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ORIGINAL RESEARCH

Effect of nursery site on the growth performance of juvenile sea cucumber, *Holothuria scabra*, in earth pond-based hapa systems

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Abstract

The tropical sea cucumber, *Holothuria scabra*, plays an important economic and ecological role. Aquaculture of this species has been developing rapidly, and an increasingly effective and efficient system for juvenile production is required. Nursery is a crucial process, as it involves the transition of rearing methods from indoor hatcheries to outdoor environments. This study determined the influence of various nursery sites within earthen pond systems on the growth and survival of juvenile *H. scabra*. Juvenile *H. scabra* with a mean wet weight of 1 g ($n = 50$) were held in replicate floating hapa units over 84 days across four nursery sites: reservoir pond (RP), stirred pond (SP), non-stirred pond (NSP), and main inlet sluice (MIS). Sea cucumbers in MIS exhibited significantly higher weight gain (6.95 ± 0.90 g), growth rate (0.08 ± 0.01 g day^{-1}), and specific growth rate (2.36 ± 0.15% day^{-1}) than all other treatments. Survival did not differ significantly among treatments, ranging from 64.00% ± 2.37% to 74.80% ± 5.82%. The MIS exhibited the highest growth rate for juvenile *H. scabra*, presumably supported by favorable environmental conditions and effective water exchange. These findings highlight the importance of water circulation and nursery site selection indicating that strategically positioning hapa units close to inlet zones may improve juvenile performance in commercial aquaculture.

KEYWORDS
earthen ponds, floating hapa unit, Lombok Indonesia, main inlet sluice, sea cucumber nursery

1 | INTRODUCTION

The sea cucumber, *Holothuria scabra*, commonly known as sandfish, has significant commercial value and is in great demand on global markets (Hamel et al., 2022; Purcell et al., 2018). This species is, like many sea cucumbers, also promising for development as a functional food with high nutritional value (Bordbar et al., 2011; Sroyraya et al., 2017). The overfishing of sea cucumbers has led to population depletion in the wild and alteration of animal behavior within ecosystems (Purcell et al., 2013). This depletion can affect the density, abundance, and biomass of the different populations (Hasan, 2019). Aquaculture of sea cucumbers has been developed at varying scales in many countries to counter overfishing and provide new income sources. Han et al. (2016) argue that pond aquaculture, sea ranching, and stock enhancement are the most viable and environmentally sustainable approaches to address the enormous commercial demand for wild sea cucumbers, while also preventing their overexploitation.

Feeding requirements, space limitations, and cost-effectiveness frequently render indoor sea cucumber nursery culture inefficient, requiring the transfer of juveniles outdoors in order to minimize the hatchery rearing period in both *Apostichopus japonicus* and *H. scabra* culture (Juinio-Meñez et al., 2017; Purcell et al., 2012; Xie et al., 2019). Maintaining juveniles in the nursery stage is a critical issue for farming and sea ranching of *H. scabra* (Purcell & Agudo, 2013). An initial nursery phase in outdoor ponds has been suggested as a viable approach to optimize *H. scabra* culture (Lavitra et al., 2010). Furthermore, Xie et al. (2016) indicated that rearing the early juvenile stage in ponds is considered a solution, owing to the availability of mud and potentially leftover nutrients from previous farming activities, which can serve as an alternative natural diet source.

In this study, we used earthen ponds converted from abandoned traditional salt ponds; these offer an alternative environment for *H. scabra* nurseries. In pond conditions, juvenile sea cucumbers generally do not require supplemental feed since they rely on natural food sources such as organic detritus, microbial biofilms, and benthic organisms within the substrate (J. Chen, 2004; Ren et al., 2010; Yaqing et al., 2004). Seawater entering the ponds during water exchange is typically abundant in food particles and phytoplankton, thus minimizing the requirement for additional feeding (Renbo & Yuan, 2004). Furthermore, pond cultivation can effectively prevent nutrient accumulation at the bottom, thereby improving water quality (Ren et al., 2010).

Sea cucumber nursery cultivation in enclosures in earthen ponds is an alternative to the space-intensive hatchery rearing of sea cucumbers to a size suitable for subsequent stocking in the sea (Purcell et al., 2012). Pitt and Duy (2004) used fine-net bags, bigger bag nets, and pens within the ponds to rear juvenile *H. scabra* weighing a few grams to tens of grams. Purcell and Agudo (2013) highlighted the importance of size-dependent nursery strategies in *H. scabra*, showing that juveniles measuring 5–8 mm in body length are most effectively raised in fine mesh hapas before transitioning to coarser mesh hapas. The significance of utilizing fine mesh hapa for the early nursery stage before transferring juveniles to the pond sediments was further confirmed by studies in the Philippines (Cabacaba & Campo, 2019; Juinio-Meñez et al., 2012). Sinsona and Juinio-Meñez (2019) determined that a periphyton biofilm may grow on hapas and act as a natural food source stimulating the growth of juveniles.

Nursery methods for *H. scabra* in pond culture continue to be developed with numerous studies outlining size-specific transitions and rearing strategies. The transition of small juveniles from indoor hatcheries to the outdoor environment during the nursery phase is particularly challenging and requires careful management of environmental conditions, such as water quality, predation risks, sediment characteristics, and water circulation, to ensure their survival and growth. Nevertheless, further studies are still needed to investigate site-specific approaches and optimize nursery techniques, particularly the impact of certain pond conditions on juvenile performance. This study aims to analyze the influence of various nursery sites within pond systems on the growth and survival of juvenile *H. scabra* in earthen ponds, thus addressing a critical gap in the development of sustainable pond-based nursery systems.

