Hindawi
Aquaculture Research
Volume 2024, Article ID 6685325, 14 pages
https://doi.org/10.1155/2024/6685325

WILEY | Hindawi

Research Article

Growth and Survival of Scallops *Austrochlamys natans* (Philippi, 1845) and *Zygochlamys patagonica* (P. P. King, 1832) in Suspended Systems and Land-Based Tanks in Chilean Patagonia

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Received 27 June 2023; Revised 5 December 2023; Accepted 8 January 2024; Published 30 January 2024

Academic Editor: Mahmoud Dawood

The southern scallop (*Austrochlamys natans*) and the Patagonian scallop (*Zygochlamys patagonica*) are vital species in the fisheries of Chilean Patagonia. However, overfishing has led to stock depletion, necessitating research for stock restoration and commercial production. This study aimed to evaluate the growth and survival of these scallops in suspended systems and land-based tanks across various Patagonian regions. Eight experiments were conducted, three with southern scallops and five with Patagonian scallops. For southern scallops, two experiments involved suspended systems at different shell heights and three tested land-based tanks at various temperatures (9, 11, and 13°C). Patagonian scallop experiments included one suspended system in an endemic area, land-based tanks with different temperatures (9, 11, and 13°C), and three suspended systems outside the species' endemic zone. In suspended systems, southern scallops grew from 15.1 to 42.7 mm (shell height) in 322 days, with a rate of 0.085 mm/day and a survival rate of 43.7%. Patagonian scallops reached 46.0 mm shell height in 466 days, with a growth rate of 0.079 mm/day and a survival rate of 57.2%. Experiments in controlled-temperature tanks revealed that 13°C was the lethal temperature for southern scallops. Notably, higher growth rates occurred at temperatures between 9 and 11°C. Both species show potential for future commercial cultivation, contributing to Chilean aquaculture diversification.

1. Introduction

Chilean Patagonia is a region rich in biodiversity, particularly in its coastal marine environments, approximately from parallel 41°S to the south. This unique and exclusive area is an important source of fishery resources, but it faces the issue of overexploitation, much like many other regions around the world [1]. The southern scallop (*Austrochlamys natans*) and the Patagonian scallop (*Zygochlamys patagonica*) are examples of species that are economically and socially significant for the region but are currently facing overfishing. When analyzing the southern scallop fishery over the past two decades, a clear upward trend in catches is evident, reaching a historic peak of 3,662 tons landed in 1998. Subsequently, a significant decline became apparent, with only 209 tons recorded in 2000, marking the initial signs of overexploitation. This trend raised concerns within the administrative authority, prompting the implementation of resource conservation measures. Consequently, in recent years, conservation initiatives related to aquatic resources have been actively promoted, with the expectation that they would ultimately yield benefits for both conservation and productivity sectors.

Nevertheless, initial assessments suggest that these endeavors may primarily confer advantages to recreational fishers and tour operators, possibly resulting in the displacement of long-standing fishermen who have traditionally relied on these regions for their livelihood [2]. Furthermore, changes in local well-being and the emergence of inequalities have been observed, even within the frameworks of comanagement for protected areas [3]. This has been the case, for example, in the Marine Protected Area of Multiple Uses of the Almirantazgo Sound in the Chilean Patagonia, where the main natural banks of *A. natans* exist [4]. In addition, the extraction of *Z. patagonica* and *A. natans* is prohibited until 2023 (Ministry of Economy and Undersecretariat of Fisheries and Aquaculture of Chile, Exempt Decree No. 09 of January 29, 2019). This scenario suggests that it is necessary to provide the greatest number of methodological tools to support the sectors most adversely affected by these new public policies. In that sense, the development of technologies for the cultivation of benthic species, such as these scallops, among artisanal fishermen appears to be a promising alternative solution.

In this context, efforts have been made to cultivate scallops in southern Chile. First, in southern Patagonia with *Z. patagonica*, growth was compared in two locations within the same region, concluding that the maximum shell height reached 60 mm, with no significant differences between the locations. Second, in the Los Lagos region with *Argopecten purpuratus* [5], growth was evaluated in different suspended systems and densities, with the conclusion that it is feasible to introduce such cultivation in the north of Patagonia [6].

The present study provides significant information about the growth and survival of *A. natans* and *Z. patagonica* when cultivated in suspended systems or land-based tanks (controlled environment), spanning from the early stages of development to commercial size. Production tests were conducted at four different locations, ranging from southern Patagonia with oceanic influence to the northern Patagonia region with a greater freshwater influence.

2. Materials and Methods

2.1. Locations. The study comprised eight experiments, with three involving *A. natans* and five concerning *Z. patagonica*. This approach encompassed the entire life cycle of scallops, from the juvenile stage to the commercial shell size, and also investigated the impact of water temperature on scallop growth and survival in land-based tanks. Additionally, the study evaluated the growth and survival of *Z. patagonica* in suspended systems outside their typical development area. These experiments were conducted in four regions of Chilean Patagonia (see Figure 1):

(a) Metri Research Center, University of Los Lagos: situated 30 km east of Puerto Montt (41°36″ S; 72°42″ W), where the ZS2 experiment took place.

(b) Concession of mussel farming company owned by Luís Marín, Cheuquiar Channel: located 2.2 nautical miles south of Calbuco (41°47′ S; 73°04′ W), serving as the site for the ZS3 experiment. This location is used as a reference due to its history in commercial mariculture.

(c) Concession of Cernamar Limited Abalonera company, Teupa Bay: positioned 28 km south of Castro on Chiloé Island (42°37′ S; 73°45′ W), where the ZS4 experiment was conducted. These three areas exhibit estuarine characteristics and are influenced by freshwater contributions.

(d) Bahía Laredo Marine Culture Center (CCMBL), University of Magallanes: located 24 km north of Punta Arenas in Bahía Laredo (52°58″ S; 70°48″ W), where experiments AS1, AS2, AE1, ZS1, and ZE1 were carried out. This area is strongly influenced by the ocean, and natives are for *Z. patagonica*, very close to one of the main natural banks of the species with commercial extraction by artisanal fishermen.

2.2. Growing Conditions

2.2.1. Suspended System. The cultivation structures were installed 2 m below the sea surface and 3 m above the seabed (see Figure 2). They featured floaters at the upper end and 1.5-kg anchors at the lower end. The lanterns comprising the cultivation structures had a height of 1.5 m and a diameter of 0.5 m, divided into 10 levels. The containment mesh used in the construction of the lanterns was made of synthetic monofilament and had different mesh openings according to the experiment: for AS1 and ZS1, the mesh opening was 6 mm, while for AS2, ZS2, ZS3, and ZS4, the mesh opening was 20 mm.

2.2.2. Land-Based Tank System. The scallops were kept in square fiberglass tanks measuring 1 m on each side and 0.5 m in height, with a useful volume of 450 L, for a duration of 126 days. The water used was sourced from Laredo Bay without any filtering treatment, ensuring the scallops received the highest possible organic content. Each tank had a water flow rate of 10 L/min, continuously, and cleaning was performed every 3 days, involving vacuuming the tank's bottom and walls. The land-based tanks were maintained at natural temperature (control group) and controlled at 9, 11, and 13°C. Heating to maintain the temperature at controlled levels was achieved using a titanium plate heat exchanger and automatic valve control.

Temperature readings were recorded daily using an Oxyguard® digital temperature meter. In suspended system experiments, readings were taken at a depth of 1 m, while daily temperature measurements were recorded for both the land-based tanks and lantern experiments.

