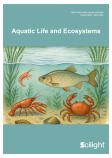
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Review and Outlook for Aquaculture of Ornate Spiny Lobster (*Panulirus ornatus*)

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Abstract: *Panulirus ornatus* is a high-value seafood species of the Indo-West Pacific. Anthropogenic pressures since the mid-20th century have led to noticeable declines in wild populations, prompting China to enact protective legislation, while other countries focus on aquaculture and germplasm research to sustain supply and preserve wild populations. Current practices rely on rearing wild-caught post-pueruli in sea net cages, as full-life-cycle commercial breeding faces challenges, high mortality of phyllosoma, poorly understood nutritional needs, and uncertain environmental factors. Juvenile cannibalism during moulting further hinders high-density culture, requiring advanced management to reduce aggression. This review synthesizes progress in *P. ornatus* aquaculture since 2000, covering germplasm resources, reproduction, larval development, artificial diets, culture techniques, and disease management. It discusses major constraints such as inadequate nutrient profiles for phyllosoma and ineffective cannibalism control for post-pueruli, which limit scalable breeding. The review identifies critical knowledge gaps, proposes research priorities, focusing on nutritional and artificial environment optimization, and underscores the need for technology to advance full-life-cycle breeding. These efforts are vital for sustainable *P. ornatus* aquaculture to meet global demand while conserving wild stocks.

Keywords: *Panulirus ornatus*; aquaculture; phyllosoma; post-pueruli

1. Introduction

Ornate spiny lobster (*Panulirus ornatus*) is a decapod crustacean belonging to the family Palinuridae [1]. *P. ornatus* is a brightly coloured species with a blue-green carapace with yellow-red spines and banded or marbled abdomen and walking legs with vivid streaks and spots. *P. ornatus* is a species relatively large in Panulirus, individuals typically reach 30–35 cm but can grow up to 50 cm in length [2]. *P. ornatus* is highly valued in the market for its distinctive, vibrant coloration and considerable body size among spiny lobsters. With global aquaculture efforts shifting from wild capture toward the development of complete life-cycle cultivation technologies, this species presents significant potential for sustainable commercial production.

Panulirus ornatus has long been a valuable resource in Indo-Pacific fisheries, prized for its culinary value and ornamental carapace. However, uncontrolled fishing and the rise of industrial fishing practices led to significant declines in wild populations by the mid-1970s, driven by overfishing, habitat degradation, and environmental pollution. In aquaculture contexts, *P. ornatus* is often compared with prawns, which reach market

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size within months rather than years. By this standard, this slow-growing species faced resource depletion, prompting conservation measures. In China, *P. ornatus* fishing is strictly regulated, and the species was designated a National Class II Protected Animal on 5 February 2021, under China's List of Wild Animals under State Key Protection [3]. Activities such as capturing, purchasing, transporting, or selling are prohibited without authorization. In response to declining wild stocks, several countries have initiated research into aquaculture techniques to cultivate *P. ornatus* under controlled conditions, aiming to reduce pressure on natural populations. Australia has claimed the completion of the entire life cycle of *P. ornatus* in a controlled setting [4], but this has apparently not yet developed into globally scalable commercial production, and supporting data on survival rates, cost-effectiveness, and operational replication remain limited or unpublished. Despite advancements in *P. ornatus* aquaculture, significant challenges persist, limiting its scalability and sustainability. An important constraint is the lack of artificially produced seed stock, with current commercial practices relying almost completely on wild-caught pueruli, perpetuating dependence on natural juvenile recruitment. These bottlenecks impede the industrialization of *P. ornatus* aquaculture and its supply chains.

To foster sustainable development, this review synthesizes global research from January 2000 to August 2025, focusing on germplasm resources, artificial seed production, and aquaculture technologies. As a high-value crustacean with substantial commercial potential, *Panulirus ornatus* faces critical barriers in artificial breeding, larval rearing, feed development, and scalable farming systems. This study consolidates existing knowledge, evaluates industrial prospects, and identifies priority scientific and technical challenges to achieve closed-lifecycle aquaculture and ensure sustainable utilization of *P. ornatus*.

2. Biological Characteristics

Panulirus ornatus is widely distributed across the Indo-West Pacific, from the Red Sea and East Africa to southern Japan, Australia, and Pacific islands. In non-breeding season, *Panulirus ornatus* inhabits crevices or caves beneath reefs in shallow coastal waters at depths of 1–8m. Adult of *P. ornatus* typically solitary or paired while juvenile may form larger groups [1].

During the breeding season, adult *Panulirus ornatus* migrates to depths of 50–60 m at the edge of continental shelf sediment beds for spawning [2]. The following data in this paragraph are derived from the same source [2] Females produce approximately 500 thousand to 2 million eggs per spawning event, with 2–3 spawning events annually. Hatched planktonic phyllosoma undergoes 11 developmental stages, involving up to 20 successive moults, reaching a final stage (>25 mm carapace length, CL). This stage metamorphoses into a lobster-like, free-swimming, transparent puerulus, which persists for 2–3 weeks while seeking suitable habitats. Upon locating a suitable substrate, the pigmented puerulus settles, moults into the first juvenile stage, and adopts a benthic lifestyle. Sexual maturity is attained in the second year post-puerulus, at a CL of >90 mm [2].

3. Materials and Methods

Literature published in Chinese was retrieved from the China National Knowledge Infrastructure (CNKI) database. The search covered publications from 1 January 2000, to 31 August 2025. The search strategy involved querying the terms "*Panulirus ornatus*" in the article title, abstract, and author keywords. All results other than academic journal articles and dissertations/thesis were excluded.

