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Analysis of the Polyculture Model of the Bivalves *Anadara broughtonii* and *Chlamys farreri* in Suspension Cages in Shallow Seas

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Abstract: This study examined the survival rates of *Anadara broughtonii* and *Chlamys farreri* with varying heights throughout winter and summer aquaculture periods under varying ratios of mixed-culture conditions in marine environments. The aim was to assess the viability and economic advantages of mixed-culture practices among different bivalve species. Results indicate that the winter (from December to February of the following year) mortality rate for *A. broughtonii* in mixed culture ranges from 12.04% to 16.85%, markedly lower than in single-species cultures. Mixed-culture *A. broughtonii* measuring 2.5–4.0 cm exhibit a significantly reduced summer (from July to September) mortality rate compared to those in single-species cultures ($p < 0.05$). No significant mortality difference was observed between the monoculture and polyculture of *C. farreri*. Growth rates of *C. farreri* and *A. broughtonii* showed no significant differences between monoculture and polyculture conditions. The optimal size for combining two different species of bivalves is 2.5 cm, with a 1:1 ratio being the most effective. An equal number of seedlings were cultivated across various seawater aquaculture systems for a period of one year. The survival rates of monoculture seedlings of *Anadara broughtonii* and *Chlamys farreri* were 60.34% and 86.55%, respectively. In contrast, polyculture seedlings exhibited higher survival rates after one year of mariculture, with *Anadara broughtonii* at 73.36% and *Chlamys farreri* at 89.74%. The polyculture of *A. broughtonii* and *C. farreri* in suspension cages demonstrates a favorable input–output ratio of 1:2.02. This approach effectively reduces winter and summer mortality rates of *A. broughtonii*, representing an efficient new method for marine bivalve aquaculture.

Keywords: *Anadara broughtonii*; *Chlamys farreri*; polyculture

Key Contribution: This study examines the effects of different polyculture ratios and specifications of cultured bivalves on both the survival rates and economic benefits of the organisms involved. The analysis encompasses survival rates, body length, wet weight, and the actual input–output ratio of the polyculture organisms. Specifically, the responses of *Anadara broughtonii* and *Chlamys farreri* were observed during the winter and summer seasons under varying polyculture conditions. The findings indicate that effective polyculture of *A. broughtonii* and *C. farreri* can significantly reduce the mortality rate of *A. broughtonii* and enhance the economic returns of aquaculture. The study proposes that implementing cage polyculture patterns for *A. broughtonii* and *C. farreri* in shallow seas represents a promising and efficient culture method, with potential implications for their survival strategies and broader aquaculture practices.

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1. Introduction

Anadara broughtonii, a commercially significant marine bivalve, exhibits a broad distribution along the northwest Pacific coast, notably in China, Japan, Korea, and Russia [1–6]. The maximum lifespan of *A. broughtonii* is 65 years, with individual masses ranging from 80 to 380 g and heights between 65 and 80 mm [7]. Owing to its promising market prospects, palatable taste, and high nutritional value, it has gained recognition as an aquaculture species in Northern China's coastal areas [8,9]. However, despite advancements in artificial breeding technology and bivalve aquaculture, disease in *A. broughtonii* seedlings has become a growing concern [10–13]. Consequently, extensive research has been conducted on the etiology and prevention of *A. broughtonii* diseases [14–18]. Bivalve mortality is influenced by various factors, including environmental stressors [19–23], quantifiable traits [24], and bacterial diseases [11,16,25–27], as evidenced by numerous studies. Genetic differentiation and phylogenetic relationships among the granulated ark (*Anadara granosa*), bloody clam (*A. subcrenata*), and ark shell (*A. broughtonii*) have been analyzed [28]. However, research on bivalve farming methods, primarily raft cultivation and bottom-seeding propagation, is limited. Research indicates that Japanese aquaculturalists transfer Chamlys spat to grow out on the seabed at 2.0–3.0 cm or even 5.0–6.0 cm in size to reduce mortality during propagation [29]. However, larger seedlings can prolong the cultivation period and elevate costs. Therefore, investigating low-cost, high-survival farming methods is crucial to enhance propagation efficiency and economic returns from bivalve cultivation.