2.3. Samples and Sampling. The experiments involved evaluating the growth and survival of both species in two different culture systems. Monthly sampling was carried out, with shell height measured using a caliper and weight determined using a digital balance with a precision of 0.01 g. Additionally, survival rates were recorded, and any dead scallops were not replaced. In the case of the tests involving ZS2, ZS3, and ZS4, scallops were transported from the city of Punta Arenas (southern Patagonia) to the city of Puerto Montt (northern

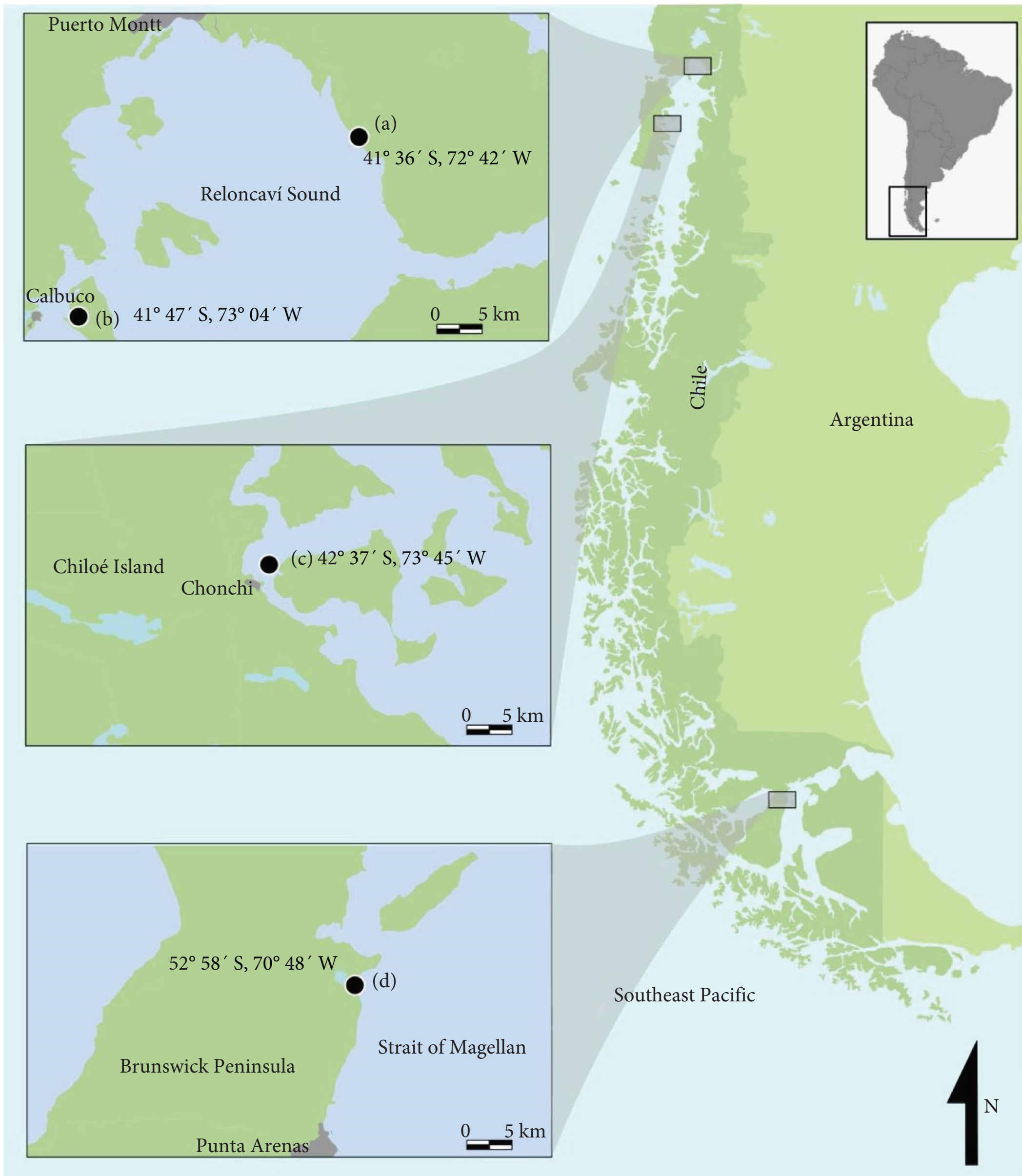

Figure 1: Representation of the four locations: (a) Metri Cultivation Center, of the University of Los Lagos, 30 km east from the city of Puerto Montt, where the experiment with ZS2 was conducted; (b) concession of the mitiliculture company of Luís Marín, in the Cheuquiar Channel, 2.2 nautical miles south from the city of Calbuco, where the experiment with ZS3 was carried out; (c) concession of the limited company Cernamar, Bahía Teupa, 28 km south from the city of Castro, on the Island of Chiloé, where the experiment with ZS4 was carried out; (d) Bahía Laredo Marine Farming Center (CCMBL), belonging to the University of Magallanes and located 24 km north from the city of Punta Arenas in Bahía Laredo, where the experiments with AS1, AS2, AE1, ZS1, and ZE1 were carried out.

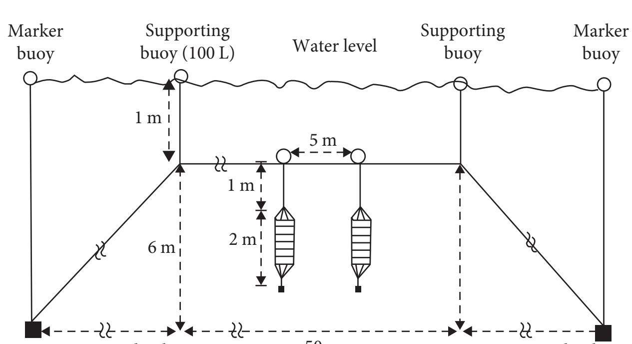

Figure 2: Deployment of the scallop lantern cages in the experimental longline culture system located in northern Patagonia.

TABLE 1: The number of scallops, shell height, experiment duration, stocking density, sampling number, and cultivation system.

Experiment	Number of scallops	Shell height (mm)	Duration (days)	Stoking density (scallop/m^2)	Sampling number	Cultivation system
AS1	33	15.13 ± 4.53	322	16.3	8	Lantern
AS2	104	43.26 ± 2.61	201	26.5	2	Lantern
AE1	40	31.62 ± 0.44	28	10	5	Tank
ZS1	439	9.09 ± 2.61	497	111.8	13	Lantern
ZS2	100	32.62 ± 4.69	263	25.5	7	Lantern
ZS3	100	33.58 ± 4.00	404	25.5	11	Lantern
ZS4	100	32.75 ± 4.30	404	25.5	11	Lantern
ZE1	40	11.52 ± 0.90	128	40	5	Tank

AS1 (*Austrochlamys natans* suspended 1), AS2 (*Austrochlamys natans* suspended 2), AE1 (*Austrochlamys natans* tank 1), ZS1 (*Zygochlamys patagonica* suspended 1), ZS2 (*Zygochlamys patagonica* suspended 2), ZS3 (*Zygochlamys patagonica* suspended 3), ZS4 (*Zygochlamys patagonica* suspended 4) ZE1 (*Zygochlamys patagonica* tank 1). The initial shell height differed in order to assess growth at various stages of the scallop life cycle.

Patagonia) by air. They were placed in isolation boxes, each lined with a 10 mm thick sponge at the bottom, which held 0.5 L of filtered seawater. The scallops were positioned on top of this layer, with another, thinner sponge moistened with seawater placed over them. The box was then filled with chopped insulation to cushion the scallops during transport. Detailed cultivation conditions for each experiment can be found in Table 1.

2.4. Statistical Analysis. Shapiro–Wilk normality and Kolmogorov goodness-of-fit tests were performed. The data were then subjected to analysis of variance or a nonparametric Kruskal–Wallis test. To ascertain the significance of the growth results, a Tukey or Dunn test was performed as a post hoc analysis. For analyzing the fit between the growth rate in total weight and shell height and temperature, a Pearson correlation coefficient test was used. For examining the degree of adjustment of the survival rate and temperature, the Spearman correlation coefficient was employed for all the above analyses [7], using the free version of Infostat© 2015 software.

3. Results

3.1. Growth and Survival in Suspended Systems

3.1.1. A. natans Experiment in Suspended System 1 (AS1). Figure 3 illustrates the variation in the size of cultured scallops throughout the 322 days. The mean shell size in the initial period was 15.13 ± 4.53 mm, and in the final period, it was 42.74 ± 3.87 mm (see Figure 3(a)). The mean weight of the scallops ranged from 0.58 ± 0,45 g at the beginning to 11.86 ± 3.68 g at the end of the experimental period. The mean survival for the entire period was 90.7% ± 10.7%, reaching a cumulative total of 43.8% for the entire study period. There was no correlation between survival rate and temperature ($r = -0.41$ p-value = 0.3639) (see Figure 3(b)).

Shell size growth for the entire period was 0.08 ± 0.03 mm/day, showing a high correlation with temperature ($r =$ 0.77, p-value = 0.0408), reaching the highest growth rate when the temperature was over 9°C (see Figure 4(a)). The growth in total weight for the entire period was 0.38 ± 0.24 g and did not have a similar trend in relation to shell height growth. The results show that a good adjustment to the exponential model was obtained, with a determination coefficient of $R^2 = 0.97$ and with a tendency towards allometry between both variables, since the value of parameter b was well below 3 (see Figure 4(b)).

