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Commercial Quality, Biological Indices and Biochemical Composition of Queen Scallop *Aequipecten opercularis* in Culture

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Abstract: Market demand for scallops has considerably increased in recent decades. Although natural populations of scallops are vulnerable, the queen scallop, *Aequipecten opercularis*, can represent a possible alternative to at-risk species. The aim of this study was to determine the effect of seawater parameters on the commercial quality, biological indices and nutritional quality of the scallop *A. opercularis* in 1900 L tanks in ex situ conditions. The condition index (CI) and meat yield (MY) peaked in autumn (89.92% and 40.29%, respectively). The muscle index (MI) showed the highest peak during the winter season (5.96%), while the gonadosomatic index (GSI) (34.06%) peaked in the spring months. Protein content (6.89–9.56 g/100 g), lipids (2.58–2.79 g/100 g) and carbohydrates (0.12–0.33 g/100 g) varied during the study period. Seasonal fluctuations in seawater temperature and pH negatively influenced the CI, MY and protein and lipid content, while positively affecting carbohydrate and moisture content. The most suitable period of the year for the consumption of the scallop *A. opercularis* was found to be the winter and spring periods, when the scallops achieved their highest nutritional value. It can be stated from this study that queen scallops in the Adriatic Sea have a high nutritional quality and that they can be proposed for higher human consumption.

Keywords: nutritional quality; aquaculture; scallop production; indices

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1. Introduction

The global production of marine mollusks for human consumption was more than 17.6 million tons per year in 2019, which was about 21% of the total marine products in the world. Most marine bivalve production (89%) comes from aquaculture, and only 11% comes from wild fisheries [1]. In the Adriatic sea, which includes the marine areas of Slovenia, Croatia and Italy, the most commonly farmed species are endemic, such as the Mediterranean mussel (*Mytilus galloprovincialis*) and oysters (*Ostrea edulis*) [2]. The demand for seafood has been rapidly rising, driven by increases in populations and their rising purchasing power. According to the literature, the leading drivers of seafood consumption are nutrition, taste and convenience [3].

In Europe, and especially in the northern Adriatic Sea, the farming of bivalves has been decreasing over recent decades. Wild mussels and oyster stocks are depleted due to unsustainable overfishing practices and climate change [2,4]. In addition to concerns about overfishing, the main barriers to consuming marine seafood are price and nutritional quality affected by human activities [5]. Although various aquatic animals have adapted and thrived in the marine ecosystem, biodiversity and productivity are rapidly changing due to climate change [6,7]. All of these facts make it necessary to investigate the potential health benefits of alternative farmed and wild shellfish consumption in relation to supply.

Bivalves represent important marine organisms due to their ecological relevance and nutritional and commercial value [8]. Recently, interest in the food properties of scallops has significantly increased in Europe [2,9]. Among bivalves, scallops represent an important part of the global seafood market supply and supporting both aquaculture and capture fisheries around the world [10]. Scallops naturally occur on firm, sandy gravel, sandy mud or shelly ground down to 190 m in depth along the east coast of the North Atlantic, as well as the Mediterranean and Adriatic Seas [2,11]. The most widespread scallop species in the northern Adriatic Sea belong to the subfamily Pectinidae and have high commercial value [12]. A major economic role is played by *Pecten jacobaeus* (L.), or the Mediterranean scallop, locally named "capesanta", which tends to be overfished in the northern Adriatic Sea [13]. Three other morphologically similar species equally known in the local market as "canestrelle" are the variegated scallop *Mimachlamys varia* (L.), the smooth scallop *Flexopecten glaber* (L.) and the queen scallop *Aequipecten opercularis* (L.) [14].

The lack of *P. jacobeus* and the higher market values in Mediterranean countries of canestrelle make this species of great interest for the higher marketable demand and development of scallop culture [10,12,14]. According to the oral reports of fishermen and traders of sea products in Istrian County (Croatia), the queen scallop *A. opercularis* is caught during commercial fishing with bottom trawls (rampons and bottom trawls). Although catches are made all year round, the largest quantities of queen scallop catches are made in the autumn-winter period. In the Rulebook on the form, content and method of keeping and submitting data on catches in commercial fishing at sea [NN 38/2018, 35/2020], *A. opercularis* is currently managed under the FAO code SCX, together with other bivalves from the subfamily Pectinidae, with the exception of scallops (*Pecten jacobaeus*), which have their own separate FAO code SJA.