In recent years, because of the development of Chinese aquaculture and overseas market demand, the fishing intensity of *A. broughtonii* has also increased and germplasm resources are at risk [30]. Consequently, the natural resource recovery and cultivation of *A. broughtonii* are of paramount importance [31]. Hanging cage culture is one of many types that is well suited to some species, especially scallops. It is susceptible to the impacts of sea waves and breezes when the wind force is above level seven. This typically results in collisions and aggressive interactions among breeding populations, resulting in damage to the mantle and impeding the growth of *A. broughtonii*. A significant intraspecific mutual interference was observed in the filter-feeding behavior of *A. broughtonii*. The average filter-feeding rates of the juveniles diminished, and the filter-feeding efficiency decreased as the density of the ark shell population increased [32]. *A. broughtonii* and *Anadara kagoshimaensis* both feed on planktonic algae. Studies have shown that the total weight, fresh tissue weight, and dry tissue weight were significantly higher in mixed aquaculture systems compared to monocultures of *A. kagoshimensis* [33]. Employing a mixed culture approach with these two species can mitigate the issues of collision and occlusion, thereby supporting their normal growth.

To enhance the survival rate of bottom-sown *A. broughtonii* and reduce cultivation costs, this study examines both monoculture and polyculture experiments involving *A. broughtonii* and *C. farreri*. By measuring and statistically analyzing their growth and survival rates under various cultivation methods, we assess the differences in survival and growth rates between these methods. Additionally, we evaluate the cost-effectiveness of bivalve cultivation in both monoculture and polyculture systems, exploring the viability of a mixed cultivation approach using hanging cages for *A. broughtonii* and *C. farreri*. This research aims to establish a cost-effective mixed cultivation strategy for *A. broughtonii* in hanging cages, alongside a relay cultivation method for high-quality *A. broughtonii* broadcast, thus proposing a novel, sustainable cultivation model for *A. broughtonii* and *C. farreri* seedlings.

2. Materials and Methods

2.1. The Conditions of the Marine Area

The experimental site was selected within the marine region of Leyuan, Changdao, characterized by favorable natural conditions including gentle water currents, minimal wave action, and an abundance of unpolluted forage. The area exhibits a scarcity of miscellaneous bivalves and algae, reducing the likelihood of excessive biofouling by organisms such as mussels, which could otherwise impede water circulation and negatively impact the growth of *A. broughtonii*.

2.2. The Arrangement of Rafts

Three rafts are installed per acre of sea surface. Each farming unit comprises 30 to 40 rafts, with a minimum inter-unit distance of 60 m. The rafts have an effective length of 100 m and are spaced at a minimum distance of 5.5 m apart. The orientation of the raft frames must align with the seawater's flow direction. Hanging cages utilized for scallop cultivation feature ten layers, each separated by approximately 15 cm. The round plastic dividers employed in the system measure 34 cm in diameter. Floats are affixed to the raft frames and connected by floating ropes. The structure of the experimental culture area and the raft culture cage is illustrated in Figure 1.

(**A**) (**B**)

Figure 1. Culture cage structure (**A**) and raft frame culture sea area (**B**).

2.3. Seed Selection and the Role of the Hanging Water Layer

When selecting seed individuals for culturing, it is essential to ensure that they exhibit uniform size, vibrant body coloration, and are devoid of any deformities. In aquatic environments, these individuals should demonstrate vigorous activity by opening and closing their shells, which must be smooth and consistently shaped, with a robust closing force. Additionally, the surface of the Ark clam shells should be adorned with neatly arranged setae, showing no substantial loss. The depth for the experimental suspended culture is informed by previous research on the hanging-cage cultivation of ark clams [34]. Accordingly, the culture depth during winter (from December to February of the following year) is set at 3.5 m, while summer (from July to September) varies between 2.5 and 3.0 m.

2.4. Comparative Analysis of Polyculture Specifications

The polyculture of *A. broughtonii* and *C. farreri* was structured across six size gradients: 1.5 cm, 2.0 cm, 2.5 cm, 3.0 cm, 3.5 cm, and 4.0 cm. The number of seedlings allocated to each size category was set at 500, 400, 300, 200, 100, and 50 per layer for *A. broughtonii* and *C. farreri*, respectively (Table 1). For comparison, a control experiment was conducted using monoculture breeding of *A. broughtonii* in hanging cages with the same size specifications. The corresponding seedling densities were 1000, 800, 600, 400, 200, and 100 per layer (Table 1). The survival rates and growth performance were monitored and recorded separately in the winter and summer periods.

Table 1. Experimental combinations of bivalves farming with different heights.

Cultured Bivalves		Number of Seedlings					
		1.5 cm	2.0 cm	2.5 cm	3.0 cm	3.5 cm	4.0 cm
Polyculture	*Anadara broughtonii*	500	400	300	200	100	50
	Chlamys farreri	500	400	300	200	100	50
Monoculture	*Anadara broughtonii*	1000	800	600	400	100	50
	Chlamys farreri	1000	800	600	400	100	50

2.5. Comparative Experiment on Polyculture Ratio

The study employed 4.0 cm *A. broughtonii* and *C. farreri* seedlings to conduct experiments with varying pairing ratios. The ratios of *A. broughtonii* to *C. farreri* were established in five gradient groups: 3:1, 2:1, 1:1, 1:2, and 1:3. Each layer contained a total of 100 seedlings (Table 2). The survival and growth conditions of the seedlings were recorded separately during the winter and summer stages.