3.1.2. A. natans Experiment in Suspended System 2 (AS2). The complementary adult growth assay of *A. natans* (AS2), in a suspended lantern system in southern Patagonia, resulted in a shell height increase of 11.18 mm and a weight gain of 16.75 g, with a survival rate of 98.07% (see Table 2). The growth rate in shell height and weight was 0.056 mm/day and 0.083 g/day, respectively.

3.1.3. Z. patagonica Experiment in Suspended System 1 (ZS1). After 466 days of culture, the scallops reached an average shell height of 46.03 ± 4.36 mm and a weight of 17.28 ± 2.78 g (see Figure 5(a)). The average monthly survival rate was 96% ± 7%, reaching a cumulative rate of 57.18% at the end of the period. A low correlation between the survival rate and temperature was identified ($r = 0.21$, p-value = 0.5193) (see Figure 5(b)).

The growth rate for the entire period was 0.09 ± 0.05 mm/day, and the total weight was 0.05 ± 0.05 g/day (Figure 6(a)). The growth rate, expressed in total weight (g/day), has a high correlation with temperature ($r = 0.77$, p-value = 0.0037), but shell height (mm/day) does not show a correlation with temperature ($r = 0.53$, p-value = 0.0772). The tendency shows an alternance between lower growth rates in winter months and higher growth rates in summer months (see Figure 6(a)). The ratio between shell height and weight shows a good fit to the exponential model, with a determination coefficient of $R^2 = 0.96$, and exhibits a tendency toward allometry between both variables since the value of parameter b was well below 3 (see Figure 6(b)).

3.1.4. Growth and Survival of Z. patagonica in Three Locations in Northern Chilean Patagonia (ZS2, ZS3, and ZS4). During the 403-day study period, the scallop group from the Calbuco sector exhibited the highest growth in shell height and total weight, in comparison to the Chiloé (p-value = 0.0141 and p-value < 0.0001) and Puerto Montt groups (p-value < 0.0001 and p-value < 0.0001), increasing from 33.58 to 57.92 mm and from 6.28 to 39.35 g. The growth difference

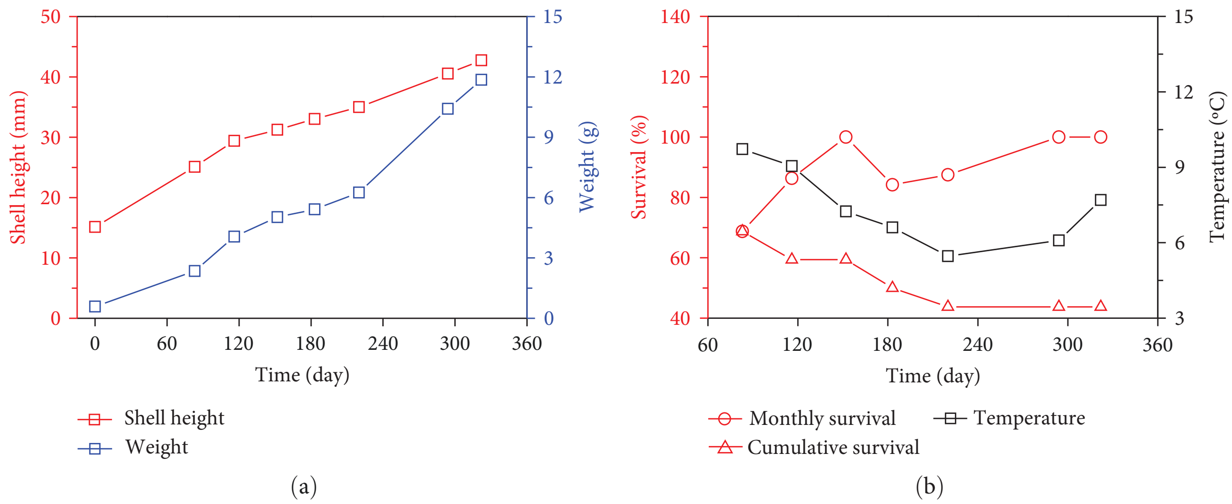

Figure 3: For *A. natans* cultivated in a suspended system in southern Patagonia: (a) variation in shell height (mm) and weight (g); (b) monthly and cumulative survival (%) and mean temperature (°C).

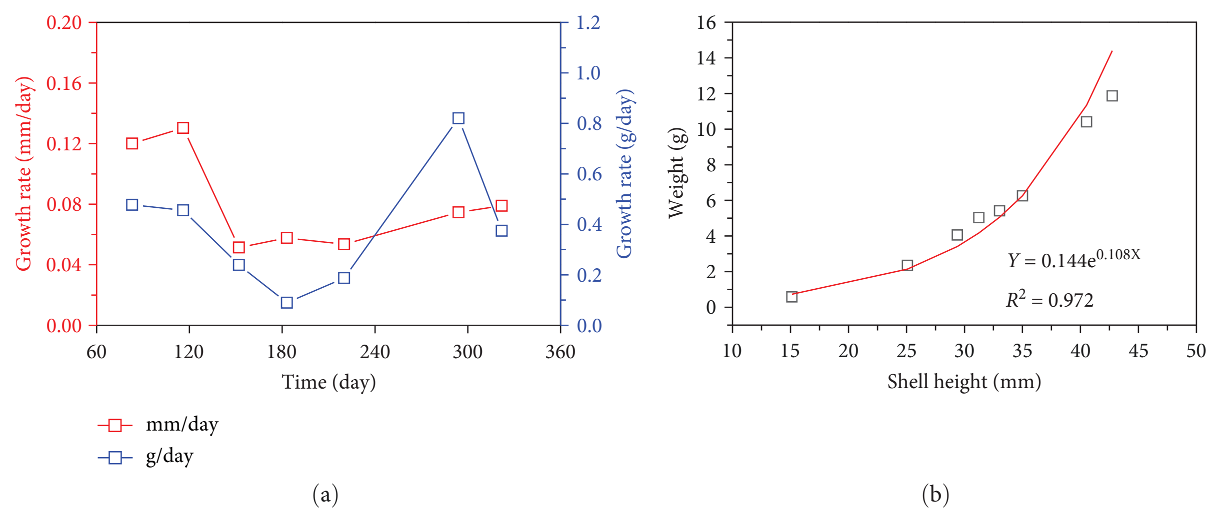

Figure 4: For *A. natans* cultivated in a suspended system in southern Patagonia: (a) growth rate in weight (g/day) and shell height (mm/day); (b) correlation between shell height and weight.

Table 2: Growth of *A. natans* adults in suspended systems in southern Patagonia.

Time (day)	Number of scallops	Shell height (mm)	Weight (g)	Temperature (°C)
—	104	43.26 ± 2.61	10.27 ± 2.49	—
201	102	54.44 ± 2.64	27.02 ± 4.31	7.94 ± 1.84

became significant primarily during the third month of culture (Day 78) and persisted until the end of the study period, except for a few brief intervals (see Figure 7).

The shell height-to-weight ratio of Calbuco, Chiloé, and Puerto Montt shows a good fit to the exponential model, with a high percentage of explained variance ($R^2 = 0.9932$, 0.9982, and 0.9975, respectively), and exhibits a tendency toward allometry between both variables, as the value of parameter *b* was well below 3 (see Figure 8).

Two of the three study sectors in northern Patagonia showed an inverse correlation between shell height and total weight growth rate and temperature (Calbuco sector $r = -0.68$, p-value $= 0.0293$, and Puerto Montt $r = -0.87$, p-value $= 0.0260$) (see Figures 9(a) and 9(c)). Only the Chiloé sector did not present such a correlation (Chiloé $r = -0.04$, p-value $= 0.9149$). However, the growth rate in shell height and total weight was almost zero 1 month after reaching the highest temperatures of the study period (see Figure 9(b)). The growth rate for the entire experiment was 0.059, 0.055, and 0.053 mm/day for the Calbuco, Chiloé, and Puerto Montt sectors, respectively.