Literature published in English was retrieved from the ScienceDirect database and the Web of Science Core Collection (SCIE). The same search term ("*Panulirus ornatus*") was applied to the title, abstract, and author keywords fields in both databases. In ScienceDirect, results were limited to research articles. In Web of Science (SCIE), results were filtered to include only articles, review articles, and dissertation theses.

Microsoft Excel was utilized to organize the retrieved information, including publication titles, author keywords, abstracts, publication dates, authors, and journal sources. The country of origin for each publication was determined by the institutional affiliation of the first author. The relevance of each publication to the target species was assessed by reviewing its title and abstract. Articles confirmed to be relevant were subsequently categorized into five thematic areas included Germplasm Resources, Reproduction and Larval Development, Artificial Diet, Culture Techniques and Diseases and Toxicology. The search window defines the primary retrieval period. A limited number of foundational works and non-journal sources published outside this window were also cited where essential for background or regulatory context.

4. Results

A total of 220 Chinese and English publications were identified through database. Among these publications, 34 publications were retrieved from CNKI, 51 from ScienceDirect, and 135 from the Web of Science Core

Collection (SCIE). After the removal of non-research publications, duplicate records, and studies irrelevant to *Panulirus ornatus*, 142 relevant publications were retained for subsequent analysis.

The number of publications on *Panulirus ornatus* has generally increased over time. The years 2022, 2023, and 2024 recorded the highest number of publications, with 14, 12, and 13 publications, respectively (Figure 1). Data for 2025 includes only publications up to August. Publication dates were determined based on the journal's official publication date. Notably, Aquaculture Volume 611, originally scheduled for 1 January 2026, was published ahead of schedule, resulting in one publication attributed to 2026.

A total of 142 publications were identified, originating from 12 countries and territories: Australia, Bangladesh, China, India, Indonesia, Iran, Malaysia, New Caledonia, New Zealand, Oman, the Philippines, and Vietnam (Figure 2). Australia contributed the highest number of publications, accounting for over half of the total. Australian research primarily focused on the reproduction and development of *Panulirus ornatus*, followed by studies on artificial diets. China contributed 21 publications, with a primary focus on germplasm resources and culture techniques. Indonesia followed with 6 publications, predominantly centred on germplasm resources. New Zealand and Malaysia respectively contributed 6 and 4 publications (Figure 2).

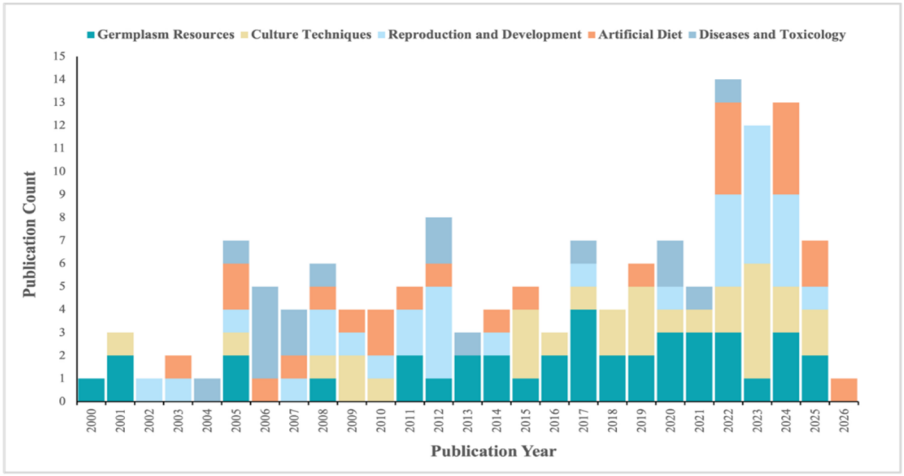


Figure 1. Annual number of publications on *Panulirus ornatus* (2000–August 2025). Over this period, publications are categorized as follows: Artificial Diet (25 publications, 18%), Culture Techniques (29 publications, 20%), Diseases and Toxicology (17 publications, 12%), Germplasm Resources (39 publications, 27%), and Reproduction and Development (32 publications, 23%).

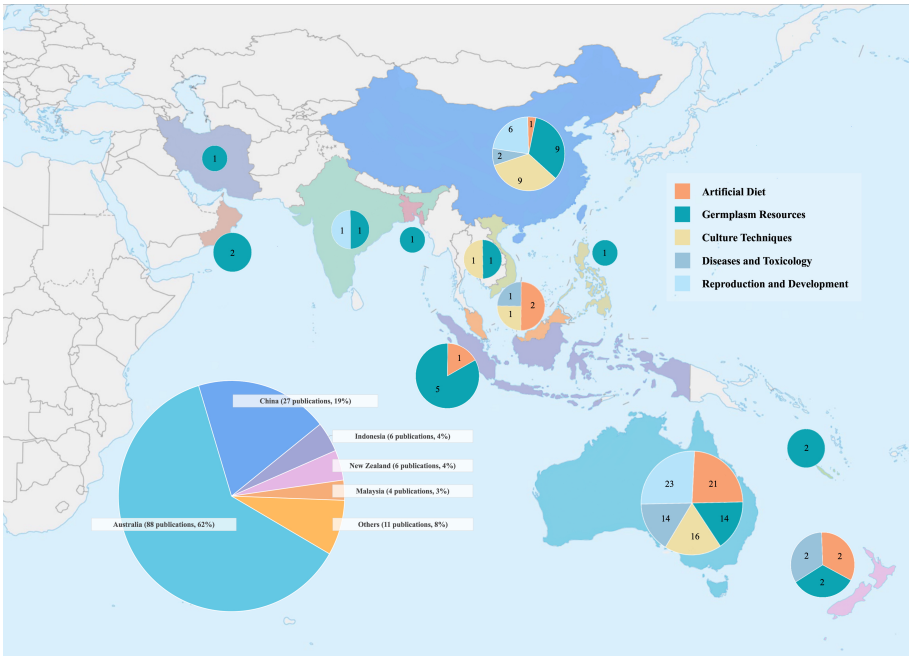


Figure 2. Country-wise origin and research theme distribution of *Panulirus ornatus* studies and proportion of *P. ornatus'* publications by country. The number in the pie chart show the country's number of published articles in the thematic areas.