Table 2. Experimental combinations of bivalve farming with different polyculture ratios.

Cultivated Bivalves	Number of Seedlings				
	3:1	2:1	1:1	1:2	1:3
Anadara broughtonii	75	67	50	33	25
Chlamys farreri	25	33	50	67	75

2.6. Data Collection and Processing

Samples were collected on the 15th day post-cage entry and at the conclusion of the winter or summer season. During sampling, three cages were randomly chosen, and specimens were collected from the top, middle, and bottom layers of each cage to assess mortality rates. Thirty specimens were randomly selected for the measurement of height size and wet weight. The obtained experimental data were analyzed using SPSS version 19.0. A one-way ANOVA and Duncan's multiple range test were applied to evaluate differences in height size, wet weight, and survival rate among farmed bivalves subjected to various farming methods and experimental conditions. The significance level was set at $p < 0.05$.

3. Results

3.1. Analysis of Different Size Specifications in A. broughtonii

The data indicate the biweekly mortality rate (after two weeks of cultivation) and the winter (from December to February of the following year) mortality rate for ark clams ranging in size from 1.5 to 4.0 cm. No significant difference was observed in the biweekly mortality rate of *A. broughtonii* across various sizes in both single and mixed farming modes, with the lowest rate recorded for the 4.0 cm size class (9.05% in single and 9.52% in mixed farming modes, respectively) as shown in Figure 2A. A significant difference was found in the winter mortality rates among different size classes in both single and mixed farming modes. In the single farming mode, the lowest winter mortality rate was observed at the 1.5 cm size (17.33%), whereas in the mixed farming mode, it was at the 4.0 cm size (12.04%). The winter mortality rate was significantly higher than the biweekly mortality rate in both single and mixed farming modes, indicating a substantial difference between the two periods.

