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The Gulf of Trieste as a potential site for *Spongia officinalis* sponge farms: An opportunity for sustainable cultivation and recovery?

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ABSTRACT

Over time, sponges have become increasingly demanded on the market not only for their traditional cosmetic use, but also for emerging applications in the biomedical, pharmaceutical, industrial sectors and as effective bioremediators. This steadily growing exploitation, driven by continuous market demand, has resulted in a significant decline in natural sponge stocks worldwide. In this context, sponge aquaculture represents a sustainable and promising alternative, as it can reduce harvesting pressure on wild populations while simultaneously acting as a source of propagules for surrounding areas. The present study aimed to assess the suitability of the Gulf of Trieste as site for the establishment of sponge farms for the cultivation of *Spongia (Spongia) officinalis*. The cultivated individuals exhibited a high growth rate during the study period (up to 250% over three years). However, a relatively high mortality rate (60–90%) was observed during the initial phase of the experiment, likely associated with handling stress and manipulation prior to fixation on the farming structures. After this early phase, mortality decreased markedly, and survival rates stabilized. In conclusion, our findings suggest that the Gulf of Trieste represents a promising site for the cultivation of *S. officinalis*, thanks to the observed high growth potential. Nevertheless, the success of sponge farming in this area strongly depends on careful collection, handling, and fixation procedures, emphasizing the need to minimize stress during the early stages of cultivation.

1. Introduction

The Mediterranean commercial bath sponge, *Spongia (Spongia) officinalis* Linnaeus, 1759 (Demospongiae, Dictyoceratida), is a widely distributed species in the Mediterranean Sea and one of the most historically significant marine resources (Voultsiadou, 2007). For centuries, the soft and absorbent spongin skeleton has made this species a highly valued commodity for bath and industrial uses (Çelik et al., 2011; Pronzato et al., 1999; Verdenal and Verdenal, 1987). Beyond this traditional role, the genus *Spongia* was also demonstrated as a prolific source of a diverse array of bioactive metabolites with biomedic and pharmaceutical potential (anti-inflammatory, antibiotic, antitumoral properties, etc.) (Osinga et al., 1999; Pronzato and Manconi, 2008; Sipkema et al., 2005; Tang et al., 2018, 2022; Tian et al., 2023). Plus, sponges are now key characters in integrated multi-trophic aquaculture (IMTA) where they act as efficient filters for the organic particulate waste from fish farms, thereby reducing the environmental impact of aquaculture (Aguilo-Arce et al., 2023; Amato et al., 2024; Gokalp et al., 2020; Khanjani et al., 2022; Pronzato et al., 1999). Furthermore, this ability to accumulate microbial pollutants, including culturable heterotrophic bacteria, vibrios, and fecal indicator bacteria, highlights their potential not only as bioremediators in impacted ecosystems but also as bioindicators of water quality (Aguilo-Arce et al., 2023; Cebrian et al., 2007; Khanjani et al., 2022).

This dual commercial and biotechnological interest, over time, led to excessive pressure on wild populations. In the last decades, the natural populations of *S. officinalis* across the Mediterranean have faced severe declines (Gerovasileiou et al., 2018; Grenier et al., 2023). This depletion is attributed to the synergistic effects of overfishing and catastrophic disease outbreaks, notably in the late 1980s, which caused mass

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mortality events bringing sponge populations near the brink of local extinctions in some areas (Cerrano et al., 2000; Corriero et al., 2004; Di Camillo et al., 2012, 2013; Gaino et al., 1992, 1992; Kružić et al., 2016; Pronzato, 1999; Pronzato and Manconi, 2008; Rivetti et al., 2014).

Nowadays, the global supply of natural bath sponges falls far short of demand, creating a pressing need for sustainable production methods (Çelik et al., 2011). In response to the collapse of wild fisheries, sponge aquaculture has been proposed as a sustainable alternative. Sponge aquaculture typically involving the transplantation of sponge fragments has emerged as a promising solution to mitigate fishing pressure on wild stocks and meet market demands. Cultivation techniques, primarily involving the suspension of these sponge cuttings on ropes in the water column, have been developed and refined in time, showing a good potential (Bierwirth et al., 2022; Duckworth, 2009, 2003; Motta et al., 2025; Oronti et al., 2012). However, growth performance is highly variable and influenced by environmental parameters such as temperature and water hydrodynamics, food availability, and farming protocols, underscoring the need for region-specific and species-specific cultivation studies (Bierwirth et al., 2022; Çelik et al., 2011; Corriero et al., 2004; Duckworth, 2009).

Beyond its commercial value, *S. officinalis* is an efficient suspension feeder in hard-bottom communities, playing a crucial role in benthic-pelagic coupling. It processes vast volumes of water, efficiently retaining particles from bacterioplankton to nanoeukaryotes (Reiswig, 1973; Stabili et al., 2006; Topçu et al., 2010; Trani et al., 2021; Varamogianni-Mamatsi et al., 2021). This intense filtration activity positions *S. officinalis* as key player in controlling water quality.

Given the critical status of its natural populations and its multi-functional role, research on *S. officinalis* is more relevant than ever. This study aimed to assess the feasibility of cultivating *S. officinalis* in the Northern Adriatic Sea by deploying sponge cuttings across three distinct sites and involving two different farming technologies (line and net farming). The success of cultivation in each location and with each technology will be quantitatively evaluated by monitoring the key biological performance parameters: growth rate and mortality rate of the explants. We hope that our findings will provide a solid base for identifying the optimal "site-technology" combination for the sustainable development of sponge aquaculture in this region.

2. Materials and methods

2.1. Study area

This study was conducted from 2011 to 2015 in the Gulf of Trieste (northern Adriatic Sea, Italy; 45°42′05.4″ N, 13°42′50.4″ E), where the distribution of *Spongia officinalis* has significantly decreased over recent decades (Di Camillo et al., 2013; Fedra et al., 1976; Stachowitsch, 1984) (Fig. 1).