The condition index (CI) and meat yield (MY) of scallops are important factors from physiological and economic points of view [8,15]. Economically, these indices reflect scallops' quality and market value, while, physiologically, they can point out the population health of a species (growth, sexual maturity, stress tolerance, etc.) in a given marine environment [16]. The condition index and meat yield, together with the gonadosomatic index (GSI) and muscle index (MI), are useful indicators of bivalves' commercial quality and may offer valuable information for decision-making processes related to the sustainable exploitation of this species [8,16,17]. The biochemical composition of any edible organism is an important indication that helps in determining the quality of its flesh in terms of nutritional value in comparison to other organisms. This is a valuable tool to assess the source of nutritive constituents for human consumption [18]. Scallops acquire proteins, lipids, carbohydrates and other components from phytoplankton when building their own biomass. The protein content is generally responsible for the largest proportion of scallop meat, followed by the carbohydrate and lipid content [15,16,19]. Depending on their storage conditions on the market or during further processing steps, the water content of scallops may vary and even exceed the natural moisture content [19]. Among nutritive values, *A. opercularis* is considered a delicacy in many countries of the world [10]. The organoleptic characteristics (taste, texture, firmness, etc.) may offer valuable information for decision-making processes on the sustainable exploitation of scallop species [20].

Seasonal storage and utilization cycles of the food reserve in bivalves are related to food availability and the annual reproduction cycle [21]. Moreover, parameters such as water temperature, food availability and the gametogenesis cycle may influence meat yield and the biochemical composition of the scallop, thus conditioning their commercial quality in natural environments and aquaculture [8,10]. Although some studies have reported on the indices and biochemical composition of scallops, only a few have paid specific attention to the indices and content of *A. opercularis*. Therefore, the aims of this study were to determine the commercial quality (CI and MY), biological indices (MI and GSI) and biochemical aspects (biochemical content) of *A. opercularis.* In order to determine the effect of environmental parameters and the most favorable season for harvesting, queen scallops were investigated for their viability to be grown ex situ in captivity for a period of one year for the first time. This knowledge will be useful in the assessment of queen scallops as species for increased harvesting and as potential candidates for aquaculture.

2. Materials and Methods

2.1. Shellfish Sampling and Ex Situ Culture

During October 2020, queen scallops were collected with a trawling boat, 2 miles SW from the Albanež shoal (northern Adriatic Sea), within the E2 fishing zone. Collected specimens (n = 160) were transported in seawater-filled thermo-insulated containers, and were immediately put into round 1900 L (165 × 90 cm) flow-through tanks in the premises of Aquarium Pula. Each scallop was marked with a small plastic number so that each specimen could be individually monitored. The shellfish culture was maintained for a period of one year in flow-through tanks with a seawater bore in the proximity of the Aquarium Pula premises. The water flow was kept at a rate of 200 L per hour. The tanks were cleaned by siphoning the bottom of the tanks each day. Scallops were fed on a daily basis with a mixture of live algae culture (*Tetraselmis* sp. and *Isochrysis* sp.) and freeze-dried algae (*Skeletonema* sp., by Phytobloom). Food quantity was adjusted according to the sample density. Algae concentration was calibrated in relation to the number of scallops inhabiting the tank in each investigated season; i.e., food quantity was abbreviated during each seasonal scallop sampling (n = 20). Water parameters (temperature, pH, oxidation-reduction potential, conductivity, dissolved oxygen concentration) were measured with a Hanna HI98194 multiparameter probe.