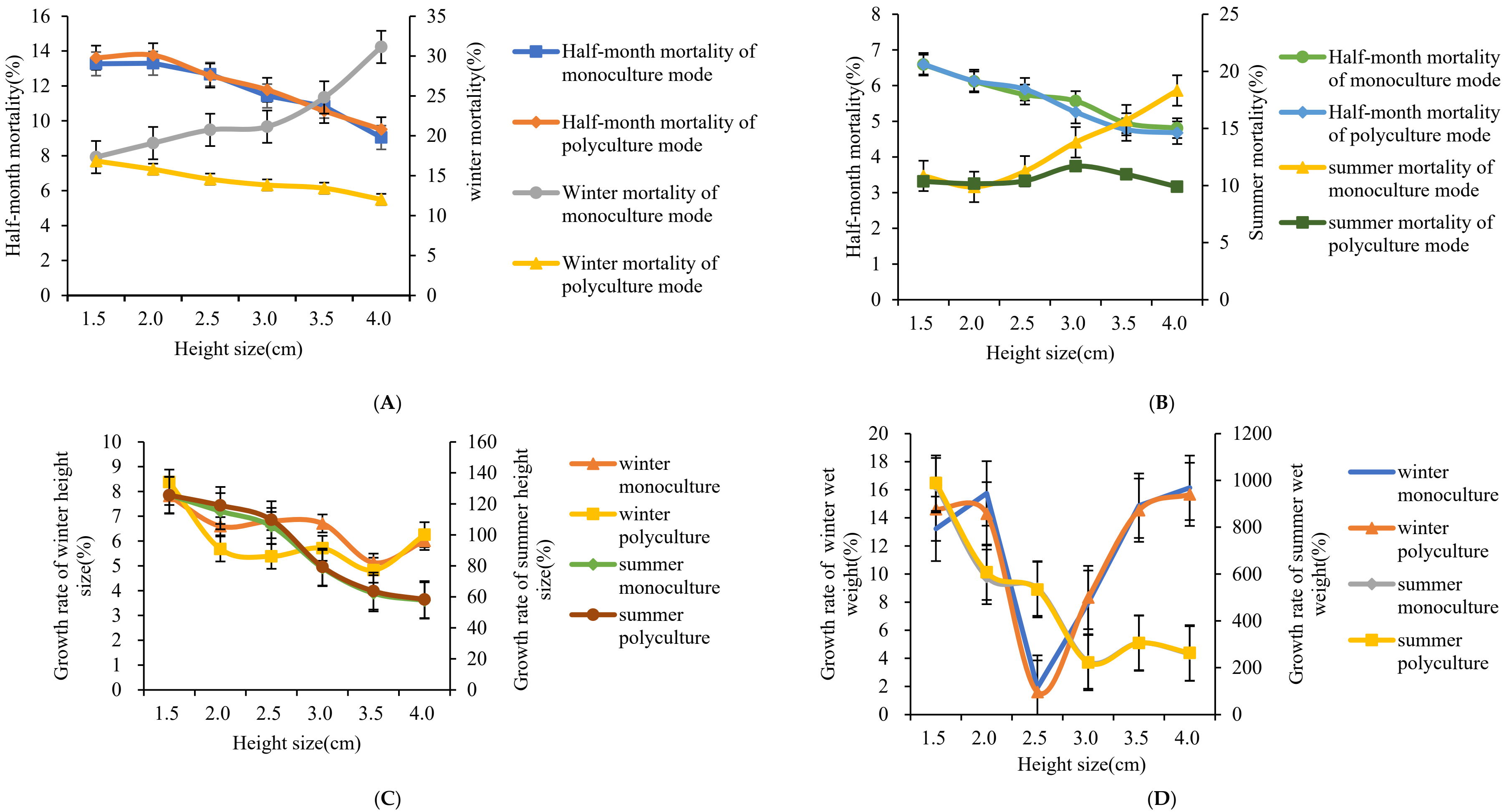


Figure 2. Mortality (**A**,**B**), height (**C**), and wet weight (**D**) growth rate of *Anadara broughtonii* during winter and summer periods.

The data demonstrate a correlation between the mortality rate of *A. broughtonii* during the summer period (from July to September) and their size, which ranges from 1.5 to 4.0 cm. As size increases, there is a gradual decrease in the biweekly mortality rate throughout the summer for both the single and mixed culture approaches, as depicted in Figure 2B. The minimum biweekly mortality rates of 4.81% and 4.68% are observed at the maximum size of 4.0 cm. Moreover, the mortality rate during the summer differs between the single and mixed culture methods. Specifically, for *A. broughtonii* larger than 2.0 cm, the summer mortality rate in the mixed culture approach is significantly lower than in the single culture approach. At a size of 4.0 cm, the summer mortality rate in the single culture method is 18.33%, in stark contrast to a significantly lower rate of 9.90% in the mixed culture method. Additionally, there is a notable distinction between the biweekly mortality rate and the overall summer mortality rate for both culture methods, with the latter being substantially higher.

The growth rates of height and wet weight for winter and summer clams were statistically analyzed. The growth rates for height and wet weight in summer clams are relatively high, demonstrating a declining trend, and tend to stabilize when the size ranges between 3.0 and 4.0 cm (Figure 2C,D). The growth rate for height stabilizes between 0.58 and 0.79, while the growth rate for wet weight stabilizes between 2.22 and 3.06. The growth rates for winter clams remain relatively constant, generally maintaining between 0.05 and 0.08. The overall performance of the height and wet weight growth rates in clams under monoculture and polyculture farming modes is consistent, with no significant differences in growth rates between the two modes. However, growth rates during the summer are significantly higher than those during the winter period.

3.2. Analysis of Various Proportions of A. broughtsnii

In the polyculture of 4 cm *A. broughtonii* and *C. farreri* seedlings at various ratios, no significant difference was observed in the mortality rate over a two-week period; however, significant differences emerged in the overall mortality rate. As the proportion of *A. broughtonii* decreased, the mortality rate did not display a significant trend across winter and summer seasons (Figure 3A). Winter mortality rates ranged from 11.63% to 19.11%, while summer rates varied from 10.67% to 16.15%. Summer mortality rates were generally lower than those in winter. Across all polyculture ratios, mortality rates exceeded those observed over the initial two-week period. Overall, mortality rates exhibited a significant trend, initially decreasing, then increasing, and eventually stabilizing. At polyculture ratios ranging from 1:1 to 1:3, both winter and summer mortality rates were lower, at 11.63% to 12.79% and 10.67% to 10.77%, respectively. It is evident that co-culturing ark clams and scallops in varying proportions reduces collisions and interlocking among ark clams as the proportion of scallops increases.

A higher survival rate for ark clams is achieved when the polyculture ratio of ark clams to scallops reaches 1:1.

To assess the specific growth rates of ark clams under varying density ratios, a statistical analysis was conducted on the height and wet weight increments observed in the ark clam polyculture. No significant differences in growth rates, both in height and wet weight, were detected across different density ratios during the winter and summer periods (Figure 3B). Notably, the height growth rate during winter and the wet weight growth rate in summer for ark clams were comparatively higher. This suggests that height size increased more rapidly during the winter phase, while wet weight gains were more pronounced during the summer.

