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Physical Properties and Continuous Cleaning Process Design for Sea Cucumber Hatchery Mesh-Panel Substrates

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Abstract

Rope-strung polyethylene mesh panels are widely used as settlement substrates in Japanese sea cucumber (*Apostichopus japonicus*) hatcheries. Uneaten feed, feces and deposited particles accumulate on panel surfaces, in mesh openings and between layers, making manual rinsing, draining and air-drying labor-intensive and restricting throughput expansion during peak hatchery seasons. To provide a basis for designing a continuous production line for cleaning sea cucumber hatchery substrates, field surveys and laboratory measurements were carried out on substrates collected from commercial hatcheries in Dalian, China. The geometry of typical assemblies was recorded; single-strand nylon connecting ropes and polyethylene monofilaments were tensile-tested at 100 mm/min; wet assemblies were oven-dried at 120 °C to determine drying mass loss and wet-basis moisture content; and fouling deposits were sampled for pH, moisture content and wet density. The results show that typical assemblies contain 7–10 mesh layers, with unfolded panels 430–480 mm long and 360–400 mm wide, mesh openings of 0.5–0.7 mm × 0.6–0.8 mm and monofilaments 0.26–0.28 mm in diameter. The breaking forces of nylon strands and polyethylene monofilaments are (357.65 ± 21.64) N and (16.38 ± 1.35) N, respectively. The mean drying mass loss per assembly is 110.00 g, corresponding to a wet-basis moisture content of (25.21 ± 1.11)%. On this basis, a continuous process line was designed integrating overhead-chain conveyance with panel guiding, staggered two-sided high-pressure water-jet cleaning, vibration dewatering, hot-air drying and automatic unhooking and counting; the cleaning wastewater is treated by trough collection, screen filtration and settling. The line throughput and hot-air water-removal load are linked to hook pitch, chain speed and the residence time of each station, providing an initial basis for station layout and prototype parameter commissioning.

Keywords

Sea Cucumber Hatchery; Mesh-Panel Settlement Substrate; Tensile Force; High-Pressure Water Jet; Vibration Dewatering.

1. Introduction

The material and surface condition of a settlement substrate can affect larval settlement and metamorphosis in the Japanese sea cucumber [1]. Industrial hatcheries use rope-strung, flexible mesh panels whose surfaces and interlayer gaps provide settlement and feeding space for early-stage and juvenile sea cucumbers. Uneaten feed, feces, and deposited particles accumulate on the panels, in mesh openings, and between layers. During replacement, workers shake off the juveniles and transfer the removed assemblies for individual rinsing, draining, air drying, and sorting. At peak volumes,

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spreading panels, handling individual assemblies, and allocating space for drying complicate operations.

Song [2] investigated chain conveying and water-jet cleaning equipment for sea cucumber settlement substrates. The cleaner disclosed by Mu et al. [3] also uses chain suspension, guides to spread the panels, staggered spray nozzles, and hot-air drying. Tests on aquaculture netting have shown that water-jet cleaning methods differ in fouling removal and surface damage [4]. Tests on micro-irrigation filter screens also showed that jet parameters affect cleaning effectiveness and damage [5]. When designing a cleaning zone for flexible multilayer panels, interlayer shielding and jet-induced sway must also be considered. Water retained by the panels after rinsing is carried into the drying stage, and wastewater from cleaning and dewatering requires collection at the point of generation.

In this study, we measured panel and rope dimensions, specimen tensile forces, and drying mass loss on actual rope-strung polyethylene substrates used in hatcheries. Together with fouling deposit analyses and observations of the replacement process, these measurements were used to work out the main design requirements-suspension and guiding, water-jet cleaning, staged dewatering, and preliminary wastewater separation.

2. Materials and Methods

2.1 Field Survey and Substrate Geometry

Field surveys were conducted from 20 to 23 March 2026 at Dalian Jintuo Aquatic Food Co., Ltd. and other hatcheries. Tank layout, the number of substrates per tank, and the post-replacement cleaning procedure were documented by observing operations, measuring tank and substrate dimensions, and confirming replacement intervals and batch cleaning quantities with hatchery staff. A set of panels strung on one connecting rope was counted as one assembly. For typical assemblies, the number of layers, panel length and width, mesh opening length and width, monofilament diameter, and connecting rope construction were recorded.