2 | MATERIALS AND METHODS

2.1 | Study site and experimental design

The current study was carried out in earthen ponds in Lungkak, east Lombok, Indonesia (8°47′16.70″ S, 116°30′14.56″ E), at a *H. scabra* culture site, which produces juveniles on a mass scale (Figure 1). The hatchery achieves an average annual production of approximately 200 million larvae. This experiment utilized juveniles derived from a single spawning batch involving of 20 females and 10 males broodstock, resulting in an estimated 2–5 million larvae. The Auricularia stage (Day 2) was raised in indoor tanks of 1000 L for around 2 weeks. When larvae reached the Pentactula stage (Week 2), larvae were moved to larger indoor tanks of 1500 L and maintained without substrate for another 2–4 weeks. Subsequently, the juveniles were transferred to outdoor tanks of 26 m^3 for an additional 2–4 weeks until they averaged roughly 1 g in body weight, at this point they were ready for use in this experiment. The experiment used a fully randomized design, with each treatment assigned to a different site, and was conducted over 84 days. The four treatment sites included a reservoir pond (RP), a stirred pond (SP), a non-stirred pond (NSP), and the main inlet sluice (MIS). Site RP functioned as a water storage area for hatchery activities, without distributing water to other ponds. Site SP was mechanically stirred every 3 days and fertilized. Site NSP was also fertilized without stirring. Site MIS was situated close to the main water intake. Each treatment consisted of five replicates within its designated sites. All replicates were confined to distinct sites and the design

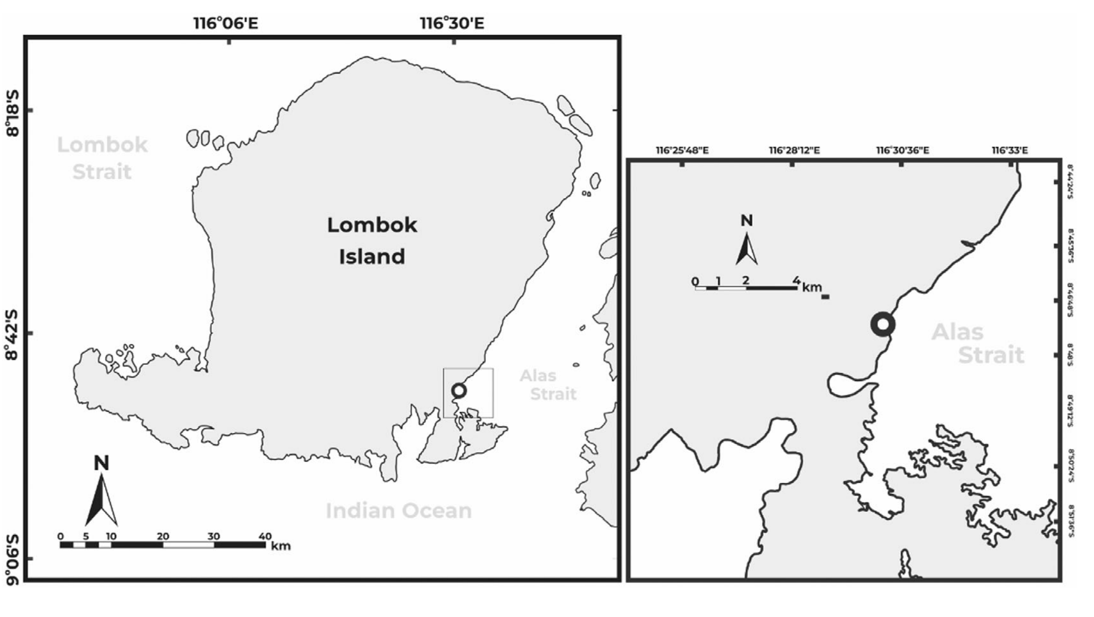

FIGURE 1 Site of the earthen pond of sea cucumber *Holothuria scabra* culture in East Lombok, Indonesia.

inherently included pseudoreplication; however, the site system size and highly representative form of ponds supports the validity of results (Hurlbert, 1984; Riley & Edwards, 1998). In order to evaluate potential site-related variability, we observed key environmental parameters (e.g., temperature, salinity, pH, and dissolved oxygen) regularly to monitor fluctuations across sites. This design provided a practical approach to evaluating nursery site impacts, future studies should consider replicating treatments across multiple sites to enhance statistical robustness and control for environmental variability. Each site was connected to the primary waterways through inlet and outlet sluices (Figure 2). Hatchery-produced juvenile *H. scabra* was randomly placed in floating circular hapa nursery units (0.5 m in diameter; 0.9 m in height). These units were constructed from a circular frame covered in 1-mm mesh nylon net. To optimize water circulation within the hapa, nets were changed monthly. The initial weight range was relatively wide from 0.34 to 1.99 g; however, the mean initial body weight within each treatment was consistent, ranging from 1.00 to 1.11 g, with a low standard error (±0.01 g). This indicates that the juveniles were fairly homogeneous in size at the beginning of the experiment. All juveniles used in this study originated from the same spawning batch and were randomly distributed into 20 hapa units ($n = 50$ per hapa), a method designed to minimize initial variation among treatments. As a standard protocol (Sewell, 1990; Sunde & Christophersen, 2023), all juveniles were not fed for 24 h to allow their gut to be emptied before being initially weighed prior to stocking into hapas in order to reduce data variability. During this period, all juveniles were kept in two indoor tanks with a volume of 1000 L each. The initial weight of juveniles in each hapa was recorded at the beginning of the experiment. The weight range for the 20 hapas varied from 1.00 to 1.13 g, with an average weight of 1.05 ± 0.01 g. While *H. scabra* can survive in sediment at this size, nursery-based maintaining in hapas provides a number of advantages, such as reduced predation risk, controlled environmental conditions, and more uniform growth. Furthermore, raising in hapas allows for easier monitoring of juvenile growth before transferring them to the sediment system. This approach is particularly useful for large-scale production since it enables effective monitoring and management of juveniles prior to their movement to grow-out system.

Prior to the experiment, the pond water was completely drained, and any waste, vegetation roots, algae, predators, and other undesirable organisms were removed by hand (Figure 3a). During the preparation of sites

FIGURE 2 Nursery treatment sites of juvenile *Holothuria scabra* in the earthen ponds-based hapa system. (a) Treatment RP (reservoir pond); (b) treatment SP (stirred pond); (c) treatment NSP (non-stirred pond); (d) treatment MIS (main inlet sluice); (e) hatchery; (f) sea; (g) estuary; (h) river; (i) water channel; ↑: inlet; ↓: outlet (Snapshot Google Earth, October 2024).