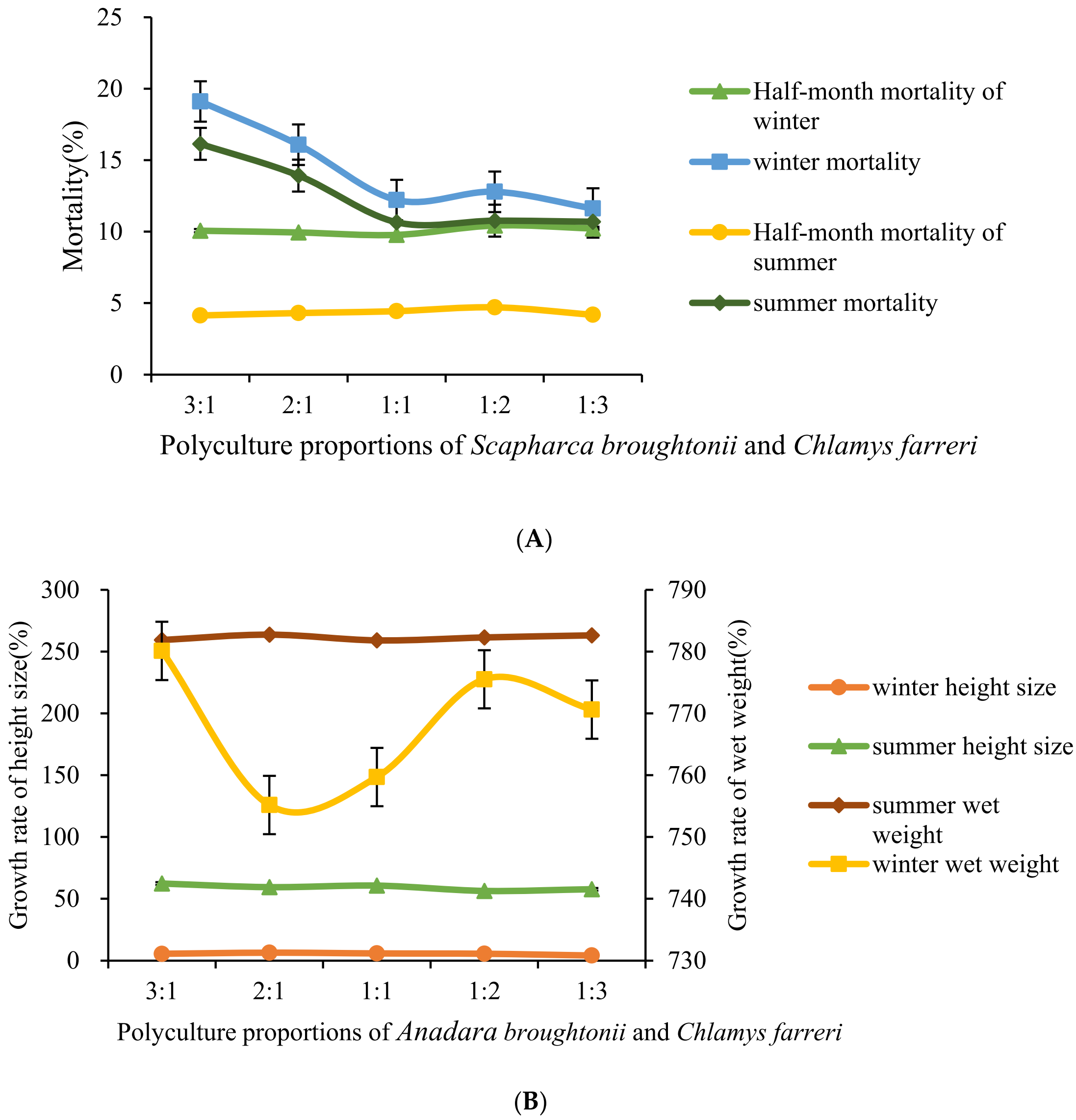