The substrates consisted of polyethylene mesh panels strung on nylon rope. A top float and a ceramic sinker at the bottom maintain their orientation in water. Each panel assembly is cleaned as a unit. Fig. 1 shows a rope-strung assembly and substrates piled up before cleaning.



(a) (b)

Fig. 1 Mesh-panel settlement substrate and substrates awaiting cleaning

(a) Rope-strung mesh-panel substrate (b) Substrates piled up for cleaning

2.2 Tensile Tests of Nylon Rope Strands and Polyethylene Monofilaments

Single-strand specimens were taken from the nylon connecting ropes, and monofilament specimens were cut from the polyethylene panels. Ten specimens of each type were tested. Each specimen was secured between the upper and lower grips of a WDB-01A computer-controlled electronic peel tester and pulled at 100 mm/min. An ACH-11M high-resolution camera recorded specimen condition. Tensile forces for each type were summarized by mean, sample standard deviation, range, and

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coefficient of variation. The initial gauge length between the grips was 250 mm. Dry specimens were tested at (20 ± 2) °C and (65 ± 4)% relative humidity.

2.3 Weighing of Substrates before and after Oven Drying

Wet masses were recorded for five assemblies of the same type after removal from seawater. Each was dried in a DHG-9240A electric forced-air circulation oven with a final program temperature of 120 °C and then reweighed. For each assembly, the mass loss on drying was calculated from the two measurements and converted to wet-basis moisture content using Eq. (1). The conversion assumes that water evaporation accounted for most of the mass loss.

$$W = \frac{m_{\mathrm{w}} - m_{\mathrm{d}}}{m_{\mathrm{w}}} \times 100\% \quad (1)$$

where W is wet-basis moisture content (%), mw and md are the wet mass and the final dried mass, respectively (g).

The procedure specified 5 min of suspended draining after removal from the water and weighing on a balance with a capacity of at least 1 kg and a 0.01 g scale interval. Once the appropriate temperature was confirmed, each repeat drying cycle lasted 30 min. Specimens were cooled to room temperature in a desiccator before weighing. Constant mass was defined as an absolute difference between successive weighings of no more than 0.10% of the preceding mass.



Fig. 2 Tensile test and oven-drying equipment

(a) Nylon rope strand under tension (b) Polyethylene monofilament under tension (c) Forced-air oven

2.4 Fouling Deposit Analysis Records

Field observations documented deposits on panel surfaces, in mesh openings, and where panels touched. Test records for three deposit samples (B-01, B-02, B-03) were compiled for pH, moisture content, wet density, and other properties.

3. Results and Analysis

3.1 Substrate Replacement Workload and Geometry

Individual tanks at the surveyed hatcheries covered about 30–40 m², with an effective water depth of about 1.45–1.75 m. Each held about 120 assemblies (typically six bundles of about 20 assemblies), which were generally used for 7–14 days before replacement, depending on fouling. A hatchery unit with 20–40 tanks held about 2,400–4,800 assemblies. When several units at Dalian Jintuo Aquatic Food Co., Ltd. replaced substrates simultaneously, about 9,000 assemblies needed cleaning in one batch. This concentrated workload requires the conveyor to accommodate the throughput of rinsing, dewatering, and collection.

Typical assemblies were about 1,500–1,750 mm high, with 7–10 mesh layers. Unfolded panels were 430–480 mm long and 360–400 mm wide. Mesh openings measured 0.5–0.7 mm in length and 0.6–0.8 mm in width. Mesh monofilament diameters were 0.26–0.28 mm, and all connecting ropes had

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three strands (Table 1). Station height must accommodate the spread panels and their fixtures when suspended. Lateral clearance and spray width should account for the orientation of the hanging panels and for sway during conveyance.