The Puerto Montt sector exhibited a strong inverse correlation between survival and temperature ($r = -0.89$,

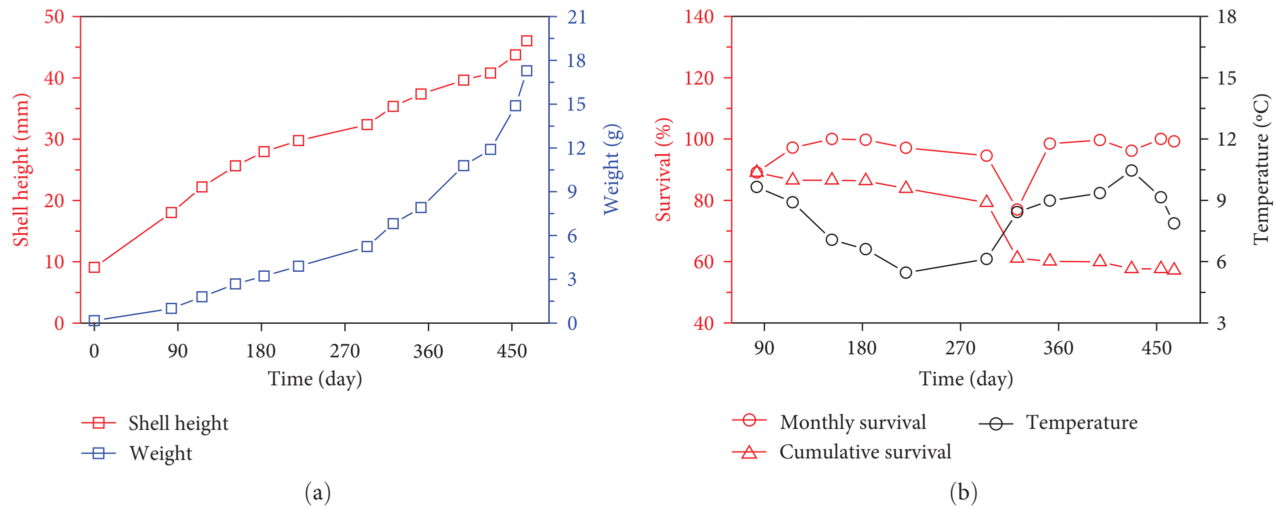

Figure 5: For *Z. patagônica* cultivated in a suspended system: (a) variation in shell height (mm) and weight (g); (b) monthly and cumulative survival (%) and mean temperature (°C).

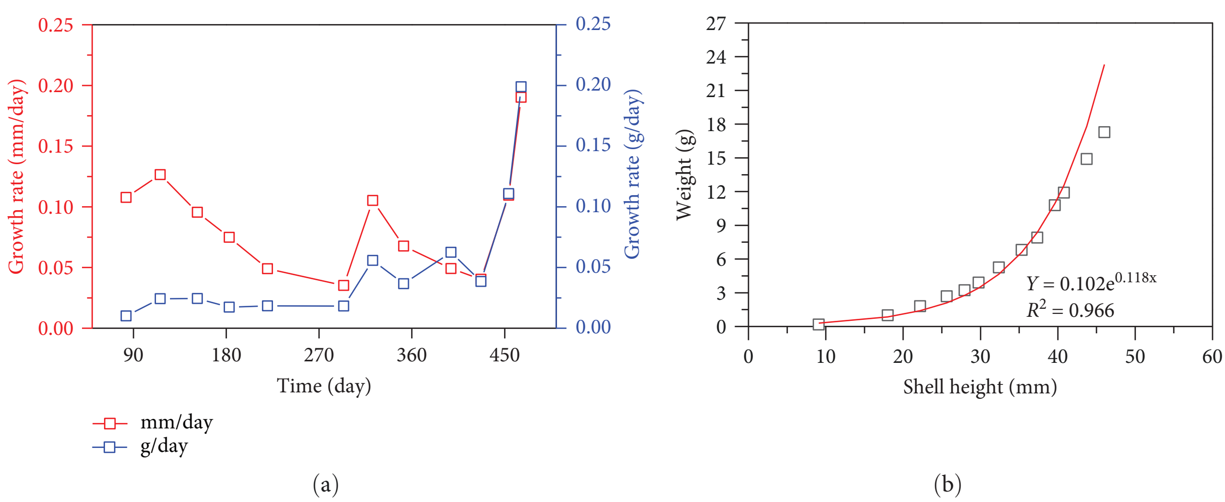

Figure 6: For *Z. patagonica* cultivated in a suspended system in southern Patagonia: (a) growth rate in weight (g/day) and shell height (mm/day); (b) correlation between shell height and weight.

p-value = 0.0476) (see Figure 10(c)). In contrast, the Calbuco and Chiloé sectors did not display such an inverse correlation (Calbuco sector $r = -0.50$, p-value = 0.1397, and Chiloé sector $r = -0.17$, p-value = 0.6669) (see Figures 10(a) and 10(b)). However, survival sharply decreased after reaching the maximum temperature of the period.

3.2. Growth and Survival in Tanks

3.2.1. Growth and Survival of A. natans, Cultured in Tanks (AE1). Figure 11 presents the variations in shell height, weight, and cumulative survival for *A. natans* cultured in tanks with different water temperatures (control, 9, 11, and 13°C). The values of the four groups and the error bars are presented for each of the six biometric samplings on the following days: 0, 25, 50, 75, 100, and 125. Different letters indicate statistical differences. In Figure 11(a), p-values were as follows: Day 25 = 0.0005, Day 50 = 0.001, Day 75 = 0.0087, Day 100 = 0.0145, and Day 125 = 0.0083. In Figure 11(b), p-values were as follows: Day 25 = 0.0043, Day 50 = 0.001, Day 75 = 0.0001, Day 100 = 0.0110, and Day 125 = 0.0067.

During the study period (125 days), the control group reached the highest growth in shell height and total weight compared to the groups at 9, 11 (p-value = 0.0083 for shell height and p-value = 0.0067 for total weight), and 13°C (p-value < 0.0001 for shell height and total weight), increasing from 31.74 ± 3.46 mm and 4.09 ± 1.48 g to 36.06 ± 3.25 mm and 5.35 ± 1.65 g. The growth difference began in the first period in the land-based tank (Day 25) and persisted until the end of the study period (see Figures 11(a) and 11(c)).

The differentiation in growth in both total weight and shell height of the control group compared to the 9, 11, and 13°C groups coincided with the initial difference that the control group had, with 5.67° ± 0.60° at the beginning of the experiment, increasing to 9.07° ± 0.71° at the end (see Figure 11(b)). The 13°C group only lasted until Day 65, and monthly survival decreased from 97.5% in the first period to

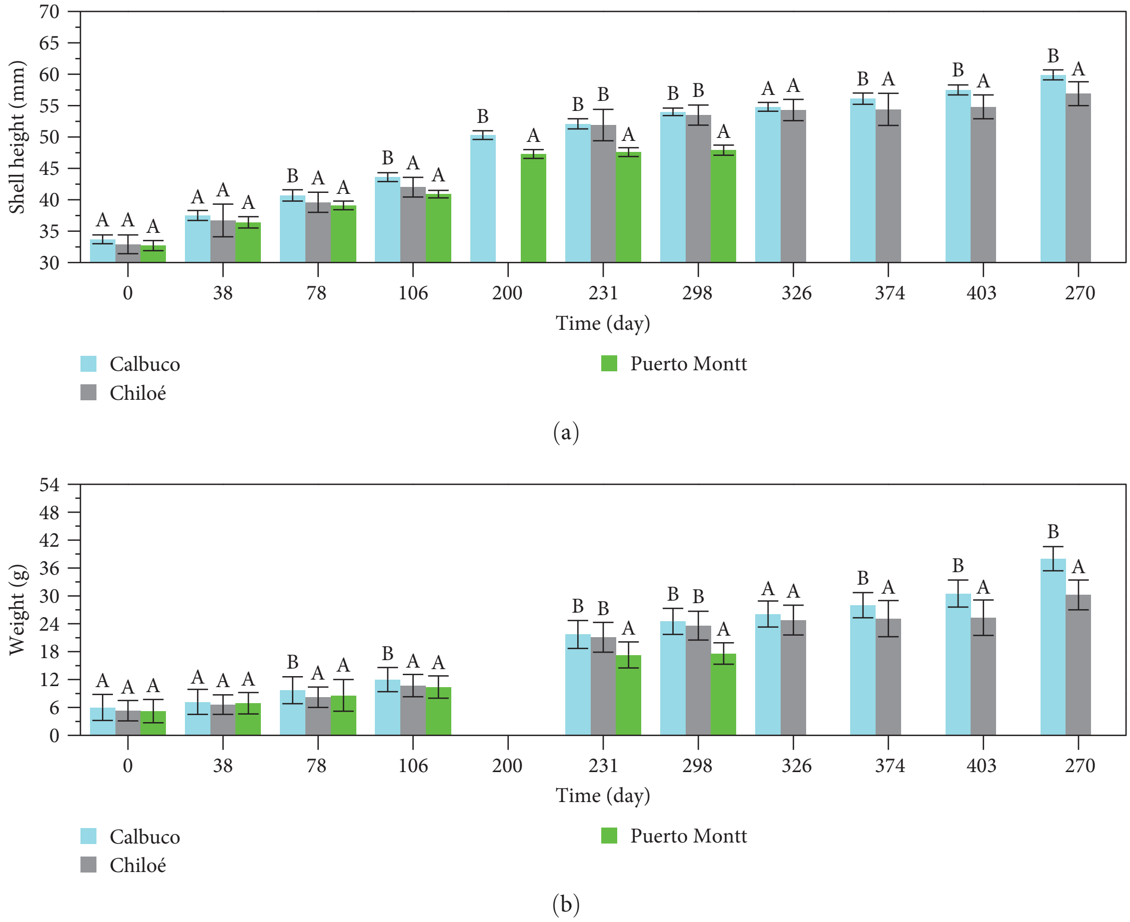

FIGURE 7: For *Z. patagonica* grown in a suspended system in northern Patagonia: (a) variation of shell height (mm); (b) variation of weight (g).