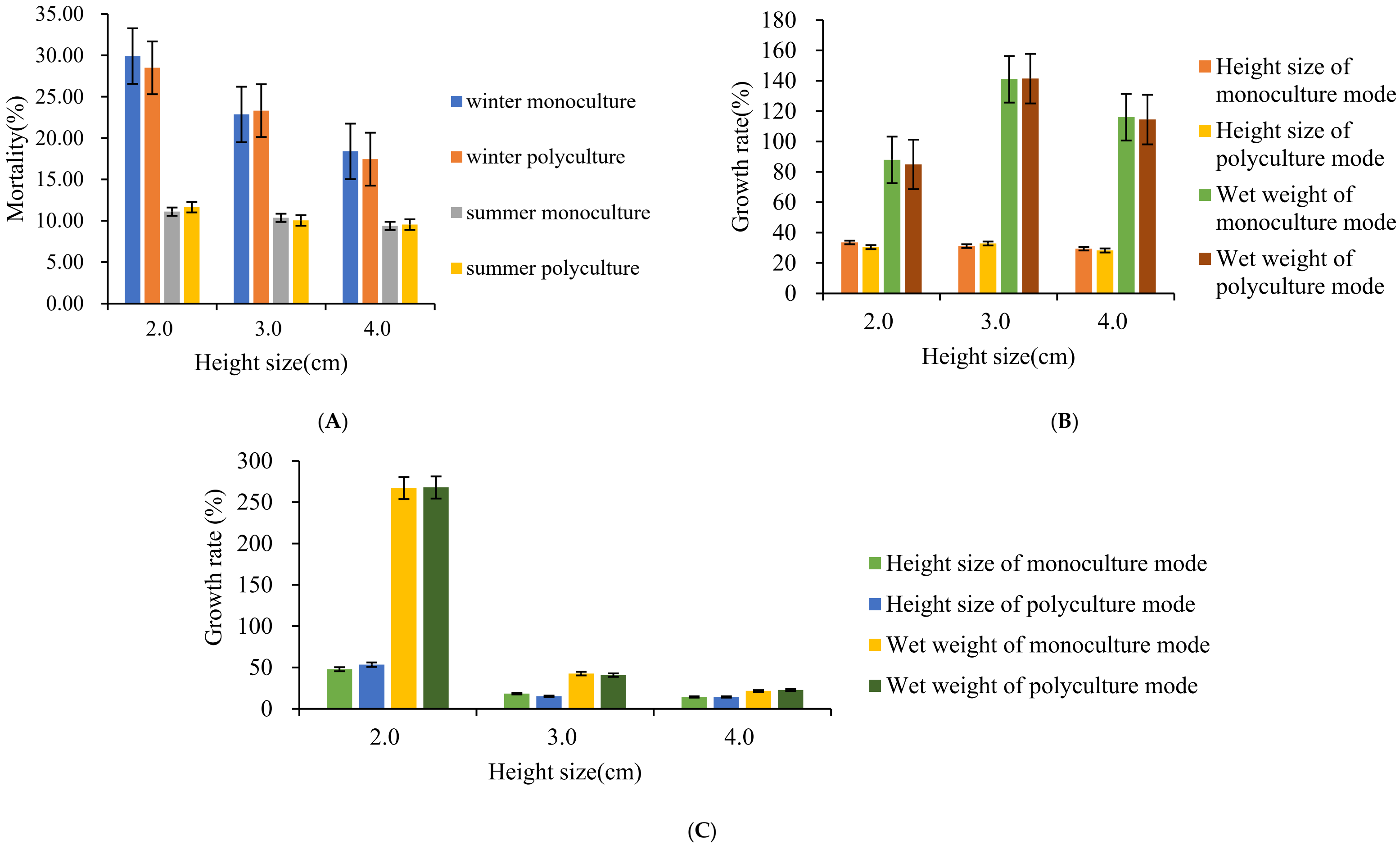