2.2. Morphological Measurements

After cleaning the fouling organisms growing on the shell, *A. opercularis* was weighed to the nearest 0.01 g (total weight), and the total shell length, shell height and shell thickness were measured using a stainless steel caliper (0.1 mm) [22] during the investigated seasons. The fineness (F) was calculated according to the equation of [23]:

$$F = \text{shell height}/\text{shell thickness}.$$

Twenty specimens randomly picked from tanks were seasonally processed (Autumn/October 2020, Winter/January 2021, Spring/April 2021, Summer/July 2021) for the evaluation of CI, MY, GSI and MI. Each scallop body was dissected, and gonads and muscle were separated from other soft tissues. CI and MY were determined according to [8,21]:

$$CI = [\text{meat wet weight (g)}/\text{shell wet weight (g)}] \times 100$$

$$MY = [\text{meat wet weight (g)}/\text{total wet weight (g)}] \times 100$$

GSI and MI were calculated as follows [23,24]:

$$GSI = [\text{gonad wet weight (g)}/\text{adductor weight (g)}] \times 100,$$

$$MI = [\text{muscle wet weight (g)}/\text{wet body weight (g)}] \times 100.$$

2.3. Measurements of Biochemical Components

Biochemical analyses were performed on representative samples made of five specimens from each season sampled (Autumn/October 2020, Winter/January 2021, Spring/April 2021, Summer/July 2021). All analyses were conducted in triplicate. Soft scallop tissues were immediately frozen in liquid nitrogen and stored at −20 °C.

The moisture and ash contents in *A. opercularis* were determined according to the standard procedures. Moisture content was calculated based on the percentage weight loss after drying 4 g of homogenized tissue to a constant weight at 130 ± 5 °C for 4 h. Ash content was determined by carbonizing the sample. Ash content refers to the inorganic residue remaining after the ignition or total oxidation of organic matter in a sample.

The protein content was determined by Kjeldahl's method and calculated by converting the nitrogen content [25]. Total lipid content was determined according to the Folch et al. [26] method, and the reducing sugar content was determined with the Dubois et al. [27] method.

2.4. Statistical Analyses

The collected data were analyzed in STATISTICA software (Version 9.0). Results are reported as means ± standard deviations (SD). Data were analyzed for normality and variance homogeneity through Kolmogorov–Smirnov and Levene's tests, respectively. Seasonal differences between morphological and biochemical parameters were determined using the one-way analysis of variance (ANOVA) test. When the variance analysis indicated significant differences ($p < 0.05$), post-hoc Tukey's test was used. In case the conditions for parametric analysis were not fulfilled, a nonparametric Kruskal–Wallis H test was used, followed by a Mann–Whitney U test. The correlations between indices and biochemical composition parameters with environmental parameters were determined using the Pearson correlation.

3. Results

3.1. Seawater Conditions

The seawater variables recorded each day are shown in Figure 1. The seawater temperature fluctuated between a minimum of 14.03 °C measured in March to a maximum of 23.50 °C in July. The pH values did not display significant changes, remaining almost constant during all seasons and ranging from 7.01 to 7.99. The oxidation-reduction potential was in the range of 179.30 mV to 318.30 mV. The highest values were measured in November and subsequently decreased, with the lowest values being measured in February. Conductivity and dissolved oxygen fluctuated in almost the same way. The lowest values of conductivity (40.18 mS/cm) and dissolved oxygen (49.20 mg/L) were measured in March, while the highest values of conductivity (51.10 mS/cm) and dissolved oxygen (182.50 mg/L) were recorded in January.