This shallow, semi-enclosed basin spans an area of around 500 km^2 with an average depth of approximately 16 m, with maximum depths reaching up to 25 m in some areas (Ogorelec et al., 1991; Petranich et al., 2018). The region is known for its complex hydrodynamics, including strong river inflows, seasonal fluctuations in temperature and salinity, and notable influences from meteorological events such as the strong and cold Bora wind (N-NE wind; Petranich et al., 2018; Raicich et al., 2013). Plus, this environment is heavily influenced by anthropogenic activities, including maritime transport, coastal industries, fishing, and tourism, which can have significant ecological implications for the region (Bajt, 2014; Cibic et al., 2008; Pagano et al., 2023; Petranich et al., 2018).

These conditions make the Gulf of Trieste a unique and challenging environment for marine research, particularly with regard to the feasibility of sponge farming, the focus of this study.

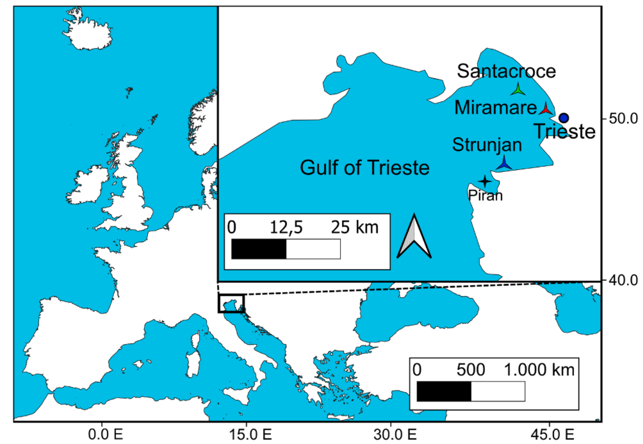

Fig. 1. Study area. The three farming sites are highlighted: Miramare (Red), Santacroce (Green), Strunjan (Blue). The black star indicates the source of specimens, Piran (Slovenia). Trieste (Italy) was reported as geographical reference.

2.2. Collection of specimens and experimental setup

Although *Spongia officinalis* is native to the Gulf of Trieste, local specimens were deemed unsuitable for commercial purposes due to their irregular shapes and bad quality, based on an expert evaluation that we specifically commissioned from specialists at the Rosenfeld sponge factory in Muggia (Trieste). Therefore, healthy and commercially viable specimens were collected from the near Gulf of Piran (Slovenia, 20 km from Trieste) to ensure high-quality samples and avoid the introduction of non-native species. The donor sponges (approximately 200) were excised using a knife to obtain 3–4 fragments around 400 cm^3 in volume per donor. One third of donors bodies were left to promote recovery, following Duckworth and Battershill (2003). Sponge specimens were temporarily placed in holding tanks (60 ×60 x 60 cm) prior to deployment. Three sites were chosen for the farming setups (Fig. 1).

The first selected farming site was inside the Miramare Marine Reserve, located approximately 100 m offshore at an average depth of 9.5 m. The design of the sponge cell was based on the methods outlined by Oronti et al. (2012) and Motta et al. (2025), incorporating six strands, each consisting of five modules spaced 105 cm apart. At the base, 15 kg concrete blocks were placed, each featuring a vertical steel rod (1 m in length and 19 mm in diameter). Two nylon twines, coated with bitumen, were anchored at two different heights on the rods (15 cm and 45 cm from the top) and stretched across the bars within the same strand. Each twine supported 24 sponges, for a total of 288 along the 6 strands (whole cell) (Fig. 2A-B).

The second main site was located within the Strunjan Nature Park in Slovenia, selected for its environmental characteristics, such as a sandy substrate and lower epifaunal colonization compared to more coastal areas. A different support system was used at this site, consisting of six 1 m^2 plastic mesh panels (Fig. 2C-D) fixed to the dead bodies at two different depths (9 m and 9.5 m), with sponge fragments attached in rows (6 rows of 6 sponge per row for each net, 2 depths, total 216 sponges). The tanks containing the sponges destined for the first and second sampling sites were transported overland by van, with a total transit time from departure to immersion at the destination sites of approximately 2–3 h.

The third site was The Dosso di Santa Croce, located 3 nautical miles from the coast at an average depth of 12.5 m, selected for its greater depth, reduced epifaunal colonization, and protected status. The same net structure of Strunjan was adopted (Fig. 2E-F). In this case, to minimize stress on the sponges, transport times were reduced as much as possible (the sponges were transported by sea, not by car) as well as the time required for cutting and bundling the pieces, which were carried