SP and NSP, specific experimental treatments were applied to improve substrate and water conditions. Dolomite (200 kg per 1000 m^2) was used to stabilize pH and increase sediment quality, saponin (1 L per 1000 m^2) was applied to eliminate potential predators like crustaceans and fish before stocking. Subsequently, a total of 0.8 kg of urea and TSP (Triple Super Phosphate) were added to the sites of SP and NSP as fertilizer in order to increase nutrient availability and promote the growth of natural food sources in the water column. All experimental sites were filled to a depth of 1 m with seawater sourced from the tides (Figure 3b). During the experimental period, the water in site SP was stirred every 3 days at four fixed corners with each spot stirred for around 15 min using a long-tail outboard motor equipped with a 6 horse-power boat engine and propeller. This method was not part of standard pond culture practices but was applied specifically for this experiment. Stirring treatment aimed to distribute nutrients, organic matter, feed particles in the water column, and enhance oxygenation (Figure 3c). This practice was intended to potentially enhance food accessibility for juveniles and prevent the accumulation of waste, thus helping to maintain water quality in the site. The seawater in each site was changed by opening and closing the sluice gates in accordance with the tidal movements. This was also applied to the MIS treatment, even though it is near the main water gate. Water exchange of around 50%, equivalent to approximately 500 m^3, occurred biweekly during the first and third weeks of each month, follows the natural tidal cycle during the high tide.

2.2 | Sample collection and measurement

Juvenile *H. scabra* wet weight was measured at the beginning and the end of the experiment. Each juvenile was dried carefully with blotting paper, weighed on an electronic balance (0.001 g precision), and immediately transferred to its experimental "hapa" and treatment site.

Regular monitoring of water quality was implemented during the experimental period. Temperature, pH, salinity, and dissolved oxygen (DO) were measured weekly at 10:00 a.m. at three points (inlet, middle, outside) within each site. Furthermore, ammonia, nitrite, and nitrate nitrogen concentrations were determined monthly using a HACH portable spectrophotometer DR-1900 from the similar points and time. All water samples were collected from outside the hapa units.

Samples of phytoplankton were collected once before and after seawater exchange from three areas within each site (inlet, middle, outlet) to assess community composition and spatial variability. These samples were used for descriptive analysis of the phytoplankton community at the site. The selected areas were determined based on expected gradients of water flow and nutrient dynamics. The inlet is affected by entering seawater, potentially introducing new phytoplankton and nutrients. The middle part represents the main water column, where phytoplankton may interact with the organic materials and nutrients

FIGURE 3 Pre-experiment cleaning process (a); experimental pond site (b); periodic water stirring in site stirred pond (SP) (c).

distributed within the sites. The outlet indicates the conditions of water being discharged, which may accumulate phytoplankton due to water movement and flow patterns. Sampling these three locations provides insight into phytoplankton dynamics across different points of the sites and how water exchange affects their community structure. Phytoplankton samples were identified in the laboratory at the Brackish Water Aquaculture Development Centre, Situbondo, Indonesia.

Sediment samples were collected once per treatment site (RP, SP, NSP, MIS) and analyzed in triplicate using a HORIBA LA-950 laser diffraction spectrometer to ensure instrumental precision. Nevertheless, these triplicates represent technical replicates rather than independent biological replicates. Consequently, statistical comparisons between the sites were not feasible. We recognize this limitation in the revised Section 2. The number of biological replicates per site will be increased in future studies to address this constraint. The parameters were calculated using GRADISTAT (Blott & Pye, 2001) and Microsoft Excel software. To quantify the sediment dry weight (DW) and organic content (OC), samples were collected from each treatment site (10–15 cm depth) and dried overnight at 110°C to determine water loss. The drying temperature of 110°C was chosen, as it is widely recognized as a standard method for determining sediment water content and dry weight in soil and sediment studies (Dettmann et al., 2021). The dried samples were then combusted in a muffle furnace at 550°C for 2–4 h to quantify organic content through weight loss on ignition.

2.3 | Calculations of growth and survival were calculated using the following equations

(Mean) weight gain (g):

$$\text{Weight gain (g)} = (\text{final weight} - \text{initial weight})$$

Growth rate (daily weight gain):

$$\text{Growth rate}\left(\text{g day}^{-1}\right) = (\text{final weight} - \text{initial weight})/\text{days}$$

Specific growth rate (SGR):

$$\text{SGR}\left(\%\text{day}^{-1}\right) = (\ln \text{final weight} - \ln \text{initial weight})/t \times 100$$

Survival rate (SR):

$$\text{SR}(\%) = (\text{number of final}/\text{number of initial}) \times 100$$

2.4 | The sediment DW and OC are calculated using the following formula

$$\text{DW}(\%) = \frac{m_1 - m_2}{m_1 - m_0} \times 100$$

where m_0 = weight of the empty tray (g); m_1 = weight of the tray + sample before drying (g); m_2 = weight of the tray + sample after drying at 110°C (g).

$$\mathrm{OC}(\%) = \frac{m_2 - m_3}{m_2 - m_0} \times 100$$

where m_2 = weight of the tray + sample after drying at 110°C (g); m_3 = weight of the tray + sample after ignition at 550°C (g).

2.5 | Statistical analysis

A linear mixed-effects model (LMM) was applied to analyze the survival rate, with treatment as a fixed effect and site as a random effect to account for variability among sites. Pairwise comparisons between treatments were conducted using Tukey's HSD test. Growth rate (GR) and specific growth rate (SGR) parameters were initially tested using LMM; however, the model failed to converge, likely due to the limited number of sites and low inter-site variance. Given this limitation, a one-way analysis of variance (ANOVA) was implemented to evaluate the effect of treatment on the GR and SGR. The assumptions of normality and homogeneity of variance were determined utilizing the Shapiro–Wilk test and Levene's test, respectively. Post hoc comparisons were applied using Tukey's HSD test to identify significant differences between treatments. The statistical analyses were carried out using R studio 2023.03.0.

3 | RESULTS

3.1 | Growth performance

Growth performance of juvenile *H. scabra* showed considerable variation between treatments (Table 1). The growth in the MIS treatment outperformed the other systems, with the highest weight gain of 6.95 ± 0.90 g (mean ± SE), growth rate of 0.08 ± 0.01 g day^{-1}, and specific growth rate of 2.36 ± 0.15% day^{-1}.

TABLE 1 Growth performance of juvenile sea cucumber *Holothuria scabra* in different nursery sites in an earthen ponds-based hapa system.