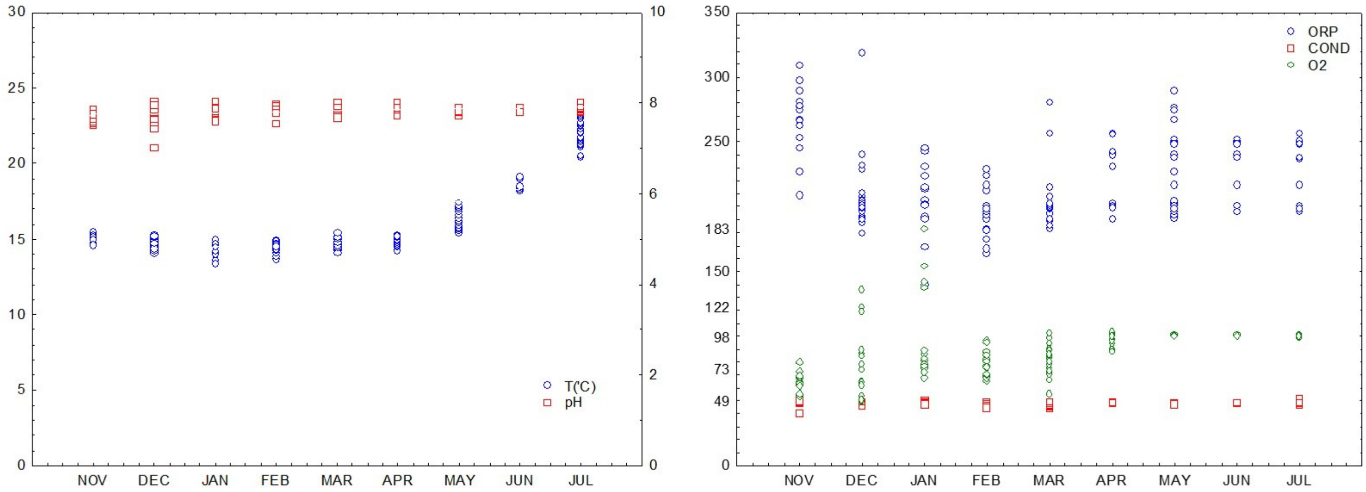

Figure 1. Temperature (T), pH, oxidation-reduction potential (ORP), conductivity (COND) and oxygen concentration (O_2) during the investigated seasons measured in *ex situ* conditions.

3.2. Morphology

Scallop weight exponentially increased with shell height (Figure 2), which resulted from the increase in total body weight, shell weight and soft body weight in equal proportion. No significant difference between the rate constant (k) of the slopes of the increase in the weight parameters and shell height was found. Fineness was constant and ranged from

2.91 ± 0.22 to 3.01 ± 0.22 without statistically significant differences in the investigated seasons (Figure 3).