0% in the third period. The 11°C group had an average survival rate of 86.9% ± 15.6%. On the other hand, the control group and the group at 9°C had a survival rate of 96.8% ± 2.0% and 97.4% ± 2.4%, respectively (see Figure 11(d)).

The shell height increment (mm/day) exhibited similar patterns across all groups, with high growth rates at the beginning of the experimental period, except for the 13°C group, and very low rates at the end (see Figure 12). The shell height growth rates for the entire research study were as follows: 0.034 mm/day for the control, 0.025 mm/day for the 9°C, 0.012 mm/day for the 11°C, and 0.003 mm/day for the 13°C.

3.2.2. Growth and Survival of Z. patagonica, Cultured in Tanks (ZE1). During the 127-day study period, the 9 and 11°C groups achieved the highest shell height growth compared to the control and 13°C groups (p-value < 0.0001 for shell height), measuring 11.69 ± 0.99 and 11.65 ± 0.97 mm, respectively. The difference in shell height and total weight growth began in the initial phase within the land-based tanks (Day 25) and persisted until the conclusion of the study period (with the exception of total weight, which was only observed until the 50th day due to scale failure) (see Figures 13(a) and 13(c)).

The 9 and 11°C groups achieved the highest cumulative survival rates, with 87.5% and 82.5%, respectively. The control group displayed a survival rate of 75.0%, while the 13°C group had a rate of 72.5%. Furthermore, this difference was evident in the fourth sampling and persisted into the fifth sampling, coinciding with the temperature increase in the control group from 7.02 ± 0.59°C to 8.66 ± 0.67°C (see Figures 13(b) and 13(d)).

The growth rate in shell height (mm/day) for the entire study was as follows: 0.033, 0.031, 0.027, and 0.021 for the 11, 9, control, and 13°C groups, respectively. Additionally, this difference was observed in the third period and persisted until the end of the study, in conjunction with the temperature increase in the control group from 7.02 ± 0.59°C to 8.66 ± 0.67°C (see Figure 14).

4. Discussion

Suspended systems are used worldwide for rearing scallops because this technology maximizes growth and survival when compared to natural banks [8, 9]. For example, *Placopecten magellanicus* takes more than 6 years to reach commercial size when grown in natural banks. However, when cultivated in suspended systems, it can be harvested after

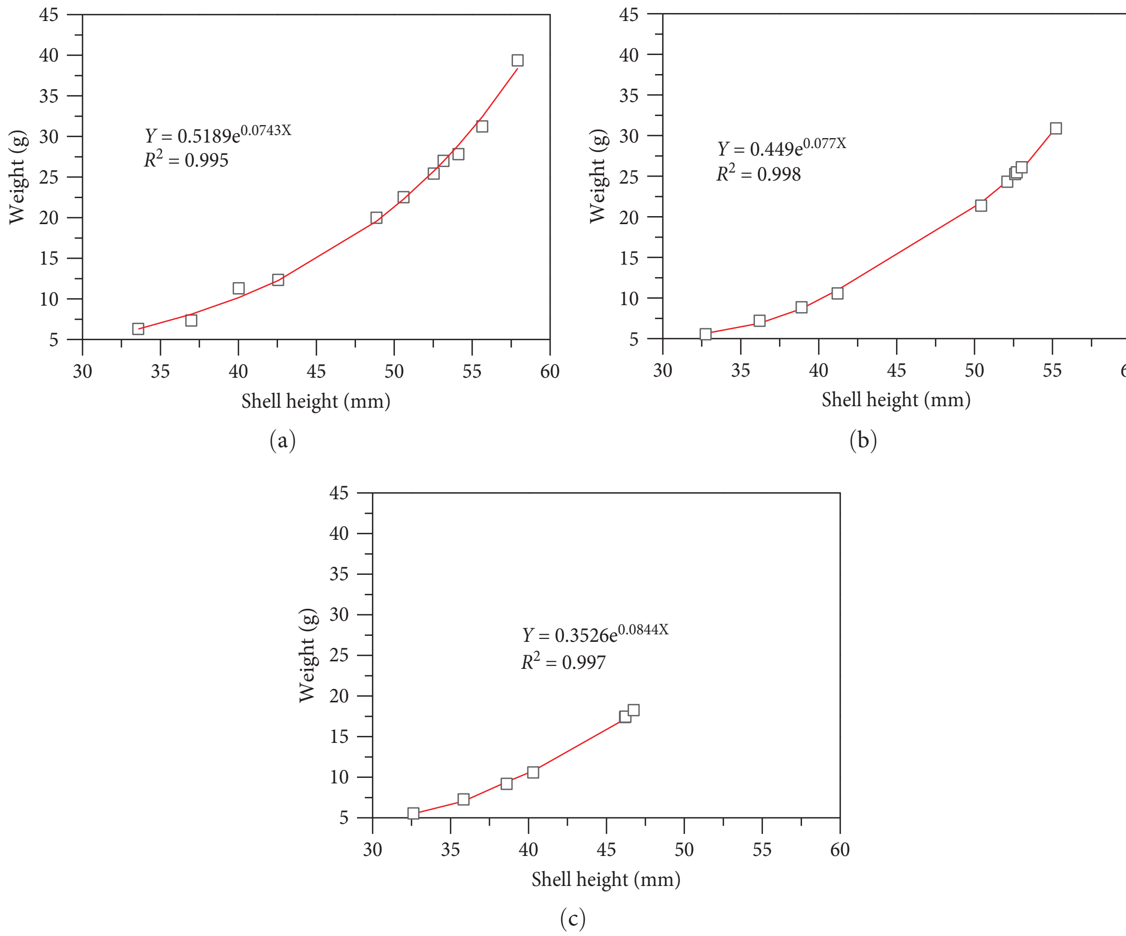

FIGURE 8: Correlation between shell height (mm) and weight (g) for *Z. patagonica* cultivated in a suspended system in the northern zone of Patagonia: (a) Calbuco; (b) Chiloé; (c) Puerto Montt.

3–4 years [10]. The growth of *Pecten maximus, Chlamys opercularis, Chlamys islandica*, and *Patinopecten yessoensis* is significantly higher in lanterns. This is because the stress of predation is reduced, water temperatures can be higher, and the food supply in the water column is greater than at the sea bed [11]. The Peruvian scallop *A. purpuratus* takes 14–16 months to reach the commercial size of 90 mm when cultivated in suspended systems in northern Chile (29°S) [12]. However, when cultivated in southern Chile (41°S), it takes the species between 16 and 21 months to reach the commercial size [6].

Apparently, scallops from high latitudes tend to be more susceptible to temperature-related growth differences. For example, in the case of *P. magellanicus*, summer growth rates (16°C) were found to be 10 times higher than during the winter months (2°C) [13]. According to the data recorded in various experiments conducted, the temperature in Laredo Bay (52°S) tends to average 10.5°C in summer and 5.5°C in winter.

Scallop growth has generally been associated with water temperature [14]. Furthermore, it has been suggested that the growth rates of cold-water scallop species are regulated by water temperature, and the maximum sizes they attain are more influenced by food availability. It is suggested that, in the marine environment, temperature is the primary factor limiting growth, rather than food [15–17]. However, in the case of natural *Z. patagonica* banks in the South Atlantic, differences in growth rates are believed to be constrained by hydrographic processes that influence primary productivity [18]. Conversely, the combined impact of rising ocean temperatures and carbon dioxide levels in seawater has significant physiological and ecological consequences for numerous Antarctic and sub-Antarctic marine invertebrates [19]. Additionally, rising temperatures have been observed to directly affect the survival of *Z. patagonica* [20]. Moreover, suspended culture systems can feature factors that diminish scallop survival, including excessive bioadhesive material accumulation that may partially or entirely block mesh openings and hinder food intake flow [21].