Across various research areas, germplasm resources were the most studied, with 39 publications, followed by reproduction and development with 32 publications. Diseases and toxicology received the least attention, with 17 publications (Figure 1). Australia has the most publishment within all these research areas.

5. Germplasm Resources

5.1. Species Identification

The habitat of *Panulirus ornatus* has overlap with various species of spiny lobster, accurate species identification is a critical step for collecting wild juveniles and subsequent artificial breeding. Morphological classification remains the most straightforward method. For adult and juvenile stages, the classification mainly based on differences in cephalothorax, abdomen, tail shape, and dorsal colour and spine exoskeleton morphology to achieve species differentiation [5]. For the puerulus stage, recent work in Palawan has shown that *Panulirus ornatus* puerulus possesses a terminal bulb and a single brown cross-band at the midpoint of the antenna, distinguishing it from other species [6]. Infrared spectroscopy (FTIR), second-derivative spectroscopy (SDIR), and two-dimensional correlation infrared spectroscopy (2DIR) can also enable rapid and effective identification through differences in characteristic peaks [7]. Specifically, SDIR can be used to distinguish *P. ornatus* from *Panulirus homarus*, while 2DIR further confirms variations in the types and contents of amino acids and proteins between these two species.

Molecular identification techniques are even more precise, with mitochondrial COI gene [8,9] and 16S rRNA [7] both applicable for taxonomic identification, while 16S rRNA amplification has a higher success rate than COI marker sequences [9]. The results from these molecular techniques confirmed that interspecific differences are substantially greater than intraspecific variations. Furthermore, the phylogenetic tree showed that *P. homarus*, *Panulirus ornatus*, *Panulirus polyphagus*, and *Panulirus versicolor* belong to the same clade, with *P. homarus* and *P. ornatus* being more closely related to each other within a smaller subclade [8,9]. The correlation between genetic markers and phenotypic traits enables precise molecular guidance for selective breeding and hybridization.

5.2. Germplasm Resource Management

Research on the germplasm resource management of the *Panulirus ornatus* encompasses genetic differentiation, population dispersal, and population structuring, providing critical insights for sustainable fishery management and aquaculture. Current knowledge of *P. ornatus* population connectivity derives largely from studies conducted in Australian waters, and now has progressively expanded to cover the species' entire Indo-West Pacific distribution. Ocean currents drive the dispersal of *P. ornatus* phyllosoma and pueruli [10–12], ocean eddies and sea surface temperatures can restrict larval dispersal, leading to population isolation [13]. Early genetic studies using mtDNA and microsatellite markers within the South-East Asian archipelago detected no significant structure ($\Phi ST = -0.008$; $FST = 0.003$), leading to the hypothesis of a single genetic stock across this region. However, Yellapu et al. (2017) expanded sampling to 17 locations across the entire Indo-West Pacific and, using mtDNA control region sequences, detected significant population subdivision for the first time ($\Phi ST = 0.113$), with the western Indian Ocean and western Australian populations being the most differentiated [14]. The application of genome-wide SNPs (3008 markers) by Farhadi et al. (2022) further refined this picture, revealing fine-scale genetic structure even within the previously assumed homogeneous Southeast Asian region (global $FST = 0.046$) and proposing the division of the species' distribution into five management units [15]. The long-standing absence of genomic resources from Chinese waters was addressed by Ren et al. (2024), who completed the first chromosome-level genome assembly of *P. ornatus* from a male specimen collected in Hainan, China [16]. Subsequently, Yellapu et al. (2025) employed 13 microsatellite markers across the same 17 locations as Yellapu et al. (2017) and corroborated the existence of significant genetic structure, while identifying oceanic vorticity, convergence, and sea surface temperature as key drivers of genetic divergence [13]. Synthesizing these findings, Plagányi et al. (2025) confirmed the five management units, clarified that the species' Class II protected status in China reflects local conditions rather than global decline [17]. The value of genetic approaches for traceability in supply chains are highlighted to distinguish between sustainably managed and depleted stocks. Therefore, oceanographic barriers have shaped a complex population structure in *P. ornatus*. The utilization of this resource must be distinguished across regions, necessitating the formulation of region-specific fisheries policies.

5.3. Molecular Markers, Genome, and Functional Genes

Early genetic studies of *Panulirus ornatus* relied on traditional molecular markers. RAPD analysis was used to assess genetic diversity and interspecific relationships among congeneric species [18]. Multiple panels of polymorphic microsatellite markers were subsequently developed for population genetic studies and showed transferability to related taxa [19–21]. However, technical issues such as null alleles complicated their application

in structured populations [19]. Moreover, the low efficiency of conventional marker development limited their integration into systematic breeding programs.