Figure 3. Mortality and growth rate of *Anadara broughtonii* in different polyculture proportions. (**A**) Survival rates across different proportions. (**B**) Height size and wet weight across different proportions.

3.3. Analysis of the Growth and Survival of Chlamys farreri

There is no significant difference in the mortality rates of *C. farreri* during winter and summer between the single and mixed farming methods (Figure 4A). The mortality rate in winter for *C. farreri* seedlings of various sizes is significantly higher than in summer. Additionally, as the size increases, the winter mortality rate decreases significantly, whereas the summer mortality rate shows no significant change. These findings suggest that mixed farming does not significantly affect the survival of *C. farreri*. In mixed farming, larger individuals exhibit lower mortality rates.



(**A**) (**B**) (**C**)

Figure 4. Mortality (**A**) and growth rate of *Chlamys farreri* with different heights after winter (**B**) and summer (**C**).

The results, as depicted in Figure 4B,C, demonstrate that for *C. farreri* seedlings ranging in size from 2.0 cm to 4.0 cm, there is no significant variation in the growth rates of height and wet weight across both the single and mixed culture methods during the summer and winter seasons. Specifically, during the summer months, an increase in size from 2.0 cm to 4.0 cm correlates with a notable decline in the growth rates of height and wet weight. The scallops measuring 2.0 cm exhibit the highest growth rates in both height and wet weight, with the single and mixed culture methods yielding height growth rates of 47.99% and 53.55% and wet weight growth rates of 267.03% and 267.91%, respectively. In contrast, during the winter, the growth rate of height remains relatively constant, whereas the growth rate of wet weight demonstrates a significant pattern of initial increase followed by a decrease. The 3.0 cm scallops achieve the highest wet weight growth rates in the winter, with single and mixed cultures recording rates of 141.05% and 141.45%, respectively.

3.4. Comparison of Breeding Efficiency

An equal number of seedlings (30,000/hectare) was cultivated across various seawater aquaculture systems for a period of one year. In the empirical study of aquaculture, data were collected on height, wet weight, unit input, market price of mature bivalves, unit output value, and the input–output ratio for various cultivation methods of *A. broughtonii* and *C. farreri* (Table 3). The findings indicate a consistent market price for mature bivalves across all cultivation methods. The marine aquaculture cycle for bivalve seedlings is one year. The input–output ratio for bottom sowing culture of *A. broughtonii* is the lowest observed. The cage cultures of *C. farreri* and *A. broughtonii* exhibit lower input–output ratios relative to their polyculture. Within the polyculture system, the input–output ratio achieves a value of 1:2.02, markedly surpassing those of the monoculture practices.

Table 3. The advantages of bivalve aquaculture across various operational modalities from July to the subsequent February (1 US dollar = RMB 7.0513, 21 September 2024).

Indicators	The Bottom Sowing Culture of *Anadara broughtonii*	The Cage Culture of *Anadara broughtonii*	The Cage Culture of *Chlamys farreri*	The Polyculture of *Anadara broughtonii* and *Chlamys farreri*	
				Anadara broughtonii	*Chlamys farreri*
Survival Rate (%)	55.60 [a]	60.34 [a]	86.55 [b]	73.36 [c]	89.74 [b]
Height (cm)	4.61 [a]	5.42 [a]	7.33 [b]	5.45 [a]	7.46 [b]
Wet Weight (g)	39.32 [a]	47.81 [b]	52.46 [c]	48.63 [bc]	52.91 [c]
Total Weight (Kilograms/Hectare)	656.35 [a]	865.28 [b]	1360.57 [c]	534.79 [ad]	712.09 [ab]
Price of Adult Bivalves (Dollars/Kilograms)	1.70 [a]	2.13 [b]	1.42 [a]	2.13 [b]	1.42 [a]
Unit Input (Dollars/Hectare)	638.19 [a]	992.73 [b]	992.73 [b]	1063.64 [b]	
Unit Output Value (Dollars/Hectare)	1116.97 [a]	1840.67 [b]	1929.59 [b]	2147.57 [b]	
Input–output Ratio	1:1.75 [a]	1:1.85 [a]	1:1.94 [a]	1:2.02 [a]	

Different lowercase letters in the same row indicate significant differences for the same index among different patterns ($p < 0.05$).

4. Discussion

4.1. The Relationship between Height, Proportion, and Growth Survival in Cultured Shellfish

No significant difference was observed in the mortality rate of *A. broughtonii* within half a month between monoculture and polyculture models, suggesting that seedling elimination was due to natural causes, excluding mortality from artificial damage such as cage-reversal operations. However, a significant difference was noted in the overall mortality rate, indicating that polyculturing *A. broughtonii* with *C. farreri* effectively reduced its mortality rate during the breeding process. The overall mortality rate of polycultured *A. broughtonii*, within the size range of 2.5 cm to 4.0 cm, was significantly lower than that of monocultured *A. broughtonii*. As the proportion of *C. farreri* increased, the likelihood of collision and interlocking among *A. broughtonii* decreased.

During winter and summer, as the breeding size of *A. broughtonii* increased, the growth rates of height and wet weight in both the monoculture and polyculture models decreased and stabilized within the size range of 3.0 to 4.0 cm. When polycultured in varying proportions, no significant difference was observed in the overall height and wet weight of *A. broughtonii* between the monoculture and polyculture models during winter and summer.

The primary methods of marine bivalve farming in our country have their origins in traditional tidal flat cultivation. Pond farming emerged in the 1970s, followed by the establishment of indoor factory farming and shallow sea farming in the 1990s. Recently, advanced techniques like deep-water rafting, wind-resistant deep-water net cages, and ecologically efficient integrated multi-trophic aquaculture have been increasingly explored [35,36].