	RP	SP	NSP	MIS
Initial number (ind)	250	250	250	250
Final number (ind)	187	160	182	179
Initial weight range (g)	0.41–1.99	0.34–1.99	0.40–1.99	0.42–1.98
Final weight range (g)	0.70–5.12	0.62–11.80	0.37–7.10	0.90–18.59
Initial average weight (g)	1.01–1.07	1.00–1.05	1.01–1.11	1.02–1.113
Final average weight (g)	2.07–2.87	3.20–5.37	2.84–4.24	5.57–10.59
Survival rate (%)	74.80 ± 5.82^{a}	64.00 ± 2.37^{a}	72.80 ± 2.42^{a}	69.60 ± 5.78^{a}
Weight gain (g)	1.34 ± 0.13^{a}	3.18 ± 0.37^{a}	2.35 ± 0.23^{a}	6.95 ± 0.90^{b}
Growth rate (g day^{-1})	0.02 ± 0.00^{a}	0.04 ± 0.00^{b}	0.03 ± 0.00^{b}	0.08 ± 0.01^{c}
Specific growth rate (% day^{-1})	0.98 ± 0.06^{c}	1.66 ± 0.11^{b}	1.38 ± 0.06^{b}	2.36 ± 0.15^{a}

Note: Different letters indicate significant differences ($p < 0.05$), (mean ± SE).
Abbreviations: MIS, main inlet sluice; NSP, non-stirred pond; RP, reservoir pond; SP, stirred pond.

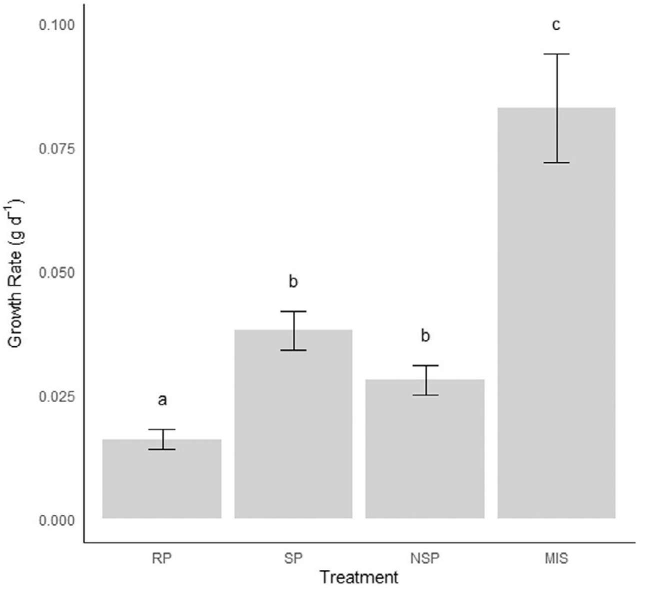

FIGURE 4 Mean growth rate (±SE) of juvenile *Holothuria scabra* in different nursery sites in earthen ponds-based hapa system. Each treatment represents a total of $n = 250$. Letters (a–c) over columns indicate significant differences ($p < 0.001$) Tukey HSD. MIS, main inlet sluice; NSP, non-stirred pond; RP, reservoir pond; SP, stirred pond.

The survival rate of juvenile *H. scabra* ranged from 64.00% ± 2.37% in SP to 74.80% ± 5.82% in RP. Overall, the variation in survival rates among the different treatment sites appeared to be relatively small. The LMM analysis showed no significant differences in survival rates among the treatments ($p > 0.05$).

The lowest GR was observed in RP (0.02 ± 0.00 g day^{-1}). The growth rate did not differ between treatments SP and NSP, with 0.04 ± 0.00 and 0.03 ± 0.00 g day^{-1}, respectively. Treatment MIS had the highest growth rate, with 0.08 ± 0.01 g day^{-1} (Figure 4).

One-way ANOVA testing revealed a significant difference in growth rate among treatments ($p < 0.05$). The Tukey HSD post hoc test showed that treatment MIS significantly differs from RP, SP, and NSP ($p < 0.001$).

Treatment MIS exhibited the highest SGR (2.36 ± 0.15% day^{-1}), followed by SP (1.66 ± 0.11% day^{-1}), NSP (1.38 ± 0.06% day^{-1}), and RP (0.98 ± 0.06% day^{-1}) (Figure 5). One-way ANOVA revealed a significant difference in SGR among the treatments ($p < 0.001$). Post hoc testing (Tukey HSD) indicated that treatment MIS was significantly different from all other treatments (RP, SP, and NSP) ($p < 0.001$).

3.2 | Grain size

The grain size analysis of sediment from each treatment site indicated diverse distribution characteristics and distinct composition (Table 2). The sediment of RP treatment, categorized as muddy sand, predominantly contains sand and mud particles. In contrast, the sediment in SP treatment is slightly gravelly sandy mud, characterized by a higher proportion of fine sand particles. The sediment in NSP treatment shares similarities with RP treatment as muddy sand, with mud and sand as dominant components. Finally, the sediment in MIS treatment, slightly gravelly sandy mud, displays characteristics similar to SP treatment.

The sediments in RP and NSP treatments indicated high sand content with moderate proportions of silt and clay, reflecting similar textural properties. Conversely, SP and MIS treatment showed finer particle distributions, with

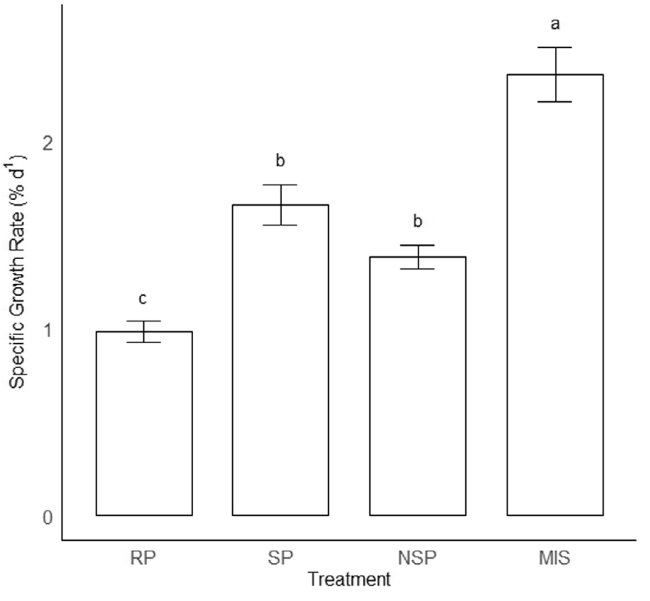

FIGURE 5 Mean specific growth rate (±SE) of juvenile *Holothuria scabra* in different nursery sites in earthen ponds-based hapa system. Each treatment represents a total of $n = 250$. Letters (a–c) over columns indicate significant differences ($p < 0.001$) Tukey HSD. MIS, main inlet sluice; NSP, non-stirred pond; RP, reservoir pond; SP, stirred pond.

