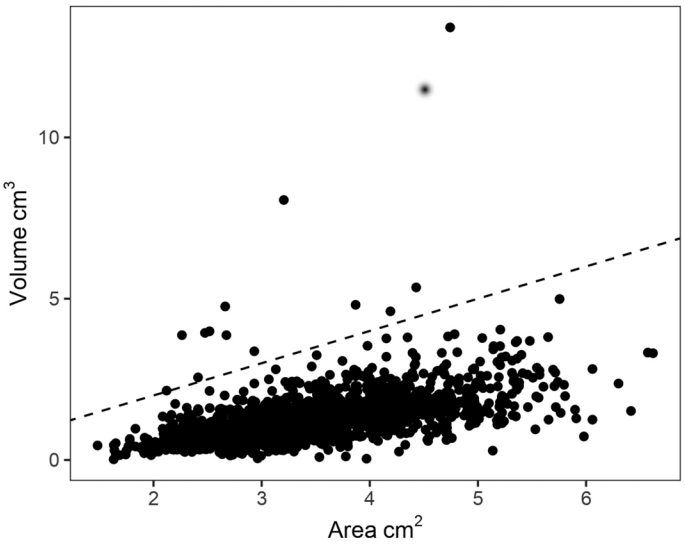

Fig. 3. Scattered plot between final volume and area of *Montastraea cavernosa* mic-rofragments used in the experiment and monitored for six months. Spearman correlation R = 0.64.

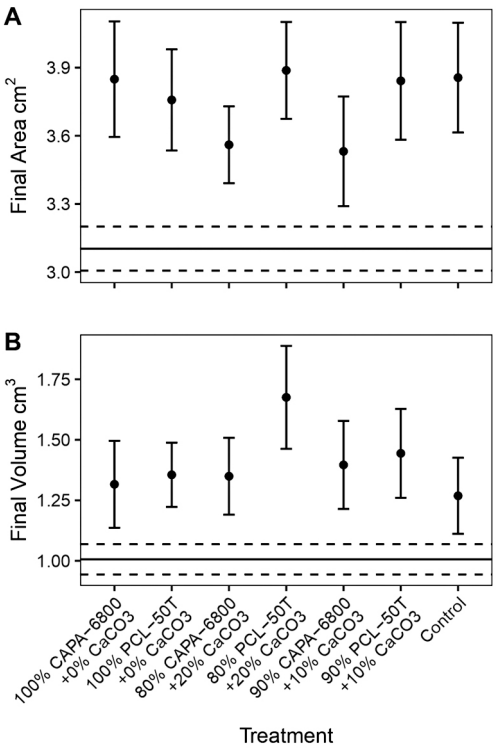

Fig. 4. Cumulative average growth for *Montastraea cavernosa* microfragments expressed **A.** in area and **B.** volume for different treatments after six months. Solid lines represent the initial average of the cohort (μ) and dote lines the 95 % confidence interval. The control consisted of ceramic plates, which is the material normally used in our operations. Note homogenous dispersion among groups.

Additionally, there was a statistically significant interaction between tank x treatment, which indicates that changes in surface and volumetric cumulative growth between treatments were not consistent among tanks (pseudo-F = 7.6, df = 12, p = 0.001) (Table 1). Cumulative growth (area and volume) was different at the beginning (T1), after three (T3) and five months (T5) in the tanks S1 (Fig. 6A) and S2 (Fig 6B), whereas in the tank S3, cumulative growth overlapped between T1 and T3 to become different at T5 (Fig. 6C).

Furthermore, there was a statistically significant effect for the factor time (pseudo-F = 8.85, df = 5, p = 0.002) and tank alone (pseudo-F = 5.01, df = 2, p = 0.01) (Table 1, Fig. 7). The bootstrap analysis confirmed there were no patterns for the treatments further supporting that chemical composition of the meshes had no effect on cumulative growth (Fig. 7). Largest differences in growth rates were observed at the beginning and by the end of the experiment and were not attributable to the chemical composition of the mesh (Fig. 6). Despite the lack of statistical significance in mesh composition, we found operational advantages of using meshes, both in the land-based facilities and during the outplanting (Table 5). For land-based facilities, labelling and handling was approximately 5–8 times faster when using meshes compared to ceramics, whereas the cleaning process was ten times faster. The most important advantage of using meshes during the outplanting phase is the number of fragments, which are duplicated with almost half of dives (Table 5).