The mixed cultivation of various bivalve species offers numerous advantages. Co-cultivation of filter-feeding bivalves, such as *Sinonovacula constricta* with *Musculus senhousei* and *Cyclina sinensis*, has increased total yield and value compared to monocultures. Notably, co-cultivating *S. constricta* with *M. senhousei* has resulted in a 62.7% profit increase over the monoculture of *M. senhousei*, signifying substantial economic benefits [37]. Regarding the cultivation environment, studies indicate that mixed cultivation of *Ostrea gigas thunbergii* and *Mytilus edulis* in hanging cages is more effective at nitrogen removal than oyster monoculture [38]. The study suggests that *A. broughtonii* and *C. farreri*, both suitable for shallow water cultivation, can be effectively co-cultivated, significantly improving *A. broughtonii* survival rates and offering advantages in seedling survival. During the winter and summering phases, as *A. broughtonii* reached larger sizes, growth rates for height size and wet weight in both monoculture and polyculture declined and stabilized at a size range of 3.0–4.0 cm. When polycultured in varying proportions, *A. broughtonii* and *C. farreri* showed no significant differences in final height and wet weight compared to monocultures during winter and summer. Considering the varied impacts on initial height and wet weight, growth rates were further assessed by analyzing changes in these parameters. The findings indicated that, while *C. farreri*'s growth rates in the monoculture and polyculture were similar during winter and summer, height and wet weight increased more substantially during the summer.

4.2. Analysis of Different Aquaculture Models

Bivalve culture is a significant bottom-seeding method in marine ranching, which plays a crucial role in enhancing the current state of fishery resources [39]. However, studies have demonstrated that bottom-sowing cultures in estuaries tend to increase the total phosphorus (TP) and inorganic phosphorus (IP) content in sediments [40].

A polyculture model involving the bivalves *A. broughtonii* and *C. farreri* can effectively mitigate the impact of bottom-seeding activities. The rapid expansion of mariculture, driven by an increasing global food demand, may significantly impact coastal mercury (Hg) cycling. This impact is attributable to environmental alterations, such as resuspension and sedimentation, resulting from maricultural activities, including bottom-sowing and harvesting [41]. The bioaccumulation of methylmercury (MeHg) occurs during anthropogenic interference.

Both the cultured species and cultivation methods significantly influence the environmental performance of maricultures. Among these methods, seaweed rafts, shellfish rafts, shellfish hanging cages, and bottom-sowing techniques are particularly impactful in supporting environmental sustainability [42]. An integrated multi-trophic aquaculture model can be promoted to reduce the ecological burden of mariculture and potentially transform it into an ecological benefit.

5. Conclusions

The polyculture model does not significantly affect the growth of *A. broughtonii* and *C. farreri*; however, it can markedly decrease the mortality rates of *A. broughtonii* during winter and summer. The mortality rate tends to increase as the size of the seedlings increased, while the benefits of polyculture become more pronounced. The optimal size for co-culturing *A. broughtonii* and *C. farreri* is 2.5 cm, with a recommended ratio of 1:1. Co-culturing these species can lead to a more favorable input–output ratio, and employing cage polyculture can effectively enhance the profitability of marine aquaculture and the efficiency of marine resource utilization. Consequently, the cage polyculture approach for *A. broughtonii* and *C. farreri* represents a viable novel method for seawater bivalve production.

This study synthesizes information regarding the effects of height, size, and seasonal variations (summer and winter) on the growth and survival of mixed-cultured *A. broughtonii* and *C. farreri*. It also analyzes the economic advantages of mixed-culture systems. The effects of different heights and mixing ratios in mixed cultures vary significantly, with more pronounced benefits observed during the winter. The co-cultivation of these two bivalve species enhances seedling survival rates and supports normal growth and development, thereby playing a crucial role in improving the growth performance of cultured shellfish and mitigating the ecological impacts associated with bottom culture activities.

The lower winter mortality rates observed in mixed-cultured *A. broughtonii* and *C. farreri* populations underscore the necessity of balancing seasonal strategies to optimize bivalve health. Effective aquaculture practices should incorporate these insights to develop farming models that adapt to environmental conditions, achieving optimal economic benefits while minimizing the impact of bottom trawling activities on marine ecosystems. Overall, the findings advocate for the implementation of mixed-culture approaches for *A. broughtonii* and *C. farreri* to promote sustainable and efficient aquaculture production.

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Institutional Review Board Statement: This study was conducted in accordance with the Guidelines for the Care and Utilization of Laboratory Animals of the Chinese Society for Laboratory Animal Science (No. 2011-2). Ethical review and approval were waived for this study, because the *Anadara broughtonii* and *Chlamys farreri* in this study are invertebrates with no sense or subjective experience.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

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Conflicts of Interest: The authors declare no conflicts of interest.

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