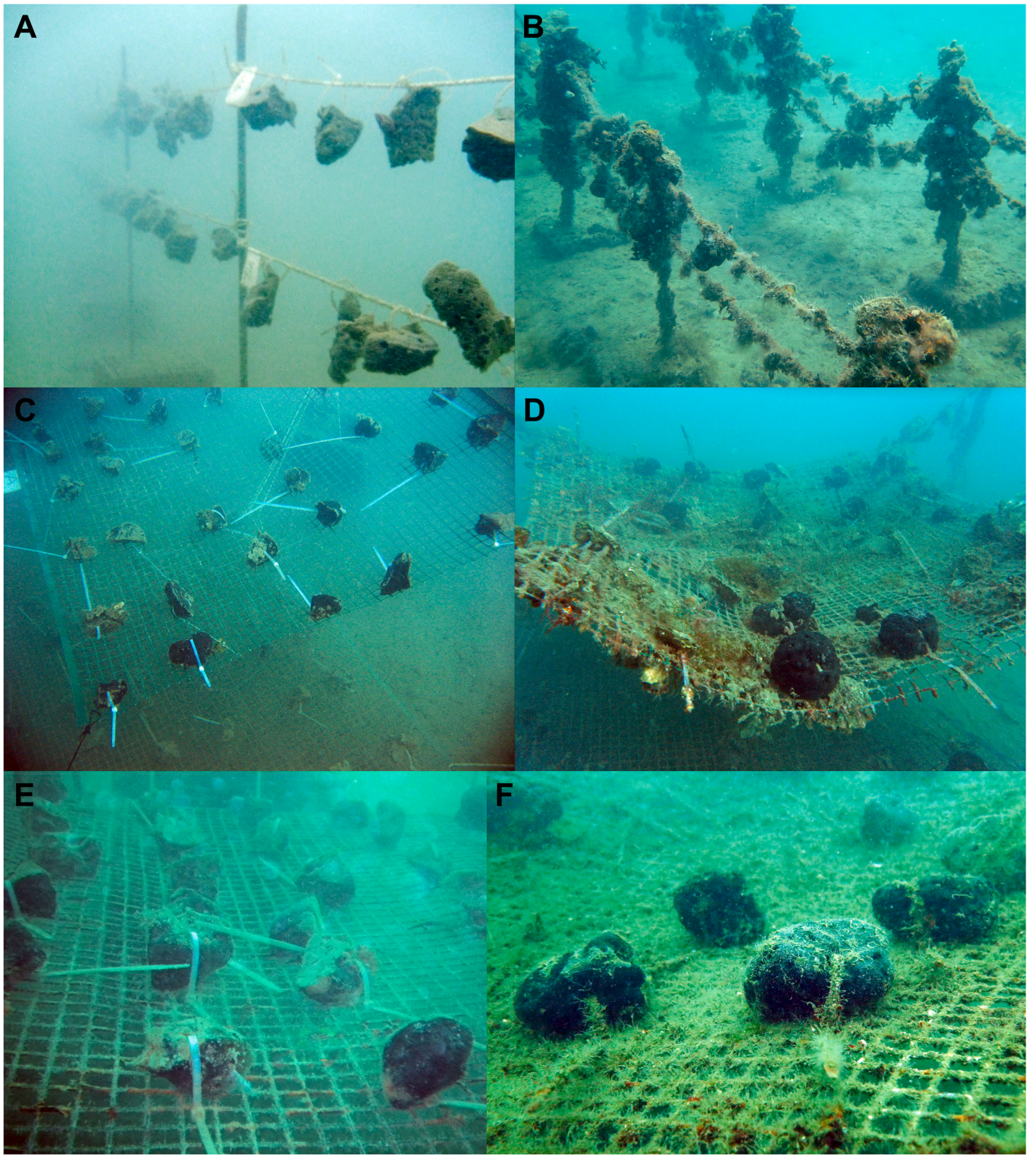

Fig. 2. Experimental setups at the three stations in the Gulf of Trieste. (A) Miramare, t0. (B) Miramare, t3; evident the settlement of many epibionts and in the foreground the lack of several sponges. (C) Strunjan, t0. (D) Strunjan, t2; here too, the settlement of various epibionts on the surface of the net is evident. (E) S. Croce, t0. (F) S. Croce, t2; note the lower settlement of epibionts on the network. Sandy surfaces of the sponge fragments in t0 indicate the fresh cutting surfaces.

out aboard the vessel. At this site, transport was carried out by sea, reducing the transfer time by approximately half compared to site 1 and 2.Sponge specimens were measured prior to deployment, and three consequent measurements t1-t3 (Miramare had two more samplings, t1.5 and t4) after 300, 600, and 1000 days from initial setting were performed for each site (Table 1). Measurements were performed during diving sessions with precision calipers assessing the three main axis of the sponges (length, width, height: x, y, z). The ellipsoid volume was chosen as reference (Formula 1).

Table 1
Sampling dates for sponge measurement at each site.

Site	Miramare	Santacroce	Strunjan
t0	10/10/2011	18/09/2012	03/08/2012
t1	08/06/2012	17/07/2013	03/04/2013
t1.5	23/10/2012	/	/
t2	18/06/2013	10/08/2014	16/09/2014
t3	22/08/2014	14/08/2015	14/08/2015
t4	01/07/2015	/	/

$$Sponge\ (ellipsoid)volume = \frac{4}{3}\pi xyz$$

Formula 1. Ellipsoid volume.

For monitoring purposes, photographs were taken to track sponge development, while the influence of epibionts, such as mussels, was also recorded.

2.3. Histological analysis for monitoring tissue regeneration and pathological processes

To monitor early tissue regeneration and detect potential pathological signs following fragmentation and implantation, a subset of sponge fragments was designated exclusively for histological analysis. These fragments were part of the aquaculture stock but were not included in the growth measurement census. Sampling was conducted at two key time points: an early stage (approximately 1.5 months post-implantation at the Miramare site) and a later stage (8 months post-implantation at all sites: Miramare, Strunjan, and Dosso di S. Croce). For comparative baseline analysis, wild specimens were also collected from the vicinity of the Miramare and Strunjan sites where naturally occurring populations were present.

Collected sponge fragments were immediately processed for histology. Primary fixation was carried out for 2 h at 4°C using 2.5% glutaraldehyde in a 0.2 M sodium cacodylate buffer (pH 7.25), supplemented with 0.36 M NaCl and 3 mM $CaCl_2$. Following fixation, samples were washed three times (10 min each) in a 0.2 M sodium cacodylate buffer (pH 7.25) containing 0.5 M NaCl and 3 mM $CaCl_2$. Post-fixation was performed for 1 h with 1% osmium tetroxide (OsO_4) in 0.2 M sodium cacodylate buffer (pH 7.25) containing 3 mM $CaCl_2$ and 0.49 M NaCl. Samples were then washed twice (10 min each) in the same buffer, followed by a final 10-minute wash in distilled water at room temperature. A graded ethanol series was used for dehydration: 30% ethanol (20 min), 60% ethanol (20 min), 90% ethanol (20 min), and three changes of 100% ethanol (20 min each).

For light microscopy (LM) observation, processed samples were mounted on glass slides. Observations were conducted using an Olympus BX50 microscope, employing both bright-field and Nomarski differential interference contrast (DIC) optics.

For scanning electron microscopy (SEM), dehydrated samples were critical-point dried using CO_2 as the transition fluid. Dried specimens were mounted on SEM stubs and sputter-coated with a gold-palladium alloy film. Examination and imaging were performed using a LEICA Cambridge Stereoscan 430i scanning electron microscope.