TABLE 2 Textural classification and composition of sediment from different nursery sites in an earthen ponds-based hapa system.

Site nursery	Textural group	Grain size classification by Wentworth (1922)	Mean particle size (μm)	Sand (%)	Silt (%)	Clay (%)
RP	Muddy sand	Fine sand	163.6	53.2	40.1	6.7
SP	Slightly Gravelly Sandy mud	Very fine sand	59.73	83.3	16.1	0.6
NSP	Muddy sand	Fine sand	210.5	53.4	40.6	6.0
MIS	Slightly Gravelly Sandy mud	Fine sand	162.4	44.5	55.3	0.3

Abbreviations: MIS, main inlet sluice; NSP, non-stirred pond; RP, reservoir pond; SP, stirred pond.

TABLE 3 Sediment dry weight and organic content of the sediment from each pond under different treatments (%) (mean ± SE, $n = 3$).

Treatment	Dry weight (%)	Organic content (%)
RP	3.05 ± 0.23^{a}	6.84 ± 0.05^{b}
SP	1.26 ± 0.18^{b}	4.27 ± 0.12^{c}
NSP	3.89 ± 0.15^{a}	7.75 ± 0.20^{a}
MIS	3.90 ± 0.18^{a}	5.79 ± 0.12^{b}

Abbreviations: MIS, main inlet sluice; NSP, non-stirred pond; RP, reservoir pond; SP, stirred pond.

higher content of sand in SP treatment and more silt in MIS treatment. These differences in sediment composition highlight the variation in environmental conditions across the treatments.

3.3 | Sediment dry weight and organic content

Treatment NSP exhibited the highest OC level of 7.75% ± 0.20%, while treatment N2 showed the lowest OC level (Table 3). One-way ANOVA indicated significant differences among treatments for DW ($p < 0.001$). Post hoc Tukey HSD analysis revealed that treatment SP had significantly lower DW values compared to treatments RP, NSP, and MIS ($p < 0.001$). One-way ANOVA also revealed significant differences in OC among treatments ($p < 0.001$). Post hoc Tukey HSD analysis demonstrated that treatment SP had significantly lower OC content compared to treatments RP, NSP, and MIS ($p < 0.001$).

3.4 | Phytoplankton

Navicula spp. was the most commonly found phytoplankton species in the sites, followed by *Nitzschia* spp. and *Synedra* spp. The genus *Amphipleura* was only found in the MIS site, and *Rhizosolenia* was only in the outlet of MIS (Figure 6). In the MIS site, particularly near the outlet, *Navicula* spp. exhibited the highest concentration (1.400 cells mL^{-1}) followed by *Nitzschia* spp. (900 cells mL^{-1}). Meanwhile, in the RP site, the concentration of *Synedra* was highest, with 223 cells mL^{-1}, specifically at the outlet. The MIS site exhibited higher phytoplankton cell densities and greater diversity compared to the other sites, particularly before the water exchange. Sites RP and SP supported a more diverse phytoplankton population, whereas site NSP showed lower diversity and lower overall concentrations of phytoplankton.

After water exchange, *Navicula* spp. was the dominant phytoplankton in most sites, followed by *Nitzschia* spp. and *Gyrosigma* spp. *Navicula* spp. (239 cells mL^{-1}) and *Nitzschia* spp. (88 cells mL^{-1}) had the highest concentrations of phytoplankton in the MIS site at the outlet. *Gyrosigma* spp. exhibited a more equal distribution across the sites, but its maximum concentration (11 cells mL^{-1}) was in the NSP site at the inlet. The MIS site exhibited a higher quantity of phytoplankton than other sites. The outlet still showed a tendency to have a higher concentration of phytoplankton, particularly in the MIS site.

New types of phytoplankton, such as *Chaetoceros* spp. and *Cymbella* spp., were present. *Amphipleura* spp. and *Rhizosolenia* spp. did not appear after exchange.

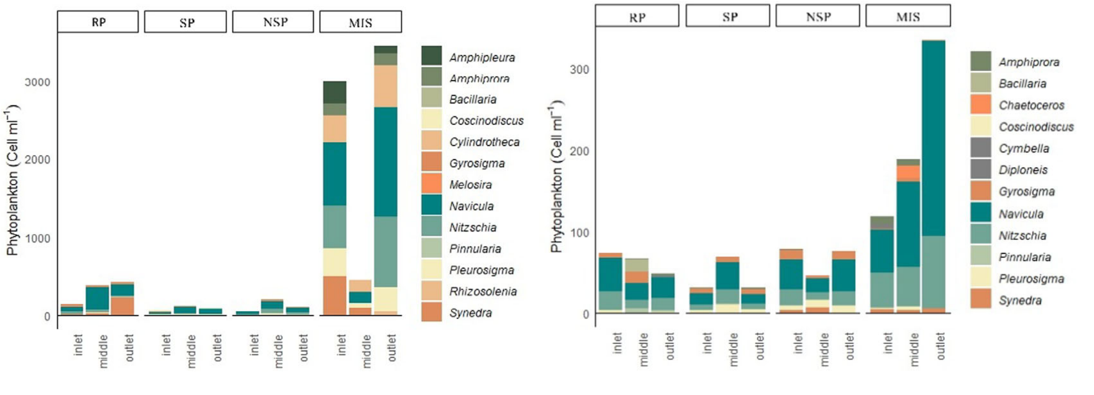

FIGURE 6 Composition of phytoplankton in different sites in an earthen ponds-based hapa system before (left) and after (right) one water exchange (pooled data). MIS, main inlet sluice; NSP, non-stirred pond; RP, reservoir pond; SP, stirred pond.

Copepods were observed in all sites, with the highest abundance recorded in the SP site, reaching 60 ind/mL^{-1} at the outlet prior to water exchange. Following the water exchange, there was a decrease in copepods in the RP site, with only one ind/mL^{-1} found at the inlet, which was the lowest concentration observed.