Table 1. Typical geometric parameters of mesh-panel settlement substrates

Layers	Panel L × W /mm	Opening L × W /mm	Mesh filament Ø /mm	Rope strands	Nylon filament Ø /mm
7	430×400	0.6×0.6	0.26	3	0.31
8	440×360	0.5×0.6	0.27	3	0.30
8	480×380	0.6×0.7	0.27	3	0.35
9	450×400	0.7×0.8	0.28	3	0.40
10	460×380	0.7×0.8	0.28	3	0.34

3.2 Tensile Forces of the Two Specimen Types

Nylon rope strand specimens had tensile forces of 308.01–386.12 N, averaging (357.65 ± 21.64) N (mean ± sample standard deviation), with a coefficient of variation of 6.05%. Polyethylene monofilament specimens had tensile forces of 14.32–18.98 N, averaging (16.38 ± 1.35) N, with a coefficient of variation of 8.24%. Fig. 3 shows individual readings and group means.

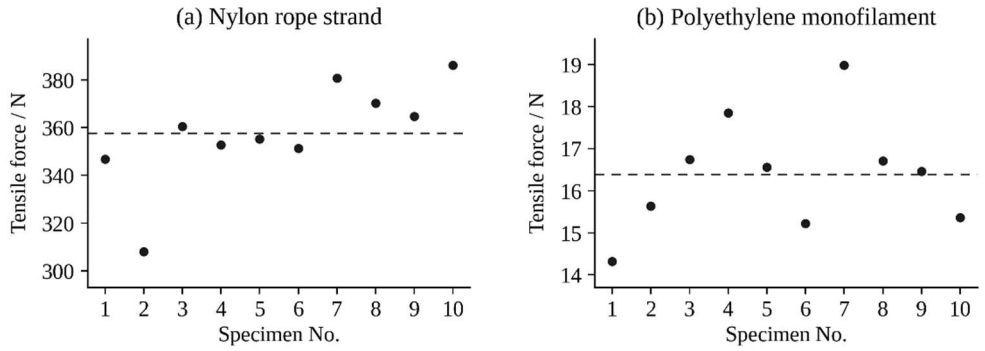


Fig. 3 Tensile forces of nylon rope strand and polyethylene monofilament specimens
Solid markers show individual measurements, and dashed lines show group arithmetic means.

These values correspond to the actual strand and monofilament diameters tested. On the line, the suspension load is borne by the rope-end connection and hook, while the jets and any restraints act directly on the panels. If we hang by the rope ends and use guides to limit lateral sway, the fine filaments are less likely to be pinched locally. For a full assembly, the allowable load at the suspension point still needs to be checked-this should include the connection itself, long-term immersion effects, and dynamic loads during conveyor start-up and stop.

3.3 Mass Loss on Drying and Wet-Basis Moisture Content

The five assemblies had wet masses of 414.04–452.41 g and final dried masses of 310.91–335.23 g, with mass losses of 102.41–120.62 g (Table 2). Mean mass loss was 110.00 g per assembly. Calculated wet-basis moisture content ranged from 23.94% to 26.74%, averaging (25.21 ± 1.11)%. Under the initial sampling conditions, the assemblies lost about one-quarter of their wet mass during drying.

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Table 2. Substrate masses before and after oven drying and wet-basis moisture content

Specimen No.	**Wet mass /g**	**Mass after drying /g**	**Mass loss /g**	**Moisture, w.b. /%**
1	414.04	310.91	103.13	24.91
2	427.69	325.28	102.41	23.94
3	434.14	327.48	106.66	24.57
4	451.05	330.43	120.62	26.74
5	452.41	335.23	117.18	25.90
Mean ± SD	435.87 ± 16.21	325.87 ± 9.15	110.00 ± 8.37	25.21 ± 1.11

The drying loss mainly reflects the water held by the substrates after immersion—some trapped in the mesh openings, some between touching panels. A certain amount drains off while the assemblies hang suspended; the rest has to be handled by the dewatering station. On a continuous line, spray pressure, residence time, and how well water can drain away all affect how much water reaches the vibration stage. In practice, the hot-air water removal load should be checked by weighing assemblies again after vibration dewatering.