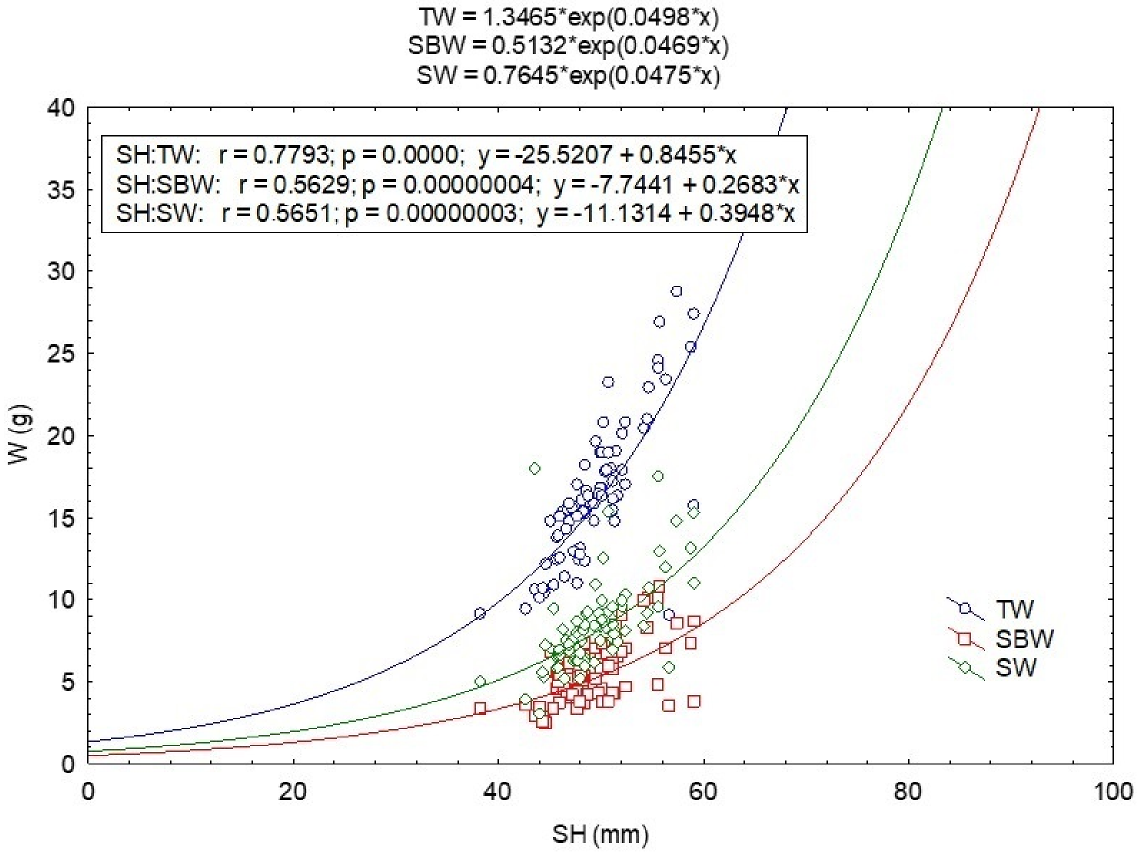

Figure 2. Relationship of total weight (TW), soft body wet weight (SBW) and shell weight (SW) to shell height (SH) of *A. opercularis* individuals.

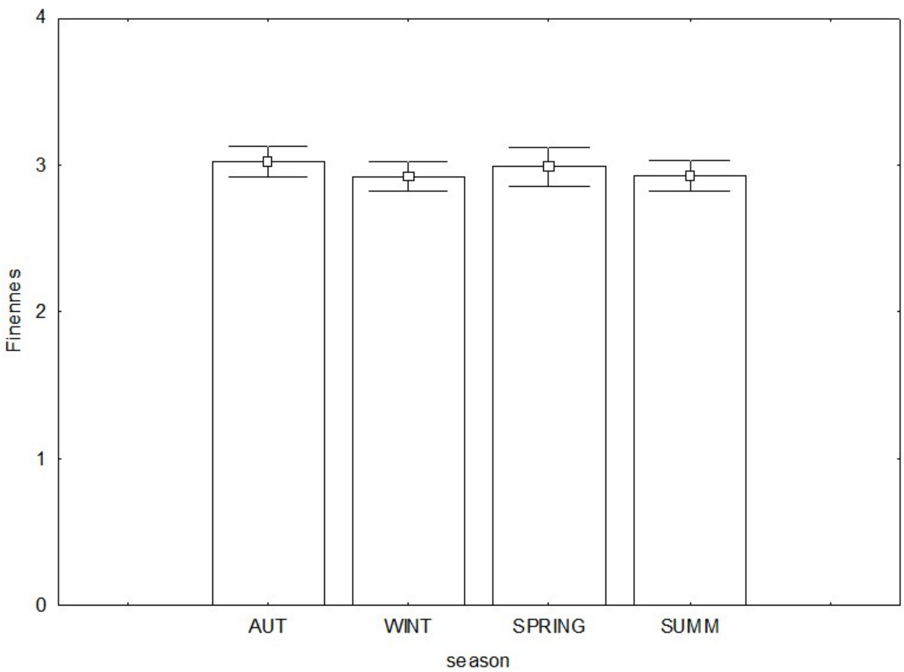

Figure 3. Fineness of queen scallops (n = 80), sampled in four seasons: Autumn (AUT), Winter (WINT), Spring (SPRING) and Summer (SUMM).

3.3. Commercial Quality and Biological Indices

Seasonal changes in the scallops' CI and MY significantly varied, but with the same pattern (Figure 4). The highest CI (94.04%) and MY (41.70%) of scallops were in autumn, and the lowest CI (46.67%) and MY (25.83%) were recorded in summer; the values of these indices were comparable in winter and spring. When comparing autumn CI to other seasons' CI, the significant difference was highest in the CI measured in summer (Tukey HSD test, $p < 0.0001$), followed by spring (Tukey HSD test, $p < 0.0001$) and winter (Tukey HSD test, $p < 0.0002$). The MY in autumn was significantly higher compared to all other seasons (Tukey HSD test, $p < 0.0001$), while the MY in summer was significantly lower than other seasons in the investigated period (Tukey HSD test, $p < 0.0001$).