The advent of sequencing technologies transformed this landscape. The complete mitochondrial genome was first sequenced, revealing a novel 89 bp duplication and validating the use of protein-coding genes for decapod phylogeny [22]. A chromosome-level reference genome was subsequently assembled for *Panulirus ornatus* (2.65 Gb, 73 chromosomes), annotating 22,752 protein-coding genes [16]. This genomic resource enabled genome-wide marker development at unprecedented resolution. SNP genotyping, for instance, has revealed fine-scale population structure and delineated distinct management units across the Indo-Pacific [15]. Genomic analyses have also begun to elucidate adaptation mechanisms linked to oceanographic barriers [13,15].

Concurrent with genome assembly, transcriptomic approaches have accelerated the characterization of functional genes relevant to aquaculture. Key discoveries include a male-specific Dmrt gene (iDMY) as a candidate master sex regulator [23]. Studies have characterized nuclear receptor genes involved in ecdysone signalling during metamorphosis [24] and detailed the cytochrome P450 superfamily associated with moulting [25]. Neuropeptide dynamics during metamorphosis have also been profiled [26]. Beyond development, transcriptomics has informed health management. Research revealed that low expression of core RNAi pathway genes underlies inefficient gene silencing in this species [27]. Transcriptomic studies have also provided insights into physiological responses to salinity and ammonia stress [28,29] as well as juvenile lipid nutrition [4]. These findings offer candidate genes for marker-assisted selection tailored to diverse aquaculture conditions.

Despite these advances, the development of domesticated *Panulirus ornatus* varieties remains nascent. Progress is constrained by continued reliance on wild seed and the species' complex life cycle. Leveraging these genomic tools and functional insights will be essential to accelerate selective breeding and achieve genetic improvement for this high-value species.

6. Reproduction and Larval Development

6.1. Reproduction and Egg Hatching

The reproduction and egg incubation of *Panulirus ornatus,* constitute a complex process regulated by both environmental factors and physiological mechanisms. Photoperiod serves as the primary environmental cue synchronizing spawning activity, with a regime of 14.5L:9.5D being more effective in stimulating spawning compared to 13L:11D; reproduction is often preceded a few days after moulting, during the hard-shelled stage. and a physiological recovery period may be required between reproductive seasons [30].

The length of *Panulirus ornatus* has a positive relationship with reproductive frequency and fecundity. Smaller individuals (93.5–105 mm CL) reproduce twice in five months, yielding 32.97–40.34 × 10^4 eggs per spawn with a 77% hatching rate [31]. Larger lobsters (1.3–1.6 kg) spawn thrice in six months, producing up to 1.6 million eggs [32]. Eyestalk ablation, which is a technique to accelerate ovarian maturation, commonly applied to enhance crustacean reproduction, is proven effective in *P. ornatus*.

Embryonic development comprises 11 stages, with key genes such as *nanos* and *brachyury* being specifically expressed during early gastrulation, while neuropeptides become active in later phases [33]. Hatching duration is highly temperature-dependent within the range of 24–30 °C, following the model: incubation days = 95.444 − 2.482 × temperature (°C); temperatures ≥32 °C led to failure of hatching [34]. Incubation lasts 22–23 days at 29.2 °C [31] while prediction models based on visual features such as eye development improve accuracy in determining hatching time [33].

6.2. Phyllosoma Development

The phyllosoma development of *Panulirus ornatus* is a complex and highly regulated process involving significant morphological alterations, physiological adaptations, and metabolic reorganization. Scientists have divided this development into 11 distinct stages [2], a process typically advanced through moulting, though not every moult is accompanied by metamorphosis [35]. In artificial culture, larval development often fails to progress beyond Stage VIII, leading to high mortality [36]. Moreover, *P. ornatus* phyllosoma are notably smaller and less developed at hatch compared to temperate spiny lobster species [37], which results in a prolonged developmental period and thereby increases the cost and risk of aquaculture. Optimized aquaculture conditions reduce the time and cost of *P. ornatus* larval rearing [38]. The moult cycle in *P. ornatus* regulates physiological, metabolic, and molecular processes, including ecdysteroid-driven metamorphosis, nutrient metabolism shifts, and stage-specific lipid and mineral requirements, guiding optimized aquaculture strategies [4,25,26,39–44]. Molecularly, 28 cytochrome P450 (CYP450) transcripts, including Halloween gene family members, regulate ecdysteroid synthesis, showing life-stage and tissue-specific expression critical for moulting and metamorphosis [25]. Ecdysteroids initiate metamorphosis, modulated by juvenile hormone, with nuclear receptor homologs indicating conserved regulation [40].

Nutrient metabolism shifts with development: digestive enzyme activity in early phyllosoma (Stages I-III) varies, reflecting stage-specific nutritional needs and informing feeding strategies [41]. Respiration studies (Stages I-IX) show declining oxygen consumption and fluctuating ammonia excretion, with an O:N ratio of 51–180, indicating proteins and lipids as primary metabolic substrates [42]. Body composition changes, with reduced ash and increased carbon, prioritize protein for growth [42]. Lipid nutrition is vital, with exponential increases in body weight and length. Phospholipids dominate, with eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) accumulation, while arachidonic acid (ARA) rises in mid-stage phyllosoma, guiding lipid requirements [43]. Between the 7th and 8th moult cycles, phyllosoma rapidly accumulate nutrient reserves; total lipids drop by day 6 post-moult, with downregulated lipid metabolism genes but no hepatopancreas cytological changes, suggesting alternative regulation [4]. Elemental analysis reveals potassium, calcium, copper, and zinc accumulation in the midgut, hepatopancreas, and epidermis, informing dietary mineral supplementation in aquaculture [44]. Neuroendocrine regulation involves stage-specific neuropeptide expression, with nesfatin downregulation during metamorphosis linked to central nervous system remodelling [26].