In the case of Euvola (Pecten) Ziczac, bioadhesion has been reported as the most significant factor affecting growth and survival in suspended systems [22]. Regarding this research, the survival of *A. natans* and *Z. patagonica* in a suspended system, including both temperature and bioadhesion factors, may have influenced the survival throughout the entire rearing cycle, resulting in survival rates of 44% and 57%, respectively. More specifically, in the case of *A. natans* cultivated in a suspended system in Southern Patagonia,

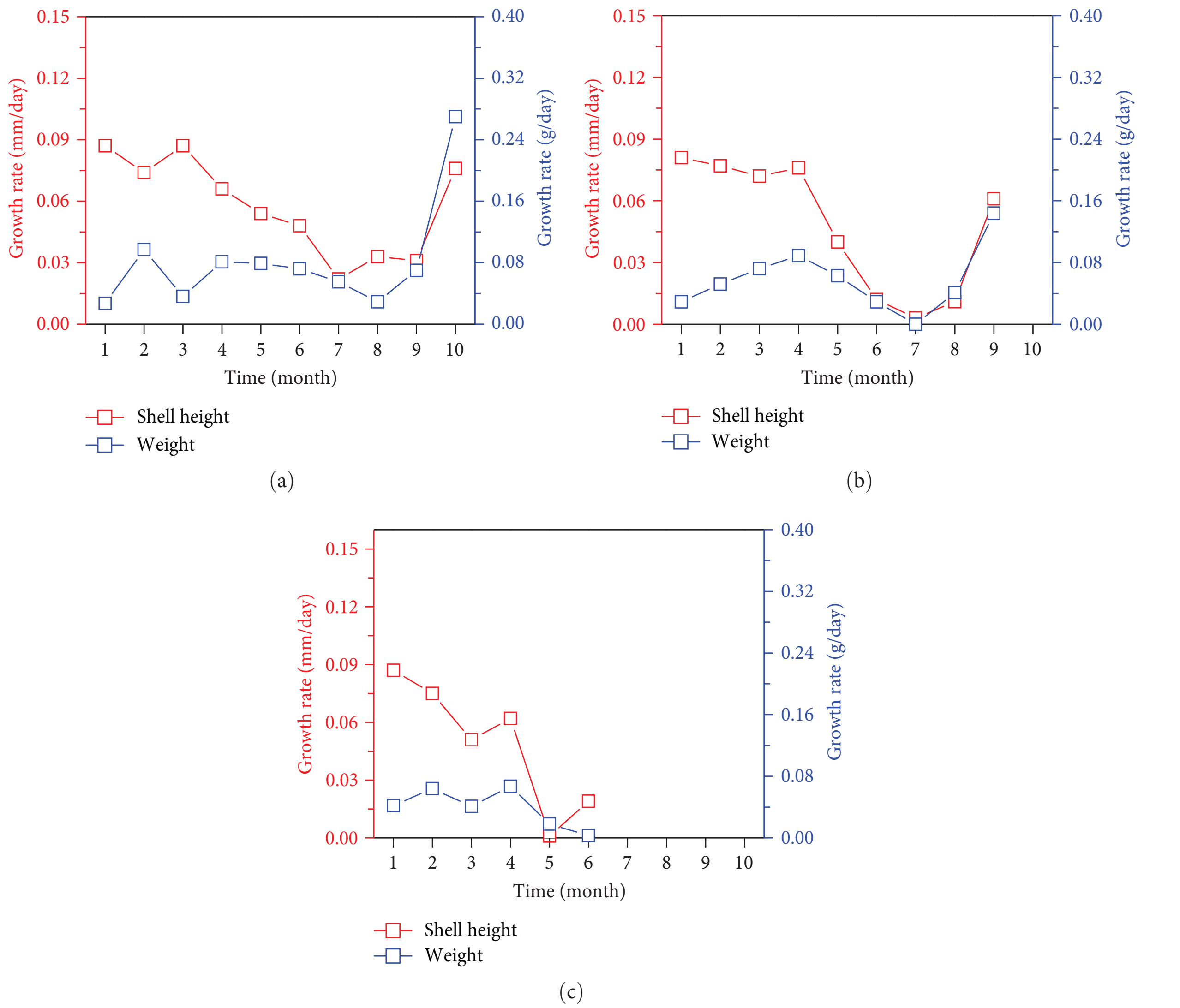

Figure 9: Growth rate in weight (g/day) and shell height (mm/day) for *Z. patagonica* cultivated in a suspended system in northern Patagonia: (a) Calbuco; (b) Chiloé; (c) Puerto Montt.

it initially exhibited a higher mortality rate (31%). However, after reaching a shell height of 25–30 mm, it showed a marked decrease in mortality (7%) (see Figure 3(b)). This trend is consistent with findings for *A. purpuratus* cultured in a suspended system in northern Patagonia (43°S), using 9-mm (shell height) scallops, where mortality was high in juveniles, reaching approximately 70%. However, once scallops exceed 30 mm, mortality does not surpass 1% [6]. The cumulative survival rates observed in this study align with those reported for *Argopecten nucleus* and *Nodipecten nodosus* [23], as well as for *Mimachlamys varia* and *A. purpuratus* in suspended systems [24, 25]. When comparing the growth performance of *A. natans* and *Z. patagonica* in suspended systems in southern Patagonia, it is reasonable to expect better growth from *A. natans* than from *Z. patagonica*. This expectation arises from the fact that *A. natans* takes less time to reach a shell height of 55 mm, given a temperature range between 5.5 and 10.5°C. In contrast, *Z. patagonica* requires an additional 6 months to reach the same size under the same growth conditions. Furthermore, significant differences are observed among the groups cultured at temperatures of 11, 9, control, and 13°C in land-based tanks for both species. Cultures at these temperatures exhibit limited growth and high mortality rates, with the 13°C group of *A. natans* experiencing 100% mortality.

It may suggest that these southern scallop species exhibit favorable growth performance when the water temperature ranges between 9 and 11°C, with growth slowing notably beyond 13°C. This physiological response is similar to what has been observed in *Z. patagonica*, where a 60% mortality rate was recorded when cultivated at 12°C and an 80% rate at 15°C [19]. This underscores the impact of seawater temperature changes as a decisive factor that can lead to a significant increase in metabolic expenditure [26].

Consequently, it has been described as the process that most profoundly affects the potential physiological growth rate. It appears that *Z. patagonica* is a species more sensitive to environmental variations [26]. If *A. natans* were to exhibit