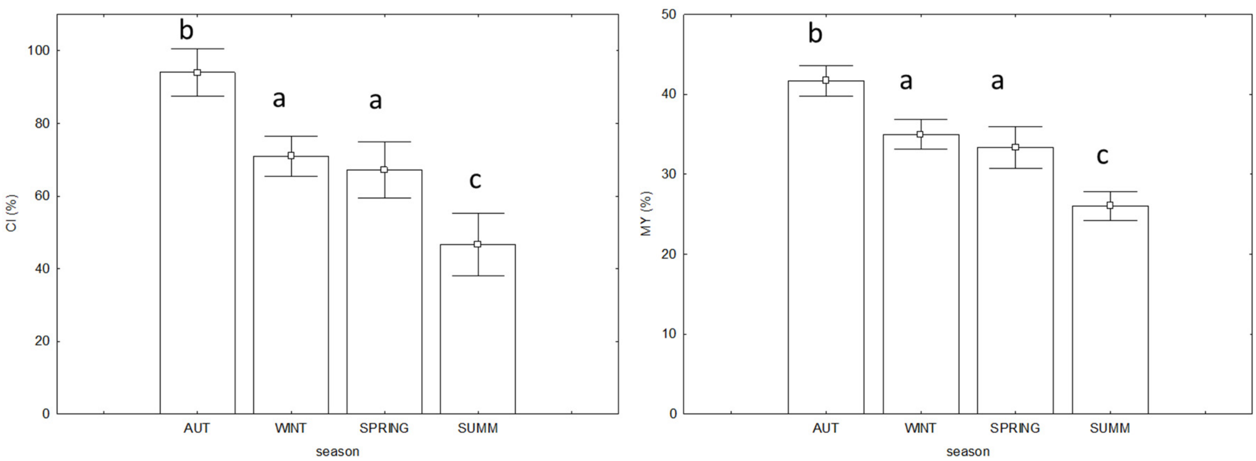

Figure 4. Condition index (CI, %) and meat yield (MY, %) of queen scallops (n = 80) from the tanks, sampled in four seasons: Autumn (AUT), Winter (WINT), Spring (SPRING) and Summer (SUMM). The means labeled by different letters are significantly different (Tukey's HSD test, $p < 0.05$).

The scallops' biological indices in the studied period seasonally varied and are presented in Figure 5. The highest MI in scallops was in the winter period (5.96%) compared to MI in summer (Tukey HSD test, $p < 0.0007$) and autumn (Tukey HSD test, $p < 0.002$). The lowest MI in scallops was recorded in the summer (3.81%) and was significantly different from the MIs measured in the winter (Tukey HSD test, $p < 0.0001$), spring (Tukey HSD test, $p < 0.0007$) and autumn (Tukey HSD test, $p < 0.03$). The scallops' GSI was highest in spring (34.06%) and significantly different when compared to the GSI in autumn (Tukey HSD test, $p < 0.0005$) and summer (Tukey HSD test, $p < 0.02$). The lowest GSI was observed in autumn (18.01%) and was significantly different when compared to the GSIs in spring (Tukey HSD test, $p < 0.0005$) and winter (Tukey HSD test, $p < 0.01$).

3.4. Biochemical Composition

The biochemical components of scallop tissue in the study period are presented in Table 1 and show seasonal variation (Table 2).

Table 1. Seasonal changes in proximate composition of *A. opercularis* during the study period. Values are mean ± S.D. (n = 3).

Parameter	AUT	WINT	SPRING	SUMM
Moisture (g/100 g)	87.18 ± 0.07	86.08 ± 0.38	88.63 ± 0.37	88.81 ± 0.18
Ash (g/100 g)	2.58 ± 0.03	2.68 ± 0.01	2.79 ± 0.03	2.64 ± 0.06
Protein (g/100 g)	8.23 ± 0.16	9.56 ± 0.29	8.59 ± 0.19	6.89 ± 0.16
Lipid (g/100 g)	0.45 ± 0.03	0.40 ± 0.06	0.33 ± 0.01	0.32 ± 0.03
Carbohydrate (g/100 g)	0.19 ± 0.01	0.12 ± 0.01	0.14 ± 0.01	0.33 ± 0.01