7. Artificial Diet

7.1. Live Feed and Inert Feed

In aquaculture of *Panulirus ornatus*, live feeds, particularly *Artemia* nauplii, outperform formulated diets for early-stage (I-VI) phyllosoma due to their suitable size and swimming behaviour [45]. However, with increasing body size and developmental changes in feeding appendages during later phyllosoma stages, *Artemia* become inefficient in both capture and nutrition. Optimal *Artemia* density for newly hatched phyllosoma is 0.5–2.5 mL^{-1}, and 7-day post-hatch phyllosoma can accept 75% formulated feed with 25% *Artemia* to promote feeding [46], supporting early artificial feed introduction within 7–14 days post-hatch. Stomach content analysis of pueruli has identified five copepod species as models for larval feed development [47].

For inert feeds, frozen-thawed mussels (*Mytilus* and *Perna*) are widely used for their palatability and nutrition [48–51]. However, results on growth and survival are inconsistent, possibly due to thawing methods, nutrient losses, or pathogen contamination [49–51].

7.2. Basic Nutritional Requirement

Formulated feed development for *Panulirus ornatus* begins with defining protein-lipid requirements. Initial studies established that protein requirements are lipid-dependent, with optimal crude protein (CP) of 474–533 $g \cdot kg^{-1}$ at 6–10% lipid [52]. Subsequent refinement using attractants and optimized feeding strategies showed that diets require ≥61% CP with a digestible protein-to-energy (P/E) ratio of 29.8 $mg \cdot kJ^{-1}$ for optimal performance [50]. More recent factorial modelling further quantified a CP requirement exceeding 64% dry matter, with 52.7% utilization efficiency and a daily requirement of 7.29 mg digestible CP per gram body weight [53]. Concurrently, a systematic P/E optimization study identified 26.6 $mg \cdot kJ^{-1}$ (55% protein, 9% lipid) as optimal for juvenile growth and digestive enzyme activity [54].

For lipids, the 10% inclusion level remains a key benchmark [52]. Beyond quantity, source and quality are critical; recent work has explored modulating lipid profiles via alternative ingredients, e.g., fish protein hydrolysate (FPH) in black soldier fly diets increased whole-body MUFA and omega-9 levels in juveniles [55]. Carbohydrate requirements are less studied, carbohydrates (mainly corn starch) are used as binders/fillers [51,55], and digestive enzyme ontogeny suggests their importance increases around hatching, indicating stage-dependent roles [56].

7.3. Amino Acid and Fatty Acid Requirements

Quantitative requirements for individual essential amino acids (EAAs) in *Panulirus ornatus* remain unestablished. Current research emphasizes overall protein digestibility over amino acid composition: enzymatically hydrolysed fish meal (HFM) promotes early-stage phyllosoma growth more effectively than intact fish meal, attributed to higher peptide and free amino acid bioavailability rather than gross composition differences [36]. Dose-response studies for specific EAAs are a critical gap.

For fatty acids, *Panulirus ornatus* shows a clear HUFA requirement but poor assimilation of dietary EPA and DHA, as captive phyllosoma fed HUFA-rich diets deposit significantly less of these fatty acids than wild individuals [43]. The lipid profile is dominated by polar lipids, suggesting higher affinity for phospholipid-rich sources over triacylglycerols [57]. For juveniles, body lipid quality can be modulated via feed formulation [58], but systematic dose-response studies for specific fatty acids (linoleic acid, α-linolenic acid, EPA, DHA, arachidonic acid) and EAAs are lacking, representing key barriers to fully optimized feeds.

Fish meal (FM) substitution research remains limited. Defatted black soldier fly (BSF) meal can replace up to 35% of FM without affecting juvenile growth, survival, or moulting; FPH supplementation further enhances growth, but >35% substitution may induce hepatopancreas damage and inflammation [55,59].

Feed additives have been investigated to improve performance and palatability. Supplementing 0.4% mannan oligosaccharide (MOS) for 56 days improved juvenile final weight (2.86 vs. 2.35 g), survival (66.67% vs. 54.76%), and immune resistance in a Vibrio challenge [60]. Krill meal (10%) enhances growth and feed interaction in moist feeds, though less effectively than fresh mussels [49]. Chemical attractants (glycine, taurine, inosine) can enhance palatability, but their effectiveness is constrained by rapid leaching in water [48], and results on feeding response have been inconsistent [61].

Beyond these, systematic research on prebiotics, probiotics, organic acids, and immunostimulants remains lacking, with optimal inclusion levels and long-term effects yet to be determined gaps that must be addressed for precision nutrition strategies.

8. Culture Techniques

The culture techniques for *Panulirus ornatus* remain at a nascent stage. Most available records of culture-environment parameters come from experimental settings for juveniles. Parameters for the larval phase and for commercial-scale culture are rarely disclosed. This imbalance partly reflects the difficulty of maintaining and monitoring larval and commercial systems. It also motivates the environment summary in Table 1, which serves as a baseline for the present work.