Averages for land-based operations are calculated from 30 repetitions during a five-month period. Average for coral outplanting is calculated from 3 independent outplanting events conducted with volunteers.

Table 4

Average and standard deviation (SD) for physicochemical variables recorded in the three experiment tanks (blocks) during five months of experimentation. PAR m (Photosynthetic active radiation recorded in the morning 8-10:30 h), PAR a (Photosynthetic active radiation recorded in the morning 14:30-17:30 h)

Tank	Salinity (g/kg)	Temperature (°C)	Alkalinity (mval/L)	Calcium (ppm)	Magnesium (ppm)	PAR m (μW/m2/s)	PAR a (μW/m2/s)
1	35.26 ± 1.69	26.49 ± 1.45	7.74 ± 1.06	392.81 ± 47.37	1339.2 ± 104.85	275.1 ± 12.90	59.75 ± 11.01
2	35.26 ± 1.63	26.35 ± 1.04	7.77 ± 0.94	394.45 ± 45.23	1341.15 ± 106.04	337.5 ± 27.53	53.75 ± 13.15
3	35.26 ± 1.61	26.49 ± 1.21	7.75 ± 0.86	396.95 ± 44.13	1339.19 ± 103.78	360.2 ± 14.14	50.5 ± 23.80

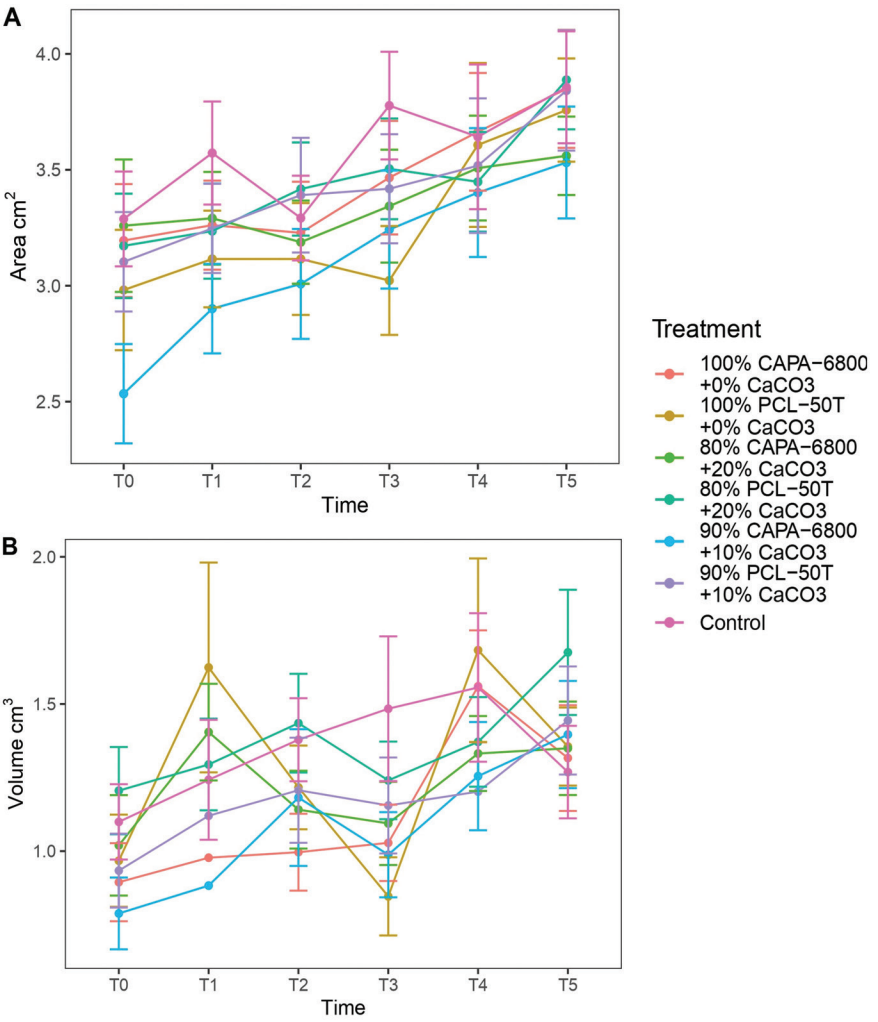

Fig. 5. Temporal trend of average (SD) cumulative growth of *Montastraea cavernosa* micro-fragments expressed **A.** in area and **B.** volume. Note homogenous dispersion among groups.