3.4 Distribution and Wet Properties of Fouling Deposits

The wet densities given here are for the bulk samples as received; actual densities at the panel surface may differ.

Table 3. Test results for fouling deposit samples

Sample No.	**pH**	**Water /%**	**Wet density /(g·cm^{-3})**
B-01	7.22	69.4	0.95
B-02	7.31	77.4	0.94
B-03	7.25	74.0	0.90

4. Continuous Cleaning Process Design

4.1 Overall Layout

An overhead chain conveyor links the stations for hanging and guiding, two-sided water-jet cleaning, vibration dewatering, hot-air drying, and unhooking and collection (Fig. 4). Once removed from the tank and cleared of juveniles, the substrates are hung manually by their connecting ropes, and guides help spread the panels. Troughs beneath the washing and vibration zones collect dislodged deposits and dripping water. The hot-air zone is separated from the wet zones. Dried assemblies are unhooked, counted, and collected in a bin at the end of the line.

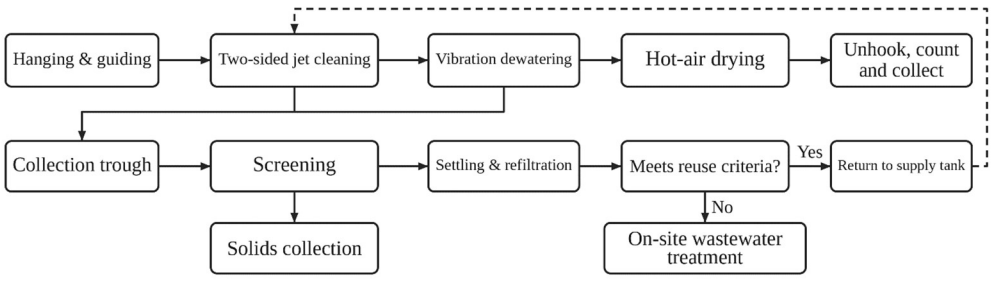


Fig. 4 Continuous substrate cleaning and wastewater treatment process

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4.2 Suspended Conveyance and Water-Jet Cleaning

Conventional high-pressure water jets provide the main cleaning action. Nozzles are staggered on both sides so that jet impact and flow along the mesh dislodge and carry away deposits. Contact between panels can shield surfaces from the jets. Guides spread the panels before spraying, limit sway, and maintain the nozzle-to-panel distance in the spray zone. Spray overlap on the two sides must be checked against the effective cleaning width on the panels. Jet pressure, standoff distance, spray angle, and conveyor speed jointly affect intensity and coverage. Parameter tests should assess fouling removal, filament breakage, and changes in mesh opening shape.

Chemical cleaning requires rinsing and residue control. Ultrasonic cleaning requires a tank large enough for the spread substrates. Dry-ice cleaning requires a continuous dry-ice supply and suitable blasting equipment. Cavitating jets have shown potential for cleaning some aquaculture nets [4]. The combined cavitating jet and carbon dioxide option considered here also requires dedicated cavitation components and carbon dioxide supply and control units, increasing procurement, consumable supply, and maintenance costs. To accommodate batch operation, the selected system uses water as the cleaning medium and consists of a pump, piping, and conventional nozzles.

The conveyor is sized according to stage residence times and the loading rate. Assuming a constant conveyor speed, evenly spaced hooks, and one assembly loaded on each successive hook, the transit time through each stage and theoretical throughput are calculated using Eq. (2).

$$t_{\mathrm{i}} = \frac{L_{\mathrm{i}}}{v}, \qquad q = \frac{3600}{s} \tag{2}$$

where ti is the transit time through stage i (s), Li is the effective stage length along the conveyor (m), v is chain speed (m/s), s is hook pitch (m), and q is theoretical throughput (assemblies/h). For spaced nozzles, local exposure time is based on the actual spray coverage length rather than the full stage length. Stage lengths need to be matched to the required cleaning, dewatering, and drying times at the chosen chain speed. When measuring actual throughput, empty hooks, loading/unloading pauses, and maintenance time all have to be taken into account.