3.5 | Presence of other organisms in the hapa

Monitoring and change of each hapa unit were conducted every 28 days, with the observation times designated as day 28, day 56, and day 84 (Table 4). Other organisms were found inside the hapa units. For RP, fish were found on every observation day. Additionally, gastropods and shrimp were discovered at day 56, while crabs were observed on day 84. For SP, only shrimp were observed at day 28. At day 56 and 84, shrimp and gastropods were recorded. Furthermore, barnacles were found exclusively at day 56 and 84. For NSP, shrimp were present on all observation days. Fish juveniles were detected at day 56 and 84, and gastropods were found only at day 84. For MIS, no other organisms were found at day 28. Nudibranchs were observed on day 56, and on day 84, shrimp, gastropods, and fish juveniles were recorded.

3.6 | Water quality

Water temperature averaged ca. 30°C throughout the experiment (Table 5). The pH levels observed in all treatments were predominantly neutral, ranging from 7.81 to 7.99. Salinity levels in this study ranged from 34.40 to 35.70 ppt.

TABLE 4 Presence of biota in hapa at days 28, 56, and 84 in different nursery sites.

	RP			SP			NSP			MIS		
Biota	28	56	84	28	56	84	28	56	84	28	56	84
Barnacle	−	−	−	−	+	+	−	−	−	−	−	−
Gastropod	−	+	+	−	+	+	−	−	+	−	−	+
Crab	−	−	+	−	−	−	−	−	−	−	−	−
Fish juvenile	+	+	+	−	+	+	−	+	+	−	−	+
Nudibranch	−	−	−	−	−	−	−	−	−	−	+	−
Shrimp	−	+	+	+	+	+	+	+	+	−	−	+

Abbreviations: MIS, main inlet sluice; NSP, non-stirred pond; RP, reservoir pond; SP, stirred pond.

TABLE 5 Water quality parameters at nursery sites in earthen ponds (mean ± SE).

Parameter	RP	SP	NSP	MIS
Temperature (°C)	30.78 ± 0.29	30.17 ± 0.32	30.35 ± 0.34	30.61 ± 0.41
Salinity (ppt)	34.40 ± 0.58	35.50 ± 0.82	35.70 ± 0.79	34.70 ± 0.75
pH	7.81 ± 0.05	7.99 ± 0.05	7.82 ± 0.04	7.99 ± 0.07
DO (mg L^{-1})	7.94 ± 0.06	7.82 ± 0.05	7.88 ± 0.12	8.27 ± 0.06
Nitrate NO_3-N (mg L^{-1})	0.04 ± 0.02	0.04 ± 0.01	0.03 ± 0.01	0.03 ± 0.01
Nitrite NO_2-N (mg L^{-1})	0.004 ± 0.001	0.004 ± 0.001	0.005 ± 0.001	0.005 ± 0.001
Ammonia NH_3-N (mg L^{-1})	0.07 ± 0.02	0.10 ± 0.03	0.08 ± 0.02	0.10 ± 0.01

Abbreviations: MIS, main inlet sluice; NSP, non-stirred pond; RP, reservoir pond; SP, stirred pond.

Dissolved oxygen, with the lowest value of 7.82 and the highest 8.27 mg L^{-1} was observed in SP and MIS, respectively. The concentrations of nitrate and nitrite were consistently low across all treatments. Specifically, nitrate concentration was less than 0.05 mg L^{-1}, while nitrite was less than 0.005 mg L^{-1}. Ammonia concentrations varied from 0.07 mg L^{-1} in RP to 0.10 mg L^{-1} in SP and MIS.

4 | DISCUSSION

Pond-based rearing systems for juvenile sea cucumbers, particularly *H. scabra* and *A. japonicus*, have been implemented in numerous countries. In China, *A. japonicus* has been reared in large ponds and net enclosures (Qin et al., 2009; Ren et al., 2010; Zhou et al., 2017). Similarly, *H. scabra* has been cultured in pond-based systems in Vietnam and Madagascar (Lavitra et al., 2010; Pitt & Duy, 2004). These findings support the feasibility of pond-based culture under appropriate management practices.

The utilization of earthen ponds for the nursery stage of sea cucumber farming can support growth performance and reduce indoor space requirements and costs for nursery stages. The current study shows nursery size juveniles of *H. scabra* exhibit significantly higher growth rates when held in hapas in inlet sluices to refunctioned ponds in Indonesia. Xilin (2004) identified pond locations for sea cucumbers, which should provide ideal conditions, including easy access to unpolluted sea water, leak-proof pond banks, and an effective drainage system. Culturing sea cucumbers in ponds without artificial diet also requires natural food sources rich in organic matter (Ren et al., 2012).

Transferring small juveniles from an indoor hatchery to an outdoor environment is more effective when using hapas rather than placing them directly on the pond bottom, as these juveniles are sensitive and have low stress tolerance. Pitt and Duy (2004) also reported that small juvenile *H. scabra* disappeared without a trace after being transferred directly into a pond. In the current study, juveniles with an average weight of 1 g (9 weeks old) were distributed into floating circular hapas (0.5 m in diameter; 0.9 m in height). Previous studies have shown that early juveniles (4–10 mm; 0.02–0.06 g) are effectively raised in sea-based floating hapa nets (2 × 1 × 1 m), which provide a controlled environment for nursery culture (Altamirano & Noran-Baylon, 2020). Rectangular 2 m^2 hapas are commonly utilized in nursery culture in the Philippines and Vietnam; however, the current study used a smaller, floating circular hapa design suitable for small-scale experimental research. This design was selected for its lightweight construction, which facilitates maintenance, monitoring, and cleaning. More comparative research is required to assess differences in efficiency between hapa designs. Furthermore, size grading is a crucial aspect in optimizing juvenile growth performance in hapas because it minimizes competition and promotes uniform growth (Altamirano & Noran-Baylon, 2020).