DISCUSSION

Our results indicate that the chemical composition of biodegradable meshes is not a determining factor to influence cumulative growth rates of *M. cavernosa* fragments. However, this technology provides a series of advantages that facilitate the regular operations in the laboratory and in the field, which represent a significant improvement for our asexual propagation coral restoration program. Biodegradable meshes have been increasingly used to cope with plastic pollution in the ocean (Suzuki et al., 2021; Wang et al., 2021). In the field of coral restoration, several authors have urged coral restoration practitioners to use biodegradable materials (Boström-Einarsson et al., 2020; Gomez et al., 2010; Kenyon et al., 2025; Leonard et al., 2022; Strudwick et al., 2023; Strudwick et al., 2024) because nonbiodegradable plastics have been shown to have deleterious effects on corals (Strudwick et al., 2024).

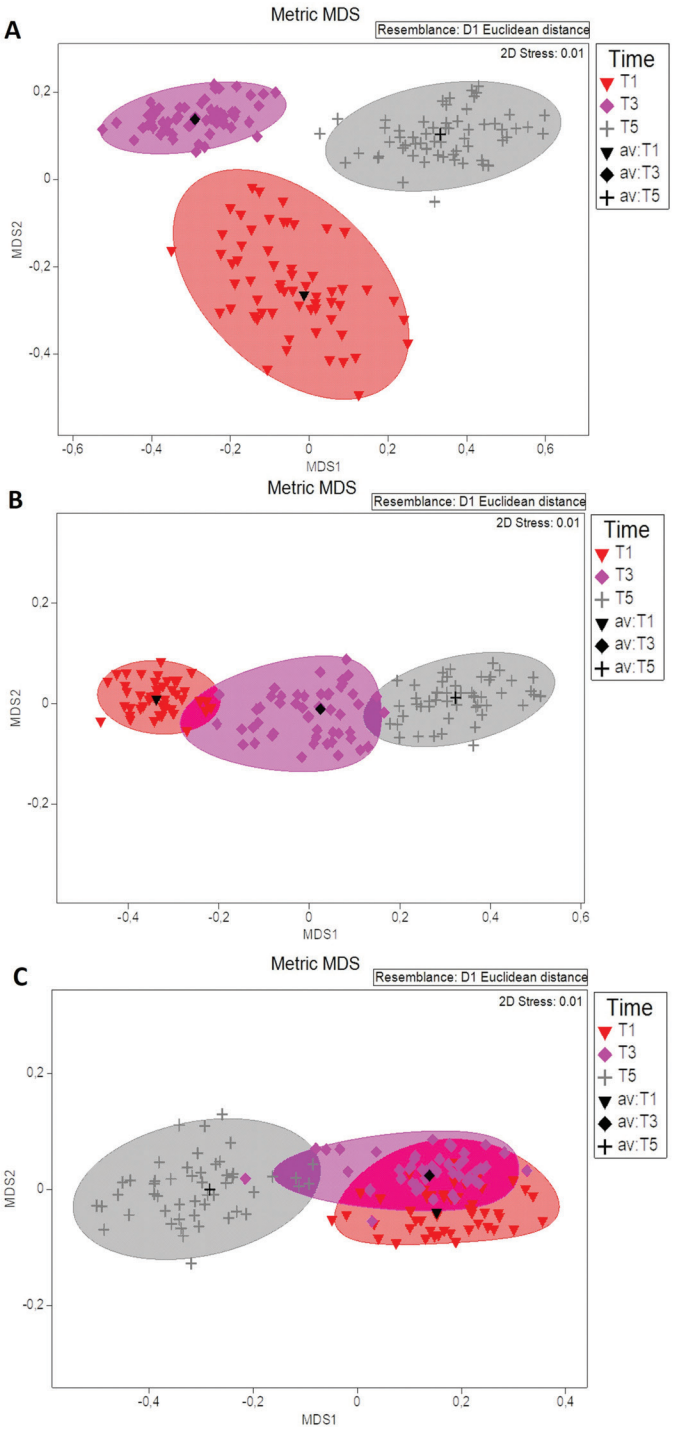

Fig. 6. Metric Multidimensional Scaling (MDS) showing bootstrapped averages of treatment by tanks regardless of time and treatment (A: tank S1, B: tank S2 and C: tank S3). Sampling times 1, 2 and 3 are only included to depict the larger differences in cumulative growth.