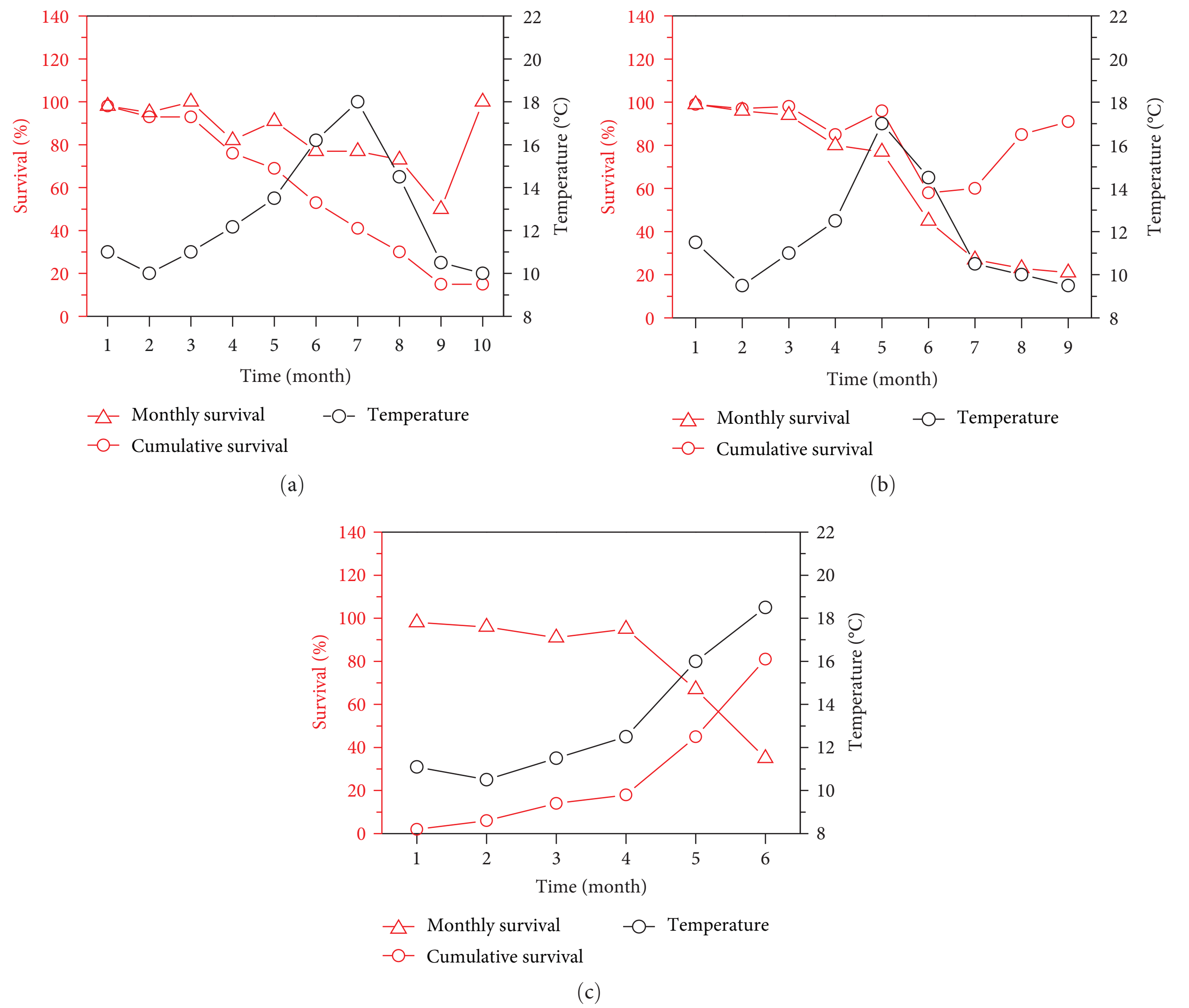

Figure 10: Monthly and cumulative survival (%) of *Z. patagonica* under cultivation in northern Patagonia, along with mean temperatures (°C), values recorded: (a) Calbuco; (b) Chiloé; (c) Puerto Montt.

a similar sensitivity [26], the situation would be even more pronounced. This study's findings indicate that the latter species is even more sensitive to temperatures exceeding 12°C.

On the other hand, transferring *Z. patagonica* to northern Patagonia allowed us to observe an increase in growth rates, especially in the sectors of Calbuco and Chiloé. According to the von Bertalanffy curve, scallops require 20–23 months to reach a size of 55 mm from a seed of 2.5 mm, which is 6–9 months less than what was observed in southern Patagonia. This difference may be attributed to the continental channels in the area, which receive a more abundant supply of fresh water compared to the oceanic zone of southern Patagonia. The primary driving force here is solar radiation on freshwater bodies, resulting in higher temperatures in summer [27]. However, in the same sites of the Los Lagos region, when the temperature rises above 14°C, a slowdown in growth appears to occur, a result that could explain the biogeographic distribution [28]. These high temperatures are generated by strong haloclines, which, either alone or reinforced by thermoclines, produce pycnoclines. These density gradients make vertical mixing difficult or even impossible, reinforcing the two-layer structure [27].

Additionally, it seems that the growth and survival rates of scallops tend to improve at greater depths, where conditions are more favorable and less influenced by daily temperature fluctuations [29]. When analyzing the maximum growth rates (shell height and weight) in all sectors, it becomes evident that these increases occur when the water temperature ranges between approximately 10 and 12°C [6].

In a study that evaluated the impact of location and culture system on the growth of the Peruvian scallop (*A. purpuratus*) in northern Patagonia (41°S), researchers observed a growth rate of 0.06 mm/day in a sector near Calbuco during the winter months. This result aligns with the findings of our investigation in the same sector, where scallops exhibited a growth rate of 0.059 mm/day over the entire 413-day period.

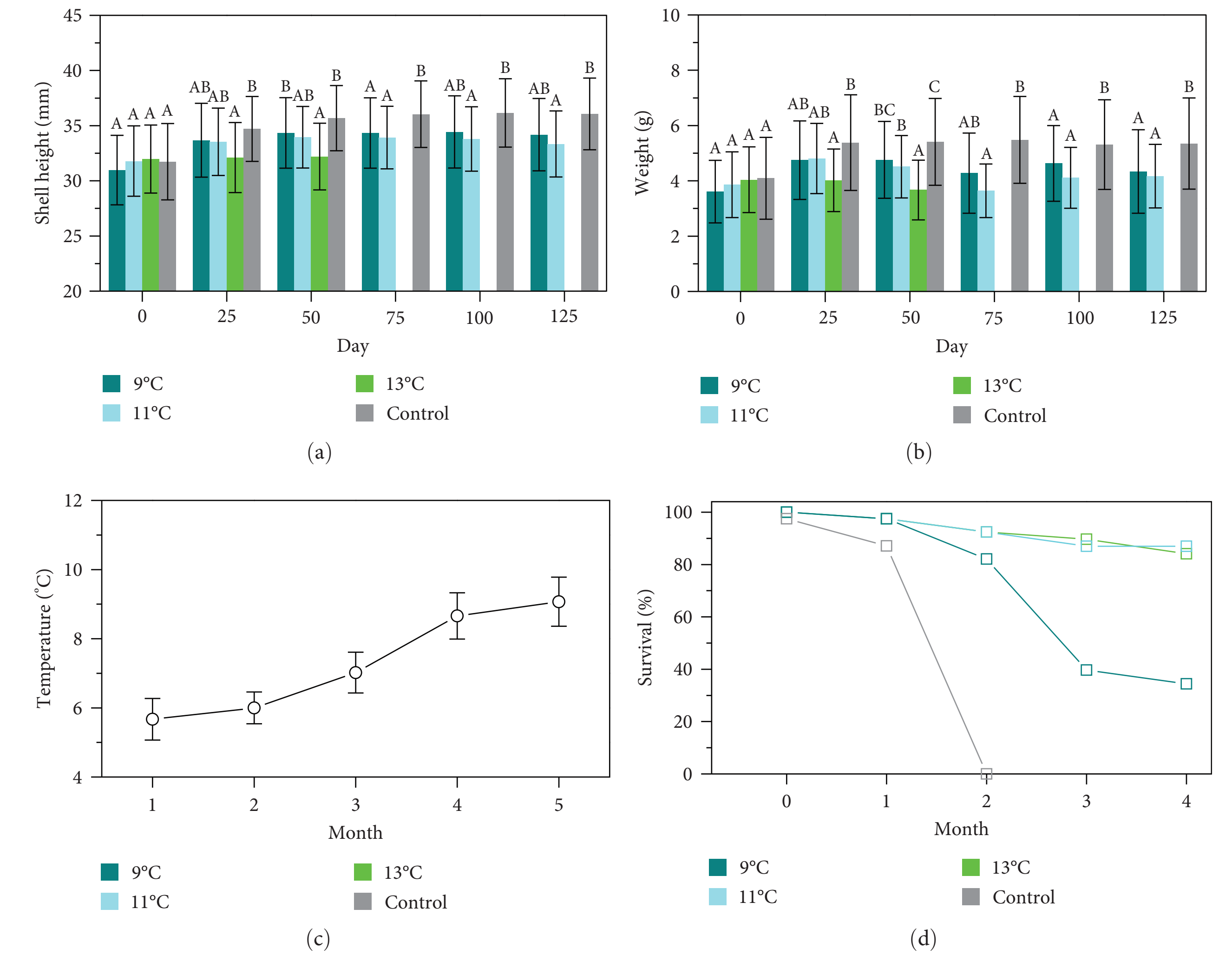

Figure 11: (a) Variations in shell height for *A. natans*, (b) weight, (c) temperature of the control group, and (d) cumulative survival for the four tested groups (control, 9, 11, and 13°C).

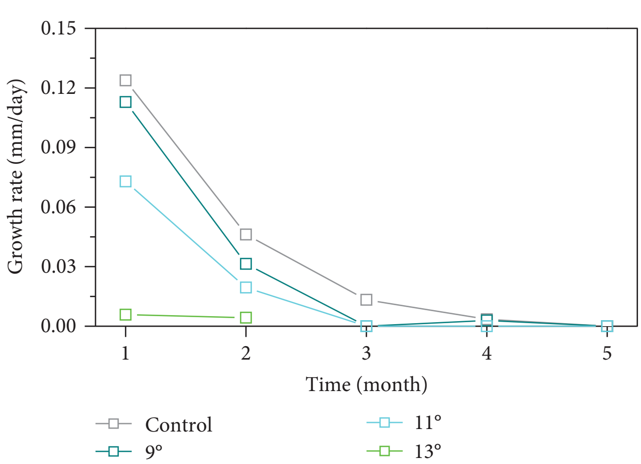

Figure 12: Growth rate in terms of shell height (mm/day) of *A. natans* cultured at four different temperatures (9, 11, 13°C, and control) in land-based tanks in southern Patagonia.