4.3 Vibration Dewatering and Hot-Air Drying

Centrifugal dewatering requires batch loading and unloading, and air drying requires a separate area for spreading and stacking the panels. A vibration stage between the rinse outlet and hot-air zone allows substrates to remain suspended and enter the drying station continuously. Reciprocating motion causes surface droplets to coalesce and fall under gravity. Guides limit sway to prevent adjacent assemblies from colliding. Hot air removes moisture remaining on and between panels. Polyethylene grades respond differently to heat [6]. The operating temperature, air speed, and residence time should be set together using the actual panel temperature rise, changes in mesh opening shape, and residual moisture content at the outlet.

The water removal load of the hot-air stage is estimated from masses measured at the outlets of the vibration and hot-air stages. With the actual throughput during continuous operation denoted by q_{a}, the mean mass difference per assembly between the two outlets is converted to a water removal rate using Eq. (3).

$$M_{\mathrm{ev}} = q_{\mathrm{a}} \left(m_{\mathrm{v}} - m_{\mathrm{f}}\right) \tag{3}$$

where Mev is the hot-air water removal rate (kg/h), qa is actual throughput (assemblies/h), and mv and mf are mean masses per assembly after vibration dewatering and after hot-air drying, respectively. Assuming the mass loss is mostly water, the difference between these two outlet masses gives an estimate of hot-air water removal. The mass drop across the vibration stage, in turn, shows how much the mechanical dewatering step contributes.

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4.4 Wastewater Collection and Solid–Liquid Separation

Wastewater from jet cleaning and mechanical dewatering is collected in troughs and passed through a replaceable screen to remove coarse solids. The screened water enters a settling tank. After further settling and filtration, the proportion to be reused is determined from water quality, the requirements of the supply system, and nozzle flow requirements. Wastewater that fails to meet reuse criteria is routed to the appropriate on-site treatment stage. Solids removal from land-based aquaculture effluent depends on particle characteristics and the separation equipment [7]. Screen aperture size and cleaning intervals should be set using measurements of wastewater particle size distribution, clogging, and flow rate.

Prototype tests will assess fouling removal from the change in visible fouled area in the same region before and after cleaning. Material damage will be assessed from filament breakage, mesh opening deformation, and assembly condition. Weighing each assembly after rinsing, vibration, and hot-air drying will assess both dewatering stages. The coordination of the stages will be assessed during continuous operation from actual throughput, water use per unit processed, and the condition of the refiltered effluent.

5. Conclusion

(1) The rope-strung polyethylene settlement substrates used in hatcheries consist of flexible mesh layers with small openings and rope-end connections. Measured assemblies had 7–10 layers, and the longest unfolded panel side reached 480 mm. Nylon rope strands and polyethylene monofilaments broke at (357.65 ± 21.64) N and (16.38 ± 1.35) N, respectively. These specimen-level data can be used as a reference when designing rope-end hanging, panel guiding, and jet-damage assessment.

(2) Oven drying of five assemblies gave a mass loss of (110.00 ± 8.37) g per assembly, equivalent to a wet-basis moisture content of (25.21 ± 1.11)%. In the proposed continuous process, vibration dewatering removes free water first, and the assemblies then enter the hot-air dryer. The hot-air water removal load can be estimated from the mass difference between the vibration and drying outlets multiplied by actual throughput.

(3) The proposed process line integrates chain suspension and panel guiding, two-sided staggered water jets, vibration dewatering, hot-air drying, and automatic unhooking and counting. Wastewater from the wet stages is collected, screened, and settled; the reusable fraction is returned to the process after further filtration. Stage length, hook pitch, and chain speed are linked by the throughput equations given above, which can be used to set initial prototype operating parameters and then verified against measured fouling removal, panel damage, and residual moisture at each station.

Acknowledgments

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