2.4. Environmental variables

The three main environmental variables (seawater temperature, chlorophyll-a, salinity) were gathered from satellite data on Copernicus Marine Service (1987–2025 for temperature and salinity; 1999–2025 for Chl-a). Details for products and data are reported in Table S1.

All variables were analyzed using the R package “heatwaveR” (Schlegel and Smit, 2018) to investigate their extremes (anomalies over the 90th or under the 10th percentile, based on a climatology, lasting at least 5 days) and to obtain a more detailed picture of their variations along the study period.

2.5. Statistical analysis

To analyze growth rate, four Generalized Linear Mixed Models (GLMMs) were applied. GLMMs models considered sponges growth as dependent variable in relation with different factors. The first model was applied to the full dataset (three-site model) and included time, zone (Miramare, Strunjan, Santacroce), and row position (upper vs. lower) and their interactions as fixed effects, sample ID was included random effect. Models 2, 3, 4 were site-specific GLMMs fitted separately for Miramare, Santacroce, and Strunjan, respectively. In these models, growth was analyzed as a function of row position, time, and their interaction, sample ID was included random effect. All models summaries and statistics are reported in Table S2-S3.

In parallel, the same model structures were applied to assess sponge survival. Four binomial GLMMs were applied, with the outcome variable as alive (0) or dead (1) in relation with Rows (upper-lower), and (2) Zones (Miramare – Strunjan - Santacroce), and their interaction with time (t0-t3), Sample ID as random factor (Table S2-S3).

All statistical analyses were conducted in R statistical environment (v.3.6.2; R Core Team, 2024), using the *stats* package (R Core Team, 2024), *lme4* (Bates et al., 2015), and *emmeans* (Lenth, 2023).

3. Results

A total of 720 sponges (Miramare, 288; Strunjan, 216; Santacroce, 216) were measured four times (t0-t1-t2-t3) during a 3-year period (Miramare had two more samplings dates, t1.5 and t4) (Fig. 3, Table 2).

3.1. Growth and mortality analysis

Growth rates were different on different sites (Table 2). Miramare recorded the highest growth rate at t3 (250%), followed by Strunjan (155%) and Santacroce, which recorded the lowest mean volume at t3 (113%). Statistical differences are shown in Fig. 4.

At structure level, no differences were found between the upper and lower row in Miramare and Strunjan, while in Santacroce higher-lower volumes were recorded at the end of the study (Table S2).

A total of 134 out of 720 sponges (18.5%) survived after the three

Table 2
Sponge growth summary. Mean Volume and Standard deviation (expressed in cm^3), mean growth rate % and standard deviation for each site and time are reported. n = number of individuals.

Zone	Time	n	Mean Volume	Std Volume	Mean Rate	Std Rate
Miramare	t0	287	419.40	167.42	0.00	0.00
	t1	109	458.64	157.43	14.00	32.81
	t1.5	33	696.81	246.68	96.67	129.12
	t2	16	568.07	285.37	34.46	67.14
	t3	17	1385.27	880.64	251.08	224.08
	t4	15	2405.40	1587.93	518.59	400.44
Santacroce	t0	213	458.10	196.91	0.00	0.00
	t1	94	391.80	175.72	−18.43	27.06
	t2	87	682.09	335.53	48.32	68.47
	t3	87	967.02	503.25	113.39	110.47
Strunjan	t0	204	438.42	164.82	0.00	0.00
	t1	33	451.96	216.30	13.85	44.77
	t2	30	774.35	523.01	103.27	133.79
	t3	30	1006.46	595.35	155.33	151.08

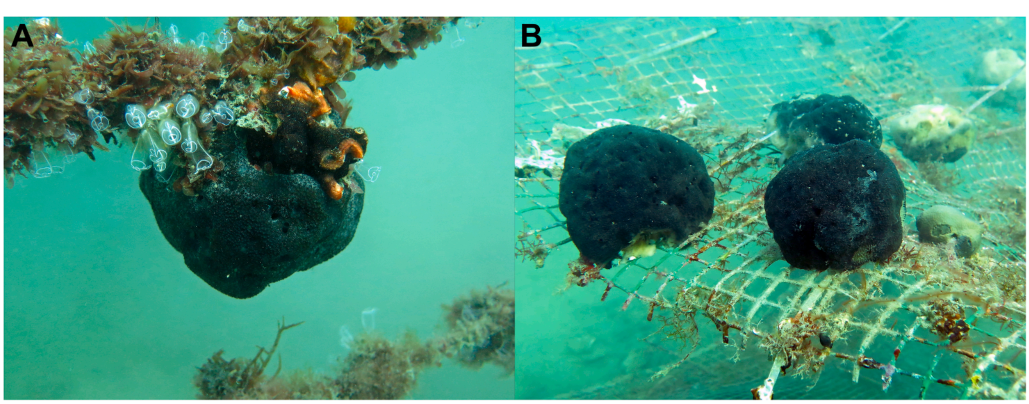

Fig. 3. Growth of the sponge fragments at t3. (A) Miramare, with some ascidiaceans, *Clavelina lepadiformis*, and a partial covering of an encrusting bryozoan. (B) Strunjan.