Table 5
Average and standard deviation (SD) expressed in minutes for different activities when using ceramics (for land-based operations) and pyramids (for coral outplanting).

Activity	Ceramics		Mesh	
	Average	SD	Average	SD
Labeling	1.36	0.06	0.29	0.03
Handling	0.81	0.02	0.10	0.01
Cleaning	56.18	65.90	5.90	1.46
plugging	0.96	0.03	0.87	0.03
Activity	Pyramids		Mesh	
	Average	SD	Average	SD
Dive time	42.50	0.89	38.90	0.78
Number of divers	2.50	1.01	1.20	0.89
Number of units	102.33	32.10	91.90	5.30
Number of micro-fragments	722.10	50.60	1331.80	14.80

Advantages of plastic biodegradable meshes for coral restoration: Land-based nursery operations depend on a series of interconnected processes that must be bound to specific objectives (Forsman et al., 2006; Forsman et al., 2015). For example, live support systems and scheme production of coral microfragments must be coordinated since the arrival of donor colonies, during the period of quarantine and microfragmentation, monitoring in the laboratory and transplantation of the microfragments into the reef. Biodegradable meshes facilitate this workflow in different ways.

First, when donor colonies are cut, practitioners do not need to plug microfragments into individual pedestals, they can use the mesh as a single unit bearing multiple surfaces. From our observations, this advantage allows faster manipulation of the asexual fragments which reduces stress in the colonies. Another advantage is increased efficacy and control to monitor the performance of the microfragments in the laboratory (Rivera et al., 2023). By plugging corals into a mesh, practitioners can track growth rate and survivorship of multiple fragments by monitoring a single unit. In terms of data collection, it is easier to identify microfragment cohorts from specific genotypes by linking the mesh to a specific donor colony. As for maintenance, because of the flexibility of the mesh, practitioners can twist and flip the mesh to remove algae from specific areas, while the unit, rather than individual rigid pedestals, are cleaned. In five months, we observed no mortality on the 126 fragments attached to biodegradable plastics and the ones plugged into ceramic plugs; further suggesting no visible toxic and/or adverse reactions to the meshes at least during a six-month period and for the species *M. cavernosa*.

Advantages of meshes to improve outplanting operations: One of the biggest challenges and bottlenecks of microfragmentation is in the outplanting phase (Mies et al., 2025). In the past, different technologies have been used to plug coral microfragments when outplanted into the reefs. Ceramic, cement plugs, and pyramids are amongst the most popular solutions to attach microfragments into the substrate (Mostrales et al., 2022). Normally, individual plugs are deployed close to each other to foster the fusion of microfragments either to re-skin partially dead colonies or to form new colonies (Page et al., 2018).

Whether or not the outplants survive, the process demands extensive hours in the field as coral microfragments must be handled