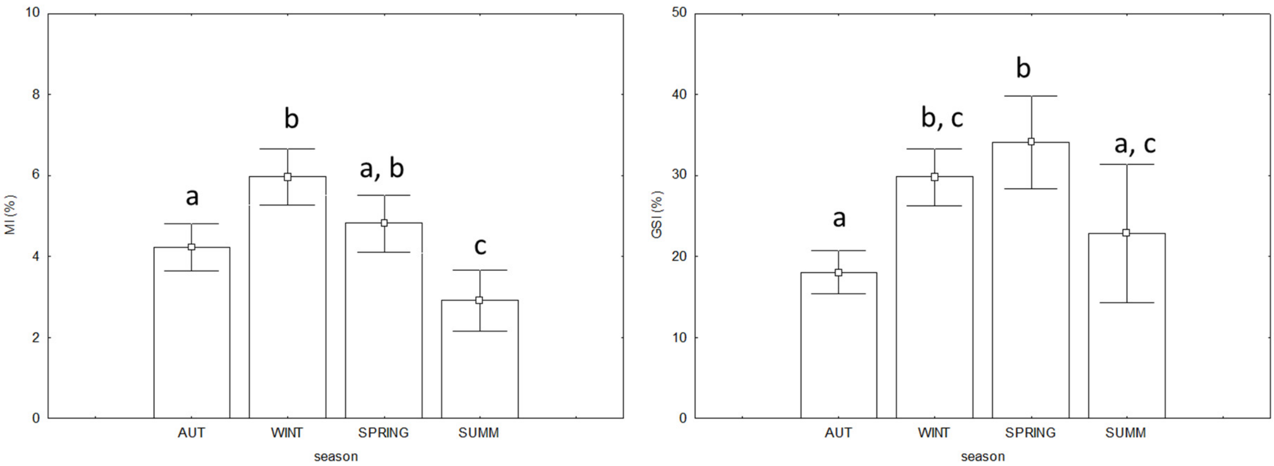

Figure 5. Muscle index (MI, %) and gonadosomatic (GSI, %) of queen scallops (n = 80) from the tanks, sampled in four seasons: Autumn (AUT), Winter (WINT), Spring (SPRING) and Summer (SUMM). The means labeled by different letters are significantly different (Tukey's HSD test, $p < 0.05$).

Table 2. Results of the scallop biochemical content analysis with Kruskal–Wallis H test. Statistically significant differences are represented in bold. Significant Kruskal–Wallis H test was followed by a Mann–Whitney post hoc test and when relevant p values are given in the text.

Parameters	H	df	p
Moisture	9.35	3	**0.02**
Ash	8.31	3	**0.04**
Protein	10.38	3	**0.01**
Lipid	6.75	3	0.08
Carbohydrate	10.76	3	**0.01**

Generally, moisture content was the greatest weight component throughout the whole studied period. The winter values (86.08 ± 0.38) of moisture were lower than in other seasons, albeit not significantly, except in summer. The moisture value was highest in summer (88.81 ± 0.18) and significantly different when compared to winter (Mann–Whitney test, $p < 0.05$). The highest ash content value was recorded in spring (2.79 ± 0.03) with a significant difference to the lowest, which was in autumn (2.58 ± 0.03) (Mann–Whitney test, $p < 0.01$).

Significant seasonal differences in protein content were observed in scallop tissues, with the winter protein content (9.56 ± 0.29) being higher than in the summer period (6.89 ± 0.16) (Mann–Whitney test, $p < 0.01$).

The lipid content in the scallop tissue was the only component that remained statistically unchanged over the studied period, with the lowest values being in summer (0.32 ± 0.03) and the highest in winter (0.45 ± 0.03).

The peak of the carbohydrate content in scallop tissues occurred in summer (0.33 ± 0.01) and showed higher values in all seasons, with significant differences from winter (Mann–Whitney test, $p < 0.01$) and spring (Mann–Whitney test, $p < 0.01$).

3.5. Correlation of Morphological, Biological, Biochemical and Environmental Parameters

The correlations of the scallops' body and environmental parameters are presented in Table 3. Environmental parameters had the highest influence on CI and MY: temperature and pH negatively affected the CI (−0.51; −0.61) and MY (−0.53).

Table 3. Pearson correlation of *A. opercularis* morphometry and indices with seawater parameters: temperature (T), pH, ORP (oxydo-reduction potential), conductivity (COND), oxygen (O_2). Statistically significant differences are ($p < 0.05$) represented in bold.