8.1. Cannibalism

The moult cycle governs both development and behavioural interactions in juvenile *Panulirus ornatus*, with the Brix index, hepatosomatic index, and ecdysteroid levels serving as stage markers [39]. Communal rearing promotes growth and moulting frequency compared to isolated individuals [62], yet cannibalism, primarily targeting post-moult individuals, remains a major mortality cause among small juveniles (1–3 g), driven by population biomass rather than stocking density per se [58,63,64]. In the limited controlled culture experiments available, mortality is consistently attributed to cannibalism of moulting individuals rather than to density per se, despite considerable variation in reported densities, body sizes, and rearing systems (Table 2). Importantly, cannibalism in this species is selective rather than indiscriminate, being triggered by specific chemical, behavioural, and environmental cues.

Cannibalism is triggered by chemical, behavioural, and environmental cues. The moult-released metabolite N-acetylglucosamine-6-phosphate (GlcNAc-6-P) acts as a key attractant, detected via antennal chemoreceptors, which increases movement and aggression toward unfamiliar conspecifics [65,66].

Mitigation strategies include non-destructive pre-moult detection via ultrasonic imaging [58,67], though spectral and computer vision methods remain unreliable for pre-moult identification due to pigmentation variation [66,67], alongside optimized shelter design, feeding regimes [68], and chemical communication manipulation [65,66].

8.2. Particulate and Soluble Wastes Management

The particulate waste (faeces and uneaten feed) and dissolved inorganic nitrogen (DIN) generated by lobster aquaculture contribute to environmental loading on sediments and water quality. Effective management of nitrogen and carbon waste is crucial in *Panulirus ornatus* culture. Faecal settling velocity varies with feed type (0.30 $cm \cdot s^{-1}$ for seafood-based feed; 0.22 $cm \cdot s^{-1}$ for formulated feed), correlating positively with faecal weight, volume, and density, but not with individual body size. Feeding doubles DIN excretion rates, although no significant differences in carbon or nitrogen content were found in faeces between dietary treatments [69]. Modelling of sea-cage aquaculture indicates that annual carbon deposition can reach 0.1–0.8 $kg \cdot C \cdot m^{-2} \cdot year^{-1}$, with average DIN concentrations around cages ranging from 5.6 to 25 $\mu g \cdot N \cdot L^{-1}$, and peak levels up to 165 $\mu g \cdot N \cdot L^{-1}$ [70]. The use of trash fish results significantly higher carbon and DIN release compared with formulated feed. Thus, improving feed composition can substantially reduce environmental impact. Pollution is generally localized directly below cages, with high stocking densities and low-quality feed markedly exacerbating the effects [70]. Integrating *P. ornatus* with macroalgae, such as the brown algae *Sargassum siliquosum*, in recirculating aquaculture systems (RAS) offers an effective strategy for mitigating nitrogen waste. Nitrogen excretion in, *P. ornatus*, is primarily in the form of ammonium (with urea accounting for 8–13%), and increases significantly after feeding, remaining elevated for 32–38 h. The algae exhibit saturable uptake kinetics for both ammonium and nitrate, with a higher affinity for ammonium. To offset nitrogen pollution in RAS, the recommended biomass stocking ratio of algae to lobster should be maintained between 3.09×10^{-4} and 5.15×10^{-4} [71].

Table 1. Summary of experimental design and culture conditions for *Panulirus ornatus.*

Region	Weight (g)	Stocking Number	Life Phase [a]	Feed	Culture System/Facility	Environmental Parameters				Publications
						Temperature (℃)	Salinity	pH	Photoperiod	
Australia	1.15 ± 0.49	60	Juvenile	IMAS commercial feed	Polyethylene vessels Recirculating Aquaculture System (RAS)	27.8 ± 0.2	25–34	8.18 ± 0.2	\	[28]
	0.0025 ± 0.0001	3000	Phyllosoma	Formulated diet + HFM [b]	U-shaped tanks	26 ± 0.5	34	\	12L:12D	[36]
	2.06 ± 0.08	220	Juvenile	Mussel	Tanks	28 ± 0.16	34.07 ± 0.03	8.11 ± 0.01	10L:14D	[49]
	1.28 ± 0.01	132	Juvenile	Trash fish + 0.4% MOS [c]	Fiberglass tanks	26–28.5	32.5–34	7.01–7.94	\	[60]
	0.48 ± 0. 01	140	Juvenile	IMAS commercial feed	Polyethylene vessels	28	34 ± 0.1	\	12L:12D	[64]
	0.93 ± 0.05	385	Juvenile	Commercial Dry pellet feed	Polypropylene tanks	27.7 ± 0.0	33.7 ± 0.03	8.10 ± 0.01	12L:12D	[72]
China	150	\	Juvenile	Commercial Eel diet + trash fish	Net cage	27–31	28–30	8.3–8.6	\	[73]
Malaysia	0.19 ± 0.01	180	Juvenile	Formulated feed + FBSF [d] + DBSF [e] + Liquid FPH [f]	Aquarium (RAS)	29–30	\	\	12L:12D	[55]

[a]. Stage definitions follow second paragraph of Biological Characteristics. The juvenile stage extends to sexual maturity; [b]. Enzyme hydrolysed fishmeal (HFM); [c]. mannan oligosaccharide (MOS); [d]. Full-fat black soldier fly (FBSF); [e]. defatted BSF (DBSF); [f]. fish protein hydrolysate (FPH).

Table 2. Comparison of stocking density and cannibalism across juvenile *Panulirus ornatus* culture experiments.