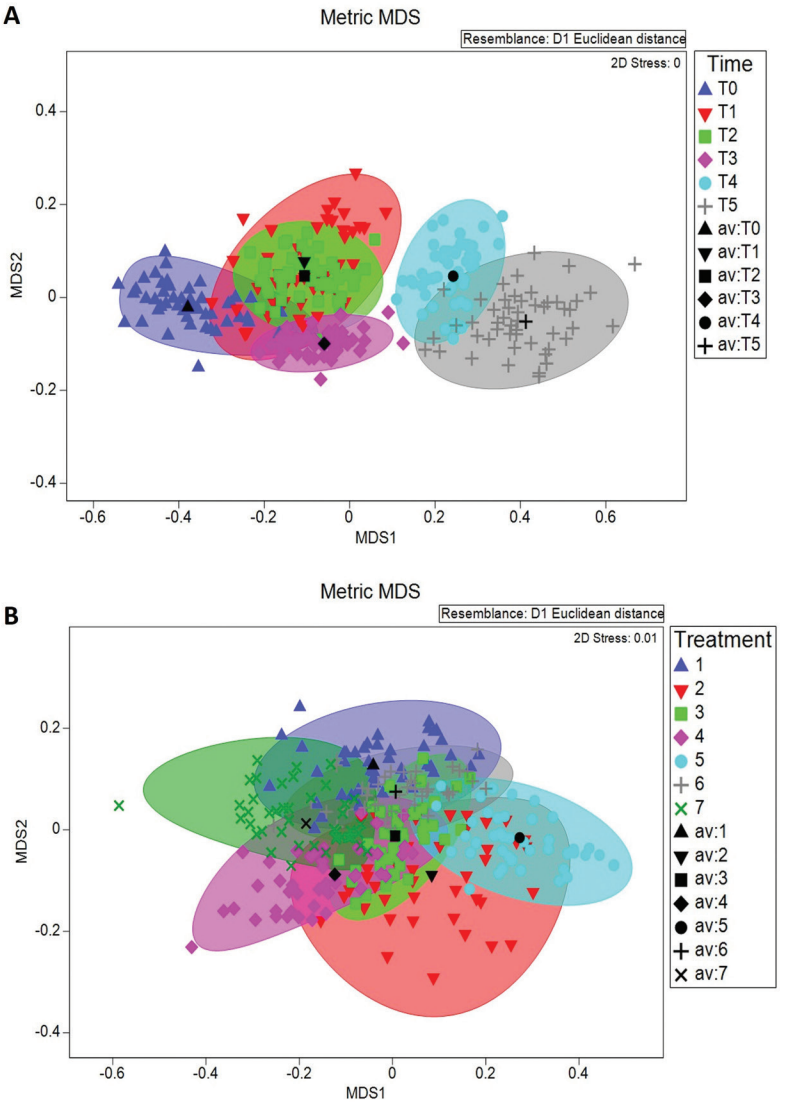

Fig. 7. Metric MDS, showing bootstrapped averages of temporal change in **A.** volume and area regardless of treatments (mesh types) and **B.** between treatments regardless of time, represented in a Euclidean ordination space.

individually on the boat and in the water. In the case of ceramic plugs, in our experience, each one must be deployed and fixed on the reef or on the pyramids which takes substantial effort. Biodegradable meshes represent a unique solution for these challenges as tens of coral microfragments can be plugged as a single unit, each microfragment having an optimal distance to grow and fuse faster with others. In terms of monitoring, the units can be easily allocated, while the performance of cohorts from different coral donor genotypes can be tracked in a simpler way. The mesh breaks down in about 12 months without compromising the fusion among microfragments (Rivera et al., 2023).

Our experiment indicates that the composition of the meshes is not a limiting factor to use this technology as cumulative growth expressed

in area and volume was similar for all combinations of materials tested. Thus, fragment growth is likely influenced by other environmental or biological factors not controlled in our experiment rather than the substrate's chemical properties. Potential uncontrolled sources of variation in growth rates can be divided into biological (e.g. coral genotypes), environmental, physical and chemical properties of the water and ecological (i.e., the interaction between biological and ecological variables).

Growth rates as a function of the coral genotype, mutualistic interactions and environmental adaptation: We found a significant interaction between time, treatment (mesh composition) and blocks (tanks), further indicating that temporal trajectories of cumulative growth of *M. cavernosa* recorded for each mesh composition were inconsistent between tanks. While our study was not designed to determine the underlaying physical, chemical and biological processes that explain this trend, we encourage coral restoration practitioners to design experiments with replicated tanks to account for this source of variation. However, we hypothesize that uncontrolled factors in the experiment such as the coral genotype/microbiome, slight variations in the environmental conditions prevailing in each tank and a combination of these two, could be responsible for the observed statistically significant interaction.