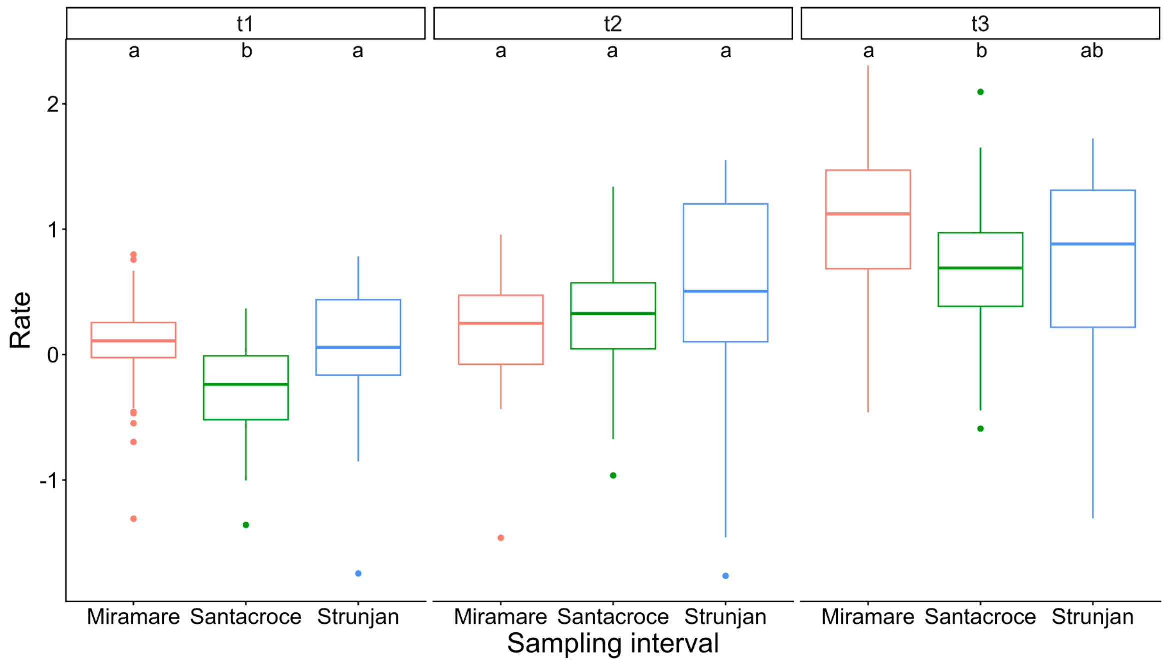

Fig. 4. Growth of *S. officinalis* for each farming site: Miramare (Red), Santacroce (Green), Strunjan (Blue) at different time intervals (t1-t3).

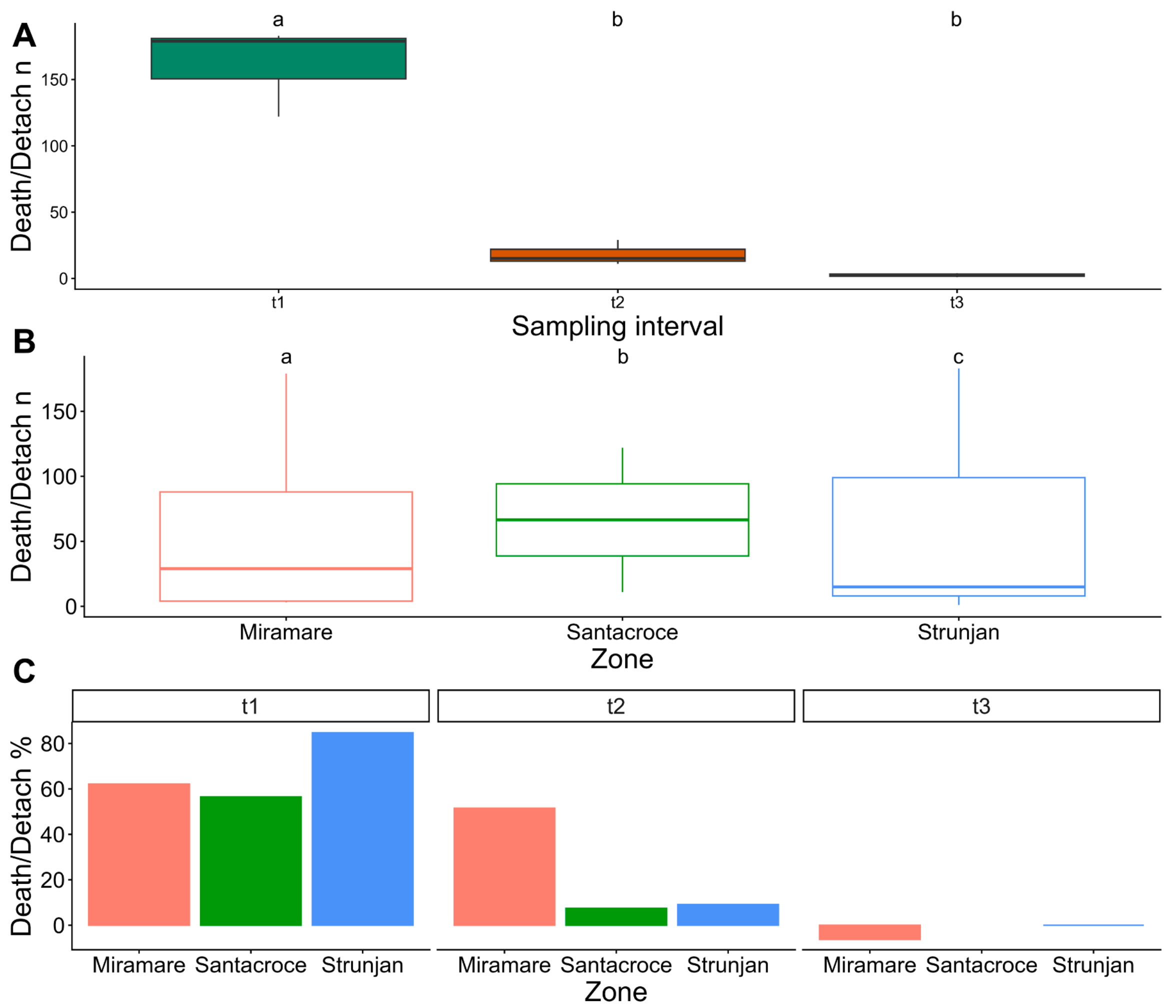

Fig. 5. Mortality analysis of *S. officinalis* for (A) each sampling time (t1, dark green; t, orange; t3, black); (B) each sampling site: Miramare (Red), Santacroce (Green), Strunjan (Blue). (C) Percentage of dead individuals for each farming area and sampling time.

years of study, 586 sponges were lost (81.5%) (Figs. 5–6).

In details, Miramare lost the highest number of individuals (94%), followed by Strunjan (86%) and Santacroce (60%). The highest detach/death of individuals happened between t0 and t1 (Table 3). No difference in mortality was observed between rows in each site (Table S2-S3).