Life Phase	Weight (g)	Stocking Density [a]	Culture System/Facility	Shelter	Experiment Day	Mortality Caused by Cannibalism (%)	Non-Moult Cannibalism	Publications
Juveniles	1.35 ± 0.05 g (J3)	11–12 ind./18 L tank	18 L tanks (recirculating)	Mesh-lined PVC shelters	30	>50	Not observed	[63]
Juveniles	3.24 ± 0.09 g	14 ind. × m^{-2}	Flow-through raceway (4000 L, 3000 L compartments)	Opaque PE platforms 600 × 600 mm + coral rubble trays	272	41.7	Not observed	[68]
		29 ind. ×m^{-2}				45.4	Not observed	
		43 ind. × m^{-2}				55.4	Not observed	

[a]. The density values are not directly comparable and are therefore presented in their original units, since the systems differ in type and configuration.

9. Diseases and Toxicology

9.1. Infection and Diseases

The expansion of aquaculture has been accompanied by increased attention to aquatic animal diseases. These present challenges for the industry due to their variety, outbreak frequency, transmission speed, and affected area. In spiny lobsters, diseases often lead to rapid mortality and moulting failure, making early detection and intervention critical. Disease etiology in Panulirus is complex, involving pathogen invasion, environmental abnormalities, nutritional imbalances, and mechanical injuries. Pathogen-induced diseases are among the most reported and have therefore become one of the focuses of research efforts aimed at understanding and managing associated losses.

Panulirus ornatus is susceptible to diverse pathogens throughout its life cycle, including fungi, bacteria, and viruses. Disease susceptibility and transmission routes vary by life stage. Pathogens are easily introduced through live feeds. *Vibrio owensii* DY05, for instance, causes rapid systemic infection in phyllosoma, with 84–89% mortality within 72 h when transmitted via *Artemia* [74]. Phyllosoma are also susceptible to fouling by protozoans (*Zoothamnium* sp.) and filamentous bacteria (*Leucothrix* sp., *Thiothrix* sp.). Such fouling impairs swimming ability and leads to mortality. The major diseases reported in *Panulirus ornatus* culture, together with their aetiological agents and characteristic signs, are summarised in Table 3.

Table 3. Summary of diseases in *Panulirus ornatus.*

Disease Name	Host Life Stage	Pathogen Type	Pathogen	Key Symptoms	Reference(s)
Vibriosis (Larval)	Phyllosoma	Bacterium	*Vibrio owensii* (type strain DY05)	84–89% cumulative mortality within 72 h. Infection cycle: Epithelial cell necrosis and bacterial proliferation in the hepatopancreas.	[74]
Fungal Egg Disease	Embryo/Egg Mass	Fungus	*Zasmidium musae* (strain IPMB LE01)	Healthy orange egg masses contain brownish-black moribund eggs. Hyphae are septate and can form pycnidial conidiomata.	[75]
White Leg Disease (WLD)	Phyllosoma	Bacterium	*Aquimarina* sp. TRL1 (closely related to A. hainanensis).	Signature symptom: Characteristic whitening of pereiopod (walking leg) tissues, which can progress to the carapace. Spot-like lesions; legs may autotomize at joints in severe cases.	[76]
White Spot Syndrome	Juvenile/Adult	Virus	White Spot Syndrome Virus (WSSV)	Lethargy, anorexia, darkening of dorsal surface, reduced activity, typical white spots.	[77]

Physical injury increases disease susceptibility. *Aquimarina* sp. TRL1 causes white leg disease (WLD) in phyllosoma; pereiopod damage serves as a major predisposing factor for infection. Because transmission of WLD is favoured by crowding and physical injury, density management and injury prevention in hatchery practice are central to limiting disease spread [76]. White spot syndrome virus (WSSV) causes 100% mortality within 120 h following intramuscular injection, whereas oral transmission is ineffective, indicating that tissue damage facilitates viral entry [77]. Preventing injury during grow-out is particularly challenging in sea cage farming, where lobsters are exposed to crowding in open water. These stage-specific differences highlight the importance of tailored disease management strategies throughout the production cycle; given the limited validated therapeutic options for most lobster diseases, prevention through water-quality management, injury avoidance, and biosecurity remains the primary strategy in *Panulirus ornatus* aquaculture [76]. These stage-specific represent importance of tailored disease management strategies throughout the production cycle.

9.2. Chemical and Biological Control Strategies

Chemical and biological interventions have been explored to mitigate disease infections in *Panulirus ornatus*, often drawing on treatment strategies established for other crustaceans. Drug baths are a common approach, yet excessive concentrations can be lethal to lobsters, underscoring the need to establish safe dosage ranges. During the embryonic stage, formaldehyde, potassium permanganate, and trichloroisocyanuric acid (TCCA) toxicity were declared, providing important safety thresholds for hatchery use [78]. In larval culture, malachite green (10 ppm), formalin (25 ppm), turmeric powder (1 ppm), and streptomycin (0.5–1 ppm) have been applied at regular intervals to reduce fouling and ectocommensal infections caused by protozoans (*Zoothamnium, Achata*, *Epistylis*, *Vorticella* spp.) and filamentous bacteria (*Leucothrix* sp.) [35].

Complementing chemical methods, probiotic interventions offer a promising biological strategy. A combination of *Pseudoalteromonas* sp. PP107 and *Vibrio* sp. PP05 provides additive protection against the highly

virulent *Vibrio owensii* DY05. Through niche specialization, PP05 colonizes nutrient-rich outer leg segments and the gut of both *Artemia* and phyllosoma to directly interact with the pathogen, while PP107 establishes on external surfaces and acts primarily within the bacterioplankton. This complementary colonization disrupts the infection cycle of *V. owensii*, significantly enhancing larval survival and demonstrating the potential of targeted probiotic enrichment in early-stage culture [79].