Pitt and Duy (2004) encountered challenges in using ponds to accommodate several groups of *H. scabra* juveniles with varying sizes at the same time. This led to the ponds not being dried for months, resulting in increasing eutrophication. The hapa nets used became clogged, the hapas floors muddy, dissolved oxygen levels dropped, and the nets deteriorated rapidly due to exposure to sunlight. Ren et al. (2012) cleaned the polythene net enclosures holding sea cucumbers in their experimental study biweekly to remove fouling organisms and ensure that water quality within the enclosures remained similar to that outside. During the experimental period, hapas were changed every month and checked weekly to ensure they were in good condition.

Furthermore, Pitt and Duy (2004) initially introduced the usage of hapas for *H. scabra* nursery systems, indicating that raising juveniles in ponds could be more effective than tank-based nurseries. Nevertheless, nursery techniques have evolved significantly, with recent studies demonstrating improved methodologies. Altamirano et al. (2021) evaluated the effects of environmental conditions on the growth and survival of *H. scabra* juveniles by conducting a comparative study on floating hapa nursery systems across multiple geo-climatic zones in the Philippines. Their study found that growth performance was positively connected with chlorophyll-a concentration and mean temperature, while survival was impacted by the composition of the biofilm. On the other hand, unfavorable conditions such as strong wind stress, high rainfall, and increased biomass density negatively impacted growth and survival rates. These results highlight the importance of site selection and environmental stability in the implementation of hapa-based nursery system. These findings correspond with recent studies emphasizing the role of environmental conditions, hapa maintenance, and stocking techniques in raising survival rates (Altamirano et al., 2021; Gorospe et al., 2023). While hapa nets are effective during the early stages of nursery, a transition period in sediment-based systems may benefit larger juveniles. This allows them to practice burying behavior, which is necessary for survival, but not feasible in suspended nets. This conditioning could enhance juvenile *H. scabra* robustness prior to growing out or ranching. The MIS treatment, placed in the main inlet sluice, exhibited the highest weight gain, growth rate, and specific growth rate, indicating that it provides the most favorable conditions for juvenile *H. scabra* growth. The reservoir of RP treatment consistently showed the lowest value for growth performance of juveniles. The growth of juveniles is affected by habitat conditions such as natural food sources in the form of suspended and settling organic matter provided via water exchange (Han et al., 2016). The similar growth performance between SP and NSP might be the cause of comparable pond conditions. Pond SP and NSP underwent the same preparation, which included dolomite, saponin, and fertilizer, which may have resulted in similar nutrient availability. Despite stirring being applied in SP, it has much affected the environment or ecological conditions compared to NSP. The proximity of MIS to the main water gate implies good water exchange, obtaining water that is abundant in nutrients and has a higher phytoplankton composition than the other treatments. On the other hand, water exchanged into sites RP, SP, and NSP must go through water channels, which may decrease the amount and content of nutrients in the water reaching each site. The lower growth performance recorded in treatments RP, SP, and NSP may not only be attributed to water flow but also characteristics of sediment. Although the composition of sediment was not specifically tested as a factor in this study, we recognize that the finer sediment texture in these sites may have contributed to suboptimal feeding conditions for juvenile *H. scabra*. The site with the highest growth, MIS, contained fine sand sediment with a mean particle size of 162.4 μm and low clay content (0.3%). In addition, Mercier et al. (1999) reported that juvenile *H. scabra* demonstrated a preference for consuming medium sand (~360 μm) under natural conditions.

In aquaculture pond ecosystems, sediment characteristics play a significant role, particularly in microbial activity and nutrient cycling (Masuda & Boyd, 1994). While juvenile *H. scabra* was kept in suspended hapa nets without direct access to the bottom of the site or pond, sediment analysis remains relevant for comprehending environmental conditions at each nursery site that may indirectly affect growth performance. Characteristics of sediment, including texture, grain size, and organic content, reflect broader conditions of the site and may influence the quality of the overlying water column, including factors that potentially support the development of phytoplankton, periphyton, and biofilm communities, which are presumed to be important food sources for juveniles in the hapa units. Therefore, analysis of sediment contributes a more thorough interpretation of environmental variability and facilitates a more comprehensive understanding of site suitability in pond-based nursery systems. However, the low growth performance recorded in RP and NSP, despite their higher organic content, suggests that organic content alone does not explain differences between treatments. Other environmental factors, including water flow and composition of phytoplankton, may have also shaped the water column environment and affected the availability of food sources.

The sediment at the MIS site, which showed the highest growth performance, consisted of a wide range of particle sizes dominated by finer fractions. According to Robinson et al. (2013) fine sediments are known to increase surface area for microbial colonization, which influences organic matter decomposition and the release of nutrients. Sea cucumber *H. scabra* cultivated in substrate-based systems with smaller grain sizes shows improved digestive efficiency, enzyme activity, and overall growth (Sembiring et al., 2025). In this study, fine sediment particles may have contributed to organic matter resuspension, enriching the water column with bioavailable nutrients and microbial communities, which could indirectly promote growth.

OC levels varied among treatments, with the NSP showing the highest OC (7.75% ± 0.20%) and the SP the lowest (4.27% ± 0.12%). While high OC levels in sediment are typically associated with enhanced microbial activity and nutrient release (Zhou et al., 2017), the role of sediment in hapa-based systems is less direct.

This study indicated that the phytoplankton found both before and after the water exchange consisted predominantly of diatoms such as *Navicula* spp., *Nitzschia* spp., *Synedra* spp., *Amphipleura* spp., *Rhizosolenia* spp., *Gyrosigma* spp., *Chaetoceros* spp., and *Cymbella* spp. This finding aligns with Ren et al. (2010), who reported that diatoms were most abundant in the pond-based systems, amounting to 85.1% of the total phytoplankton species. Additionally, Li et al. (2015) observed that introducing the diatom *Cylindrotheca fusiformis* into sea cucumber culture ponds enhanced the growth of *A. japonicus* without negatively impacting water quality.

Among the treatments, MIS showed the highest phytoplankton concentration and diversity, suggesting that continuous water movement and nutrient influx promoted the growth of phytoplankton. In contrast, NSP exhibited lower diversity and abundance of phytoplankton, potentially due to limited nutrient circulation and reduced water movement. On the other hand, SP determined intermediate phytoplankton diversity but lower concentrations, which may be attributed to the impacts of sediment resuspension. The stirring process could have created higher turbidity and inhibited the growth of phytoplankton (Gorospe et al., 2019, 2021).