3.2. Histological observations: tissue and structural skeleton

All samples examined from the three breeding sites showed no internal structural anomalies or differences compared to the control samples. The cortical tissue areas, not affected by the cutting process, appeared homogenous across all samples. No signs of degenerative processes indicative of ongoing pathology were observed in any of the samples examined, whether taken a month and a half post-implantation (Miramare) or eight months post-cutting (from all three breeding sites). Specifically, neither superficial nor internal tissue areas showed any evidence of pathological degeneration. Consequently, it was not possible to identify, based on either macroscopic or microscopic observations, any characteristics or "indicators" that could predict the subsequent survival or mortality of the regenerated sponge fragments after several months.

3.3. Environmental variables and anomalies

Anomalies for temperature (Heatwaves and Cold spells), together with Chl-a and salinity, are reported in Fig. 7. Except for a cold wave registered between march and February 2012, temperature never fell below the 10th percentile during the period of study. Differently, short heatwaves were registered each summer. High Chl-a values were recorded in correspondence with each winter season in correspondence with winter storms and water column mixing. Salinity showed the most variability throughout the study period.

Table 3
Mortality of *Spongia officinalis* for each Time and Site. The number of dead individuals for each time are reported per time interval and refer to the alive individuals at the previous time interval, rather than to cumulative mortality.

Time	Zone	Alive individuals	Dead individuals
t0	Miramare	288	0
t1	Miramare	109	179
t2	Miramare	16	93
t3	Miramare	17	0
t0	Santacroce	216	0
t1	Santacroce	94	122
t2	Santacroce	87	7
t3	Santacroce	87	0
t0	Strunjan	216	0
t1	Strunjan	33	183
t2	Strunjan	30	3
t3	Strunjan	30	0

4. Discussions

The farming of marine sponges has gained increasing importance in recent decades, both as a solution to the continuous decline in the natural stocks of these organisms due to overfishing and diseases, and as a source of organisms to be used for biomedical, pharmaceutical, or biofiltration purposes in aquaculture systems (Duckworth, 2009; Gaino et al., 1992; Rivetti et al., 2014). In the Mediterranean Sea, where *Spongia officinalis* has experienced a drastic decline in abundance, establishing sponge farms may also serve as high-density zones of these organisms, promoting the dispersion of propagules, fragments, and larvae parenchimulae into surrounding areas, with the potential to assist in the repopulation of natural stocks (Leong and Pawlik, 2010a, 2010b).

Growth rate, the most important indicator of sponge farm efficiency, along with mortality (Duckworth, 2009; Mohite et al., 2020), in this study varied across different sites, with low values recorded at Santacroce, while higher values of 155% and 250% were measured at

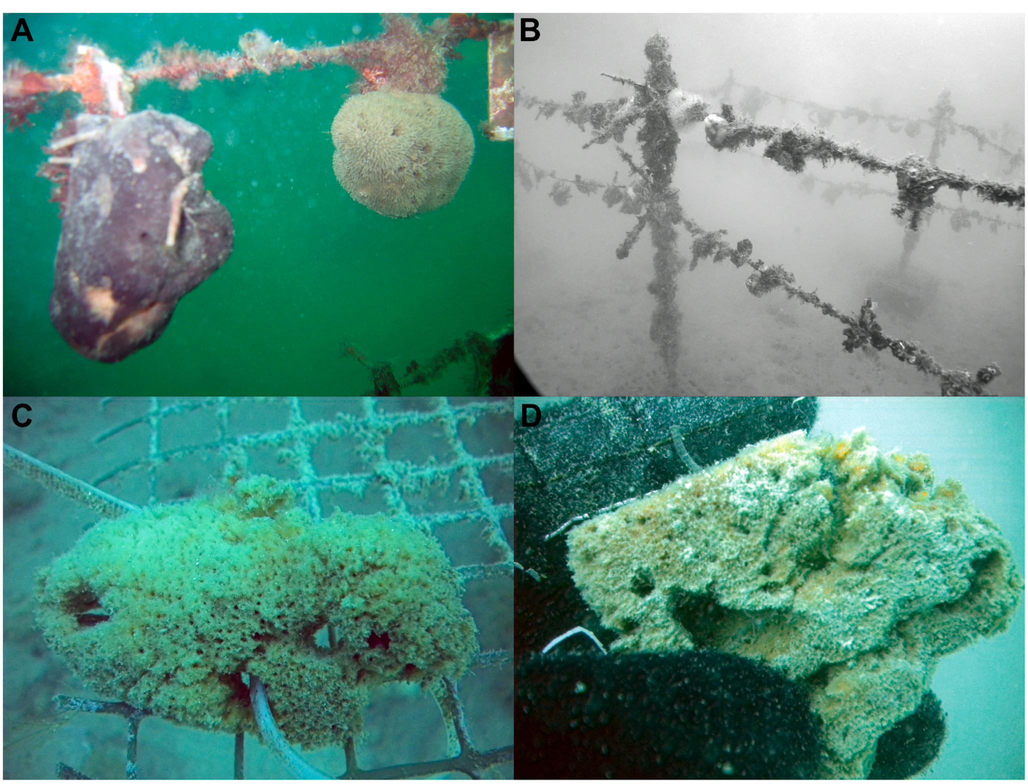

Fig. 6. Some examples of dead sponges. (A) Miramare t1. In the background a dead sponge. (B) Miramare t3. In the foreground the lower row is devoid of sponges. (C) Strunjan t2. In the foreground a dead sponge. (D) S. Croce t1. A dead sponge.