Growth rates in corals are highly influenced by genotypes and the community of photo symbionts associated with corals. In *Acropora cervicornis* coral nurseries, growth rates have been shown to be extremely variable depending on the genotype and the local environment (Drury et al., 2017; Jones & Berkelmans, 2010; Ladd et al., 2017; Lirman et al., 2014). In natural habitats, coral growth rates have been shown to be affected by light (Enochs et al., 2014; Gutierrez-Estrada et al., 2025) and temperature (Crabbe, 2007); and at larger spatial scales by the saturation of aragonite and magnesium concentration in the water column (Dullo, 2005; Martin-Garin & Montagonni, 2023; Mavromatis et al., 2022; Pratchett et al., 2015).

Like in natural habitats, coral growth in land-based facilities and aquariums have also been shown to vary depending on a series of environmental variables. Normally, corals in natural habitats grow faster compared to ones held in tanks (Yap & Alvarez-Molina, 2003). However, with recent advances in aquarium technologies, growth rates and survivorship of corals maintained in land-based facilities might perform similar to wild corals. According to Borneman (2008), there are 8 tenet variables to control to optimize growth and survival of corals in a husbandry: (1) temperature, (2) salinity, (3) pH, (4) nitrites, (5) phosphates, (6) photosynthetic active radiation (PAR), (7) calcium saturation and (8) alkalinity. While all these variables are controlled in the Center of Marine Innovation of Punta Cana, our system is semi open, which explains the slight variations of physicochemical settings recorded among tanks that could have influenced the outcome of the experiment (Table 4). The position of each tank within the husbandry and the position of the mesh and the treatment within each tank may have influenced the effective PAR levels reaching the colonies and therefore, their growth rates. Our results highlight the importance of robust replication following experimental design standards (*i.e.*, true replication of treatments in experimental units, random assignment of operation units and treatments and valid experimental arrays) to test the benefits of applied technologies for coral restoration.

Finally, other biological factors such as biofouling communities that establish in the tanks have been shown to have a positive impact on coral microfragment growth (Page et al., 2023). Tanks in Punta Cana have different biofouling communities, most of them dominated by CCA and algal turfs in different proportions. Despite the statistical lack of effects of mesh composition on coral microfragment growth, our results demonstrate that biodegradable meshes as a substrate to plug and outplant corals have practical advantages. We found this technology is a feasible solution to improve handling of microfragments as well as monitoring and

outplanting procedures inside our land-based facility. More specifically, for a laboratory that produces 4000 microfrags every year with 4 permanent staff dedicated to monitoring corals per week, a 5–8 reduction in operation time (e.g. handling and cleaning), would have a positive impact to increase coral production using the same staff or to reduce staff while keeping coral production.

Suggestions and study limitations: The use of biodegradable materials for asexual coral propagation is promising. Our study showed clear operational advantages, particularly to reduce invested time, both in land-based facilities and in the field during outplanting. However, our experiment had several limitations. First, large variability of cumulative growth between tanks limited conclusions about the effect of mesh composition. Secondly, the experiment was run for 5 months, which might be too short for a species with slow growth rates. Finally, we did not control the genotypes, which is an important factor to determine growth rates. Future experiments should be planned for at least one year and include genotype as a factor with more blocks (thanks) replicated.

In conclusion, biodegradable meshes tested in this study represent a solution to optimize intensive workflows, both in the laboratory and in the field. The meshes are easy to handle; they do not affect coral growth and/or induce mortality on microfragments. While we acknowledge there were uncontrolled factors not included in the experiment (e.g. coral genotype, coral microbiome and microenvironments within and between thanks), our results remain valid because coral microfragments were randomly assigned to each treatment and to each tank. Therefore, the error is completely random and unbiased, and it is properly computed and captured in the residual of the PERMANOVA model.

Author contribution statement: Andreina Rivera executed and monitored the experiment, collected and transcribed data, interpreted results and wrote the manuscript. Shamwari Anseeuw performed the experiment, produced 3D models, collected and transcribed data and wrote the manuscript. Maria L. Ceballos performed the experiment, produced 3D models, collected and transcribed data. Scott Macdonald designed and provided the meshes. Ainhoa L. Zubillaga contributed to the experimental follow-up and manuscript final revision. Rebecca Garcia-Camps contributed to marine operations for coral colony collections. Aldo Croquer conceived and designed the experiment, performed statistical analysis and wrote the paper.

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