The physiological responses of both bivalve species are likely similar due to the environmental conditions of temperature and food availability. This contrasts with the case of the subtropical scallop species *Aequipecten tehuelchus*, cultivated in a suspended system in the San Matías Gulf, Argentina (41°S), where individuals with a valve height of 60 mm were obtained within 450 days from an initial size of 10 mm [20]. The authors noted that lower temperatures and reduced food availability during the winter months did not significantly affect their growth rate.

A. natans exhibited a higher growth rate than *Z. patagonica* when cultivated in a suspended system in southern Patagonia. However, *A. natans* showed lower growth and survival performance when exposed to temperatures exceeding 13°C. Conversely, *Z. patagonica* demonstrated better growth rates when cultivated in northern Patagonia, with the cultivation cycle averaging 21.5 ± 2.1 months from a seed with a total height of 2.5 mm.

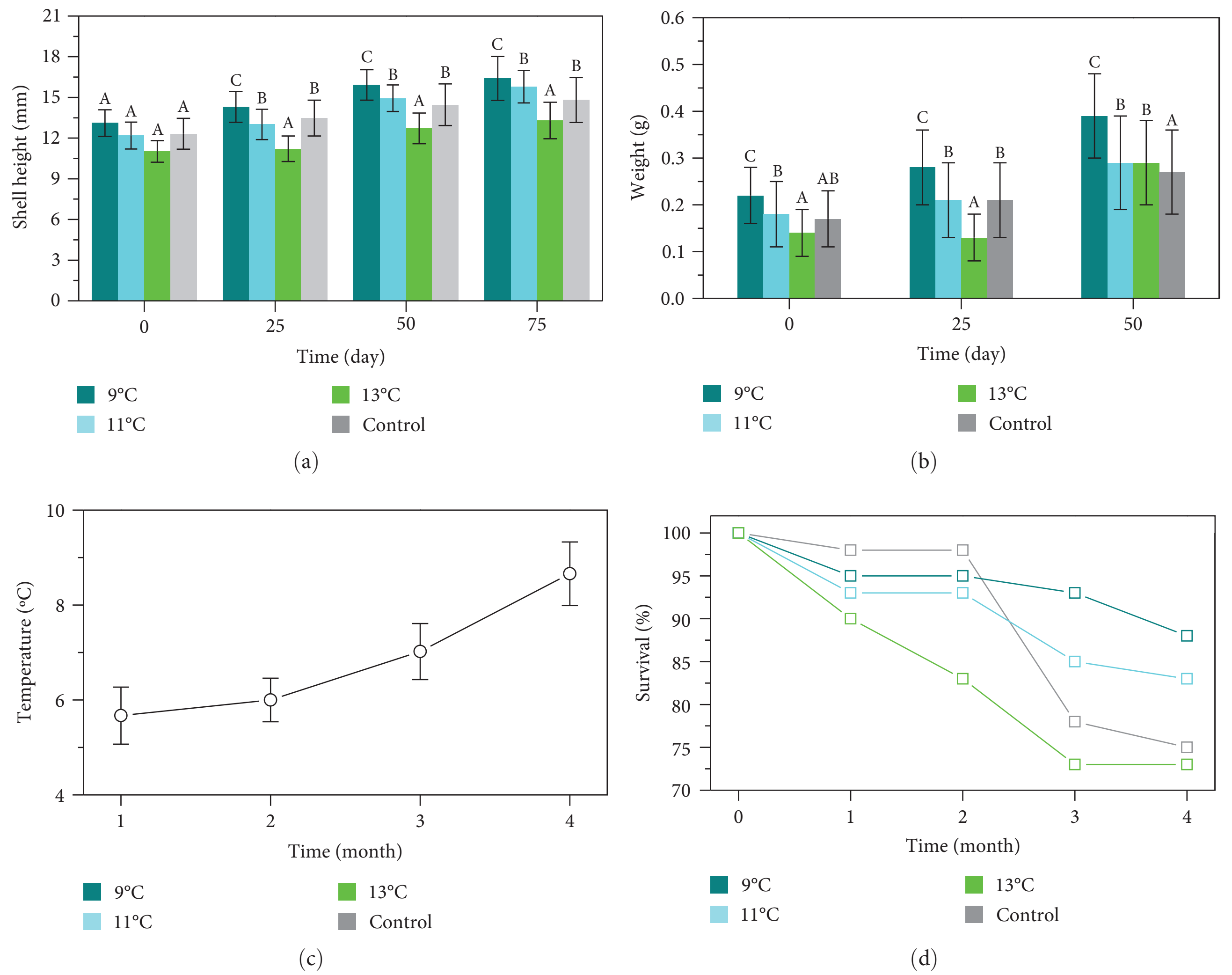

Figure 13: For *Z. patagonica* cultured in tanks (ZE1), variations in (a) shell height; (b) weight; (c) temperature of the control group; (d) cumulative survival for the four tested groups (control, 9, 11, and 13°C). The values of the four groups and the variation bars are presented for each of the six biometric samplings on the following days: 0, 25, 50, 75, 100, and 125. Different letters indicate statistical differences. The *p*-value is <0.0001 for Figures 13(a) and 13(b) (no-parametric assessment using Kruskal–Wallis).

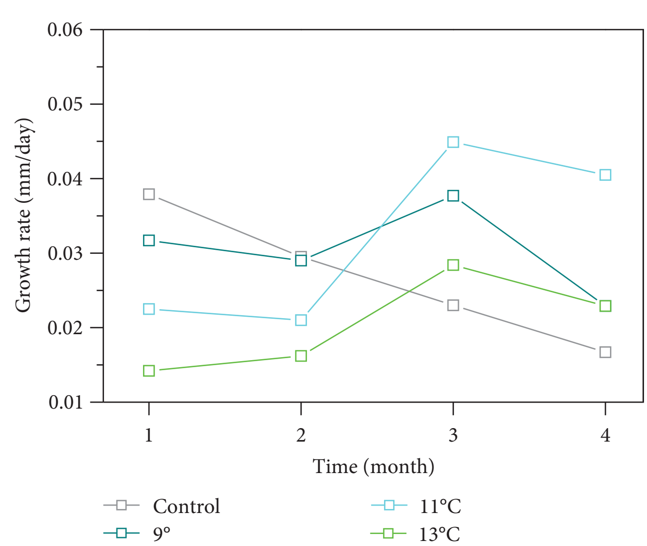

Figure 14: Growth rate in terms of shell height (mm/day) of *Z. patagonica* cultured at four different temperatures (9, 11, 13°C, and control) in land-based tanks in southern Patagonia.

This difference in growth may be attributed to the oceanic areas of the Strait of Magellan, where lower silicate concentrations in the surface layer result from the presence of marine water with low silicate content, primarily due to the consumption of phytoplankton with silicic structures, such as diatoms. This contrasts with the substantial contributions of silicate from freshwater sources in the fjords of northern Patagonia, which also correlates with the biomass of chlorophyl a, reaching a maximum of 15 mg/m^3 in northern Patagonia areas compared to approximately 5 mg/m^3 in the Strait of Magellan region [27].

Both southern scallop species present favorable conditions for suspended culture, particularly when water temperatures remain within the range of 9 to 12°C, which bodes well for the development of their future commercial cultivation.

5. Conclusions

Both *Z. patagonica* and *A. natans* demonstrate suitability for rearing under suspended or land-based tank systems in northern Chilean Patagonia under temperature conditions between 9 and 12°C. Among the two species, *A. natans* is more sensitive to temperatures above 12°C, which adversely affects both the growth rate and survival.

A. natans demonstrates a higher growth rate and shorter cultivation time compared to *Z. patagonica*, requiring a 17.86% shorter period to reach 55 mm from a 2.5 mm seed.

Data Availability

The data obtained and analyzed from this study are included in the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors would like to thank the Aquaculture Research Center Laredo team (technicians and workers) for providing the rearing support and biological material. Funding was provided by the Scientific and Technological Development Support Fund (FONDEF) (grant number: D01-1163), awarded by the National Research and Development Agency (ANID), Chile, and Call for Support of Innovation in Higher Education 2019 (grant number: MAG 19101), of Ministry of Education, Chile. The authors are also grateful to the Sao Paulo Research Foundation–FAPESP (grants no. 2022/02756-4, 2022/16545-5 and 2023/03232-1), Brazil.

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