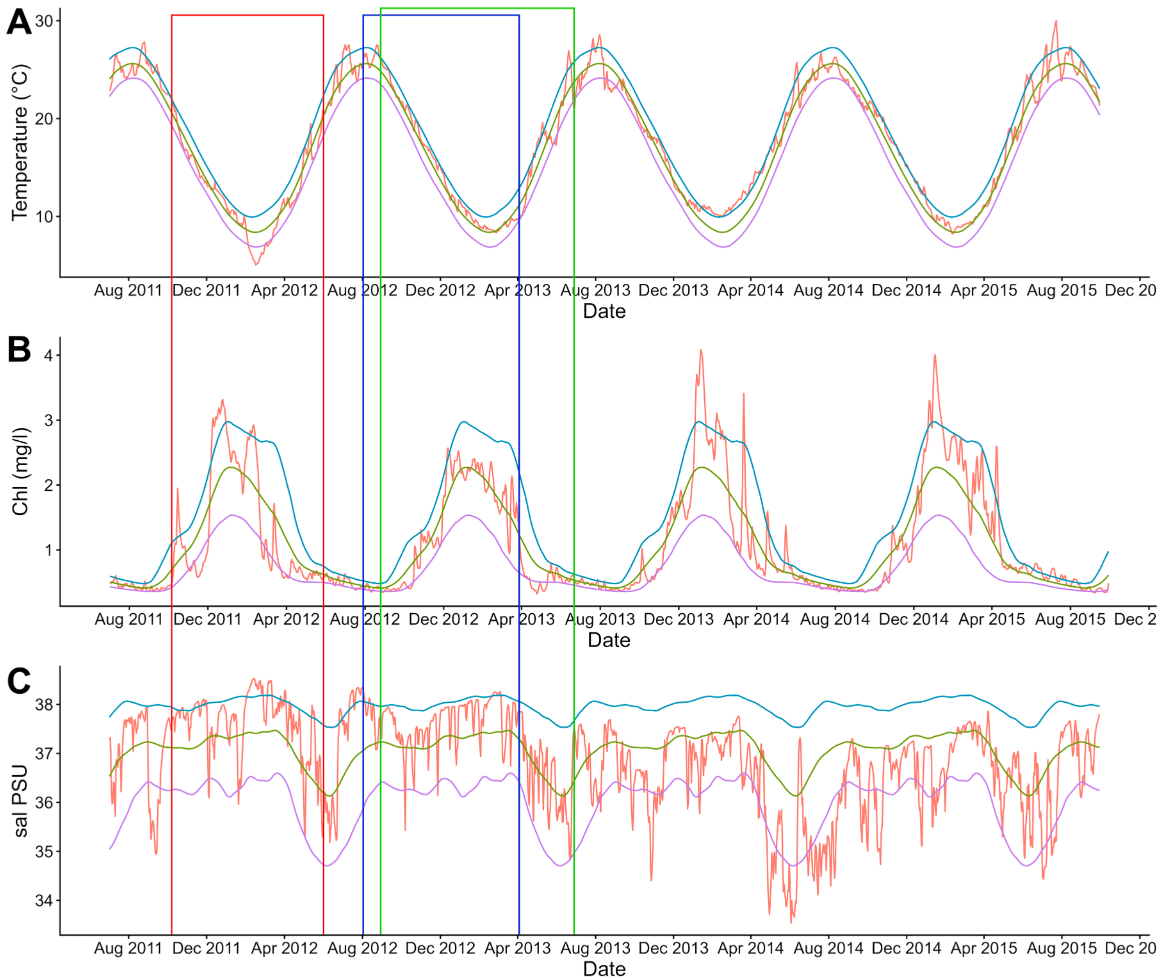

Fig. 7. Environmental variables and anomalies for (A) Temperature, (B) Chlorophyll-a, (C) Salinity. The red line is the observed daily value, green indicates the climatology, the 90th and 10th percentile are indicated by the blue and purple line, respectively. Colored vertical lines and brackets indicate the interval between t0 and t1 (where most mortality was observed) for each site: Miramare (Red), Santacroce (Green), Strunjan (Blue).

Strunjan and Miramare, respectively.

Miramare recorded the higher growth at t3, but, looking at t2, its rate was much lower than the other sites, thus showing a high acceleration in volume increase during that time interval. However, this site was hit by high mortality and detachment that undermined the overall estimation. Inshore sites like Miramare and Strunjan may be subjected to greater water turbulence and stronger planktonic blooms compared to offshore locations, which can enhance the presence of nutrients in the water column, thus potentially boosting sponge growth, especially in the Gulf of Trieste, which is subject to strong winds, particularly during the winter season (Bora winds up to 130 km/h).

Indeed, turbulence has been demonstrated to exert a strong influence on sponge growth and survival depending on its intensity. Moderate water motion enhances the flux of particulate and dissolved organic matter and prevents the accumulation of sediment on the sponge surface (Duckworth et al., 1997; Vogel, 1974). This level of flow sustains high pumping and filtration rates, improving sponge growth and reproductive output (Leys et al., 2011; Reiswig, 1971). In our study, hydrodynamic turbulence, coupled with the naturally eutrophic conditions of the northern Adriatic (Marini and Grilli, 2023), likely acted as a positive driver of sponge growth, enhancing food supply and promoting favorable conditions for filtration and nutrient uptake. Conversely, when turbulence is too strong, and in co-occurrence with elevated sediment loads, suspended particles exert abrasive forces that can damage the pinacoderm, clog the aquiferous system, and lead to tissue necrosis (Gerrodette and Flechsig, 1979; Nava and Carballo, 2013; Pineda et al., 2016), resulting in reduced pumping activity, growth rates, and in some cases leading to complete arrest of filtration and mortality (Ávila et al., 2011; Motta et al., 2025).

The lower growth rate measured at Santa Croce could be related to the more offshore nature of this site, where less nutrients are available compared to coastal areas, whereas it exhibited a lower presence of epi- and endobionts on the sponges compared to both Miramare and Strunjan. The effect of sponges' endo and epibionts is not clear in literature. On one hand, they may limit the filtration rate and growth capacity of the fragments while taking advance of food and shelter provided by the sponge, on the other hand they may contribute to sponge tissues cleaning thus boosting ventilation (Goren et al., 2021; Lira et al., 2024; Martin and Britayev, 2018; Westinga and Hoetjes, 1981; Wulff, 2006).