Despite both SP and NSP being prepared with the same fertilization protocols, which included dolomite, saponin, urea, and TSP, neither site showed the expected change in composition or increase in concentration of phytoplankton. Conversely, these treatments demonstrated a lower concentration of phytoplankton compared to MIS, which received no fertilizer input. This difference may indicate that applied fertilizers did not promote the growth of phytoplankton. Although the stirring treatment in site SP was intended to maintain better water quality, improve food availability, optimize nutrient distribution, and prevent sedimentation, current results did not show a substantial enhancement in the growth performance of juveniles in comparison to other treatments. Actually, the growth rates in SP were lower than those in MIS, which was not stirred but had a naturally higher abundance of phytoplankton. These results indicate that the stirring treatment in SP may not have been effective or necessary under the experimental conditions and emphasize that the application of fertilizer alone does not ensure increased productivity of phytoplankton, highlighting the complex and site-specific interactions within pond ecosystems. The composition, concentration, and distribution of phytoplankton appeared to be influenced by water exchange, as some phytoplankton species declined in concentration while others increased. Water exchange likely introduced new nutrients or modified environmental conditions, subsequently affecting phytoplankton growth. Monitoring these dynamics is crucial, as phytoplankton contribute to the ecological balance of pond systems, impacting water quality and the health of the cultured sea cucumbers. This study determined that *Navicula* was the dominant phytoplankton species across all sites, both before and after water exchange, indicating its adaptability to the pond environment. This is relevant since phytoplankton settling on hapa walls serves as an additional nutritional source for *H. scabra* juveniles (Gorospe et al., 2019, 2021). Moreover, sea cucumbers mainly consume benthic diatoms and particulate organic matter; sedimentation processes and natural diatom populations in the ponds appear to supply a sufficient food source, as reported by Ren et al. (2012) and L. Chen et al. (2023). Furthermore, the quality of settling particulate matter, affected by seasonal variations in biomass and community composition of phytoplankton, plays an important role in the growth and survival of sea cucumbers (Josefson & Rasmussen, 2000; Ren et al., 2010).

Monitoring and replacement of hapa were carried out regularly during the experimental period. The presence of other organisms in the hapa occurs naturally; these biotas probably entered the hapa units during their egg or larval stage and grew inside the system. The highest diversity of biota was recorded in SP, potentially due to the stirring process, which mixed the water column and made it easier for biota in their egg or larval stages to get into the hapa. Even though these organisms were smaller than juveniles in the hapas, they could still have an impact on stress factors and food competition.

Routine monitoring indicated no visible signs of food scarcity or stress-related behaviors in the hapa units. Additionally, Gorospe et al. (2023) monitored predators and competitors of juvenile *H. scabra* reared in floating hapa ocean nursery culture. They recorded fishes, mollusks, crustaceans, and polychaete worms of various sizes and stages inside hapas, which can affect the growth performance of sea cucumbers. In contrast, this study did not record high mortality or growth suppression due to the presence of these organisms. This could be attributed to the regular net changes every 28 days, which may have minimized prolonged interactions between *H. scabra* juveniles and potential intruders. Moreover, the species composition and abundance of intruders in our study differed from those reported by Gorospe et al. (2023), possibly due to differences in environmental conditions and hapa management. In pond-based aquaculture, water quality is usually maintained through water exchange facilitated by sluice gates, allowing periodic water renewal with tidal changes (Yaqing et al., 2004). This approach has been effective in maintaining food supply for *A. japonicus*, which consumes sediment-associated particulate organic matter (Sun et al., 2013). However, juvenile *H. scabra* raised in hapa nets within pond systems mostly rely on external food sources and suspended organic matter and respond differently to water exchange compared to sediment-dwelling species. In the current study, we assessed the potential of water management strategies to improve the growth performance of juveniles raised in hapas.

While the findings provide useful insights into the performance of juvenile *H. scabra*, this study acknowledges numerous limitations that may have restricted a more detailed evaluation of the environmental conditions within individual hapa-based nursery systems. Measurement of water quality was limited to areas directly outside the hapas, preventing an accurate assessment of the internal microenvironment, including the availability of nutrients. Furthermore, periphyton and biofilm that may be important dietary components were not analyzed, as the study was focused on the composition of phytoplankton to assess site variation. Other unmeasured parameters including intra-hapa water flow, fouling rates and their indirect effect, turbidity, and the composition of sediment may also have influenced water quality and food availability. Given these limitations, future research should include a more thorough analysis of environmental factors both inside and outside the hapas, and consider comparative studies between pond and ocean-based nursery systems to optimize rearing conditions for juvenile *H. scabra*.

The results of this study indicate that controlled pond environments may offer more stable conditions for nursery-reared *H. scabra* in comparison to ocean-based hapa nurseries, reinforcing the potential for land-based nursery optimization, particularly in Indonesia. The excellent growth performance of juvenile *H. scabra* in otherwise unused inlet sluices may offer opportunities for co-use of pond systems, where ponds are occupied by other species or larger sea cucumbers during grow-out. Despite the MIS site representing a small proportion of the entire site system, the current results are applicable to commercial operations as they highlight the importance of nursery site selection and water circulation, particularly in the dry season. The nursery system based on hapa utilized in this study is scalable, cost-effective, and adaptable to existing pond infrastructure. Therefore, commercial hatcheries could improve productivity by strategically placing nursery units in areas with active circulation or close to water inflow zones.

5 | CONCLUSIONS

The nursery site system using floating hapas influenced the growth performance of juvenile *H. scabra* in earthen ponds in Lombok, Indonesia. The main inlet sluice (MIS) exhibited the highest growth rates, possibly due to factors such as better water movement and natural food availability. Survival rates did not differ among treatments, and fertilization or stirring processes showed no discernible effects on the growth of juveniles. As the MIS represents only a small portion of the nursery site system, future attempts to scale up production should focus on replicating favorable conditions for successful nursery holding. These include improved water circulation, stable water quality, and increased availability of natural food across larger pond areas. The current results proffer practical recommendations for commercial aquaculture, such as the strategic positioning of nursery hapas close to water inflows to promote juvenile growth. Despite being pilot scale, nursery systems based on hapas are cost-effective, scalable, and adaptable to existing pond infrastructure. Future studies should explore how to replicate the favorable conditions of inlet areas within the larger pond ecosystems and under different seasonal conditions to ensure consistent and improved productivity at commercial scales.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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