10. Challenge and Future Goal

Despite significant advancements in research on *Panulirus ornatus*, the conservation of its wild populations and the industrialization of its aquaculture continue to face substantial challenges. The decline in germplasm resources and bottlenecks in artificial breeding remain critical obstacles. While studies on germplasm resources have been conducted across multiple countries, confirming that *Panulirus ornatus* is not globally endangered, significant local population declines have been observed in regions such as China and Southeast Asia due to overfishing, posing threats to germplasm conservation. The extent of global resource declines for *P. ornatus* remains incompletely understood. The primary cause of overfishing is the reliance of current aquaculture practices on wild-caught juveniles, as full-cycle artificial breeding technology has not yet matured, particularly for large-scale rearing of phyllosoma to the puerulus stage. Although female *P. ornatus* exhibits high fecundity, the survival rate of hatched phyllosoma is low and highly sensitive to environmental changes and absence of appropriate diets. This result in an unstable seed supply and limiting the availability of high-quality seedlings for stock enhancement programs and the broader development of the aquaculture industry. In addition, where effective feed formulations or rearing protocols remain protected by patents or trade secrets, the wider research community cannot independently verify or build upon them, further slowing progress on the bottlenecks described above.

Nutritional and feed issues constrain large-scale aquaculture. Phyllosoma have highly specific requirements for feed composition, particle size, and palatability. Current artificial feeds cannot fully replace live prey, and the utilization of lipids and essential fatty acids (EPA/DHA) provided in triglyceride (TAG) form remains inefficient. Cannibalism during culture reduces post-moult survival, while environmental stressors (e.g., high temperature, low salinity) can induce oxidative stress and immunosuppression, increasing disease risks. The disease prevention and control system is underdeveloped. Larval stages are susceptible to bacterial, fungal and virus infections, and tolerance mechanisms to toxic substances like ammonia nitrogen are not yet fully understood. These factors not only limit the sustainability of aquaculture but also pose serious challenges to ensuring the health and quality of seedlings for stock enhancement programs.

To achieve sustainable utilization of *Panulirus ornatus* resources, the following key technologies should be prioritized: First, strengthen germplasm resource surveys and advance full-cycle artificial breeding technologies. Systematic baseline surveys and genetic assessments of wild populations in major distribution areas should be conducted to clarify population structure and genetic diversity, providing a scientific basis for broodstock selection and ensuring the industry's long-term productivity and viability. Key research should focus on broodstock conditioning, spawning synchronization, and larval development regulation by optimizing photoperiod, temperature, and nutritional conditions to improve hatching and larval survival rates. Utilizing available genomic and transcriptomic data to elucidate molecular regulatory networks of moulting and metamorphosis and applying gene editing techniques to identify key functional genes will provide a genetic basis for artificial breeding and high-quality seedling production for release.

Second, innovate feed formulations and feeding strategies. Develop stage-specific feeds tailored to different developmental stages, optimize protein, lipid, and mineral ratios, and functional feeds using novel protein sources such as enzymatically hydrolysed fish meal and black soldier fly meal. The efficacy of specific attractants, including glycine and taurine, in enhancing feed palatability warrants further investigation. Simultaneously, investigate the expression patterns of key lipid metabolism genes to improve the bioavailability of EPA and DHA, aiming to cultivate robust individuals with higher post-release survival rates.

Third, optimize culture environments and disease prevention systems. Promote parallel development of land-based recirculating aquaculture systems (RAS) and offshore/deep-sea cage culture. For RAS, establish precise control of temperature, salinity, and pH, and implement macroalgae symbiosis systems to reduce ammonia nitrogen loads. For offshore and deep-sea systems, leverage superior water exchange and environmental conditions to enhance product quality, while developing biosecurity protocols to address disease risks posed by pathogens. Across both systems, develop early warning technologies for moulting to reduce cannibalism. For pathogens such as Vibrio and WSSV, research synergistic probiotic prevention strategies and analyse immune response mechanisms under ammonia stress through metabolomics to develop targeted interventions, ensuring healthy and resilient seedlings for stock enhancement.

In the long term, we suggest that future goals for the resource restoration and aquaculture development of *Panulirus ornatus* should focus on building an integrated system of "resource conservation-artificial enhancement-ecological aquaculture." By integrating multi-omics data, establishing germplasm resource banks, molecular breeding platforms, and stock enhancement evaluation systems, scientific guidance can be provided for release activities to avoid genetic pollution of wild populations. Develop intelligent aquaculture systems using sensors and AI models to monitor water quality, behaviour, and health status in real time, dynamically adjusting feeding and environmental parameters to improve aquaculture efficiency while producing high-quality seedlings for stock enhancement. Promote industry chain integration to form technical standards for germplasm resource management, artificial breeding, healthy aquaculture, and resource enhancement.

Through policy support, strengthen in-situ conservation to balance resource protection and sustainable utilization. Research capacity for *Panulirus ornatus* is distributed across multiple countries. International collaboration and open exchange of knowledge would therefore help avoid duplicated effort and accelerate progress on the bottlenecks described above. This could be facilitated through joint research programmes, shared protocols, and regular scientific meetings. Ultimately, interdisciplinary collaboration and technological innovation will promote the efficient and environmentally friendly development of *P. ornatus* resource restoration and aquaculture industry, contributing to the growth of the blue economy.

Author Contributions

Q.M.: conceptualization, investigation, writing, original draft, visualization; F.Z: visualization, writing, review & editing; D.Z. and E.L.: supervision, project administration; Y.L.: writing, original draft, writing, review & editing, funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used ChatGPT for language editing and grammar improvement. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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