In terms of farming structure, no differences were found between the upper and lower rows at the Miramare and Strunjan sites, whereas differences were observed at Santa Croce, where higher growth rates were measured in the lower row at all three sampling times. Since the same type of technology (plastic nets) was used at both Santa Croce and Strunjan, their growth difference may be attributed to environmental conditions or to the different handling of samples before fixation, as Santa Croce is located three miles offshore and experienced a less invasive transfer process compared to Strunjan. The seabed at Santa Croce is located at a greater average depth (approximately 12.5 m), and the sediment is composed of coarser sand, in contrast to the finer sand at Strunjan and the mixture of fine sand and mud at Miramare. This difference in sediment grain size could result in less suspension due to hydrodynamics (which might clog the inhalant pores and afferent canals of the organism), consequently reducing energy expenditure required for cleaning via phagocytosis and exocytosis (Bannister et al., 2007; Duckworth et al., 1997). The absence of row differences at other sites is favorable from a sponge farming perspective, as it suggests that the structure provides homogeneous growth. As a note from the authors, plastic nets needed a proper setup since, due to the turbulence in the Gulf of Trieste, when filled with epibionts which clogged the net, net movement caused displacement of the moorings and coiled onto themselves (Figure S1).

Few studies have specifically addressed the growth of *S. officinalis*, or in general the genus *Spongia*. Corriero et al. (2004), investigating *S. officinalis* var. *adriatica* on suspended ropes in Apulia (Italy), recorded exponential growth, with initial sizes of approximately 55 g reaching 200 g within three years (263.64%). Differently, *S. officinalis* farmed on suspended ropes in the Dardanelles (Turkey) showed growth ranging from 5 to 17% over 21 months (Çelik et al., 2011). In the Bahamas, Oronti et al. (2012) reported different growth rates, ranging from 900% to 1566% in 36 months for grass sponges (*Spongia tubulifera*) and from 150% to 315% for hardhead sponges (*Spongia anclotea*). Recently, Motta et al. (2025) reported a 209% growth in about three years for *S. anclotea* farmed on suspended ropes. In literature, smaller fragments of *Spongia* species tend to exhibit higher growth rates, as noted by both Çelik et al., (2011) and Verdenal (1990).

In our study, the rate observed in Miramare and Strunjan (250% and 155%) aligns well with literature, and so do Santacroce. Santacroce did record the lowest values at t3, but the growth at this site was still consistent (113%). Therefore, the Gulf of Trieste shows growth patterns which can support the setup of sponge farming, suggesting the protocol adopted in both Miramare and Strunjan (both plastic nets and line farming) as efficient for the area. These findings underscore the variability in sponge growth, which is influenced by both environmental factors and experimental protocols, thus highlighting the need for tailored setups to maximize profits.

The same reasoning applies to mortality, another key indicator of the profitability of sponge farms. Mortality rates, particularly between the initial time points (T0-T1), were very high at all sites (>60%), but subsequently decreased and stabilized at later sampling times. This indicates, as observed in other studies (Corriero et al., 2004; Giangrande et al., 2020; Longo et al., 2025; Motta et al., 2025; Pronzato, 1999), that the setup and initial stages of donor collection, cutting, transport, and placement into the farming structure are critical, and minimizing stress to the sponges during these stages is essential. In our study, it was evident that the Santa Croce site, which was handled more carefully and with greater caution, had significantly lower mortality compared to the other sites. Furthermore, as previously mentioned, Santa Croce also showed a better growth rate, potentially linked to a shorter and less prolonged stress phase during the initial period of the study. Miramare, being set during late autumn 2011 (Santacroce and Strunjan were deployed in summer 2012), probably suffered a higher initial stress due to the fast drop from temperatures near the 90th percentile down to a cold wave registered during February-March 2012. However, the effects of temperature on sponges are idiosyncratic and species-specific, and compared with many other benthic groups, sponges are typically more tolerant of temperature variation and ocean warming (Bell et al., 2018; Kelmo et al., 2013; Riisgård et al., 1993). In the Gulf of Trieste, where temperature ranges from less than 10°C during winter and more than 25°C during summer (Malačič et al., 2006; Raicich and Colucci, 2019), sponges may be relatively more resilient to temperature fluctuations.

The mortality rates documented in this study are notably higher than those commonly reported in the literature for the genus *Spongia*. Previous studies have generally indicated lower mortality; for instance, rates between 18% and 25% were reported for *S. officinalis* (Çelik et al., 2011; Verdenal, 1990), and 15% for *S. anclotea* (Motta et al., 2025). However, the literature also reveals considerable spatial variability, as exemplified by Oronti et al. (2012), who reported vastly different mortality rates for *S. tubulifera* (2.5% and 68%) and *S. anclotea* (12.5% and 55%) at separate sites. This suggests that mortality in sponge populations is inherently site-specific and likely driven by a complex interplay of localized biotic and abiotic stressors. Our elevated rates may therefore reflect a combination of unfavorable local conditions, such as anthropogenic stressors, pathogen outbreaks, or climatic anomalies. These findings highlight the vulnerability of sponge populations to localized pressures and underscore the need for further research into the factors driving such extreme mortality rates.

Based on the findings of this study, the Gulf of Trieste appears to be a promising site for the implementation of sponge farms, as the growth rates observed were consistent with those reported in other locations within the literature. However, several critical considerations must be addressed before this area can be deemed commercially viable. Notably, the mortality rate observed in this study was too high to make sponge farming profitable in the short term. Further research is essential to establish optimal protocols for identifying donor populations, as well as refining the procedures for cutting, transporting, and installing the farming systems. These latter stages, in particular, were found to be crucial in minimizing mortality and ensuring the success of sponge farming ventures. Once these challenges are addressed, the Gulf of Trieste could become a key location for both sponge production and the restoration of local sponge populations.

CRediT authorship contribution statement

Rocco Auriemma: Writing – review & editing, Methodology, Investigation, Conceptualization. **Gianluca Coidessa:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Gregorio Motta:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Antonio Terlizzi:** Writing – review & editing, Supervision. **Massimo Avian:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Massimiliano Novak:** Writing – review & editing, Investigation. **Elena Pesle:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rsma.2026.105118.

Data Availability

Data will be made available on request.

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