Parameters	T	pH	ORP	COND	O_2
Fineness	0.10	**−0.24**	**−0.03**	**−0.24**	**−0.21**
Condition index	**−0.51**	**−0.61**	0.18	0.15	**−0.37**
Meat yield	**−0.60**	**−0.53**	0.15	0.12,	**−0.39**
Muscle index	**−0.38**	−0.20	0.05	**−0.22**	−0.12
Gonadosomatic index	−0.03	0.15	−0.14	−0.20	0.12

Environmental parameters influenced the scallops' biochemical content (Table 4). Temperature (0.69), pH (0.65) and conductivity (0.74) show a high positive correlation with moisture content in the scallop tissue. pH positively influenced the ash content (0.66), while it negatively affected the lipid content (−0.58). A negative correlation between dissolved oxygen and lipid contents was observed (−0.41). The temperature had a significant negative effect on the protein content (−0.91) and a positive effect on the sugar content (0.9).

Table 4. Pearson correlation of biochemical composition with seawater parameters: temperature (T), pH, ORP (oxydo-reduction potential), conductivity (COND), oxygen (O_2). Statistically significant differences ($p < 0.05$) are represented in bold.

Parameters	T	pH	ORP	COND	O_2
Moisture	**0.69**	**0.65**	**0.45**	**0.74**	**0.16**
Ash	−0.27	**0.66**	−0.20	0.11	0.42
Protein	**−0.93**	0.16	−0.46	**−0.75**	−0.45
Lipid	−0.45	**−0.58**	0.16	−0.19	**−0.41**
Carbohydrate	**0.97**	−0.20	0.29	0.55	0.03

4. Discussion

Consumer demand for marine shellfish has significantly increased in recent decades [2,3]. Due to the lack of information about the nutritional value of the most edible bivalves, it is important to provide consumers with useful and applicable information about their beneficial properties. Our study delivered new information about the seasonal commercial values, biological indices and nutritional value of *A. opercularis* from the Northern Adriatic for the first time. Moreover, the present study described the seasonal fluctuations in the environmental parameters of the seawater taken from a depth of 30 m that can affect the indices and energy storage of the queen scallop (*A. opercularis*). The temperature and pH values represent typical annual fluctuations in the Adriatic Sea, with minimum values in the winter and maximum values during summer [1,28]. Oxidation reduction potential refers to the ability of water to break down waste products and clean itself and depends on the seasonal changes in water oxygen level, temperature, pH value and salinity [29]. Higher oxidation-reduction potential concentrations represent a healthier environment since the bacteria can decompose matter more effectively in seawater with oxidation-reduction potential levels from 150–400 mV [30]. In this research, the oxidation-reduction potential values represent acceptable concentrations for *A. opercularis* culture; nevertheless, the effect of the seawater oxidation-reduction potential on animal physiology is a rarely investigated factor [31]. Seasonal atmospheric warming affects oxygen concentrations in the water column, especially in the surface layers, with maximum values in the winter and minimum values in the summer [32]. In this study, the highest dissolved oxygen concentrations were measured during the winter months (December and January), while, unexpectedly, we measured high oxygen concentrations during the summer months (10.7 mg/L). Topić-Popović et al. [11], in their research in the Northern Adriatic at a depth of 15 m, measured the highest concentrations during the winter (5.89 mg/L). The temperature and nutrient availability in the water column are the main factors affecting scallop growth [2,5,33]. Therefore, scallops were fed each day to exclude this factor in observing the effects of varying seawater parameters.

In this research, the total weight, shell weight and soft body weight of the scallops exponentially increased with shell height, as previously described in Schmidt et al.'s study [32]. The morphological growth of queen scallops was indirectly influenced by seasonal changes in the environment, which directly affected the seawater's primary production [33]. Christopersen et al. [34] argue that the environmental parameters of temperature, salinity and food density are key factors in the development rate of juvenile queen scallops. In aquariums, scallop density is also a limiting factor; a higher density of scallops confines their growth due to the limited food availability and lack of living space [35]. Many researchers also focused on the seasonal effect on queen scallop growth based on morphological parameters [34–38]. There is a vast amount of data showing a similar relationship between scallops' morphological parameters in the environment [32,39]. However, the obtained constant fineness in this study, in comparison to natural conditions, could be due to the fact that the scallops were continuously fed with live phytoplankton of high organic content and quality or due to a possible reduction in the scallops' metabolic rate due to the maintenance of the specimens in a laboratory under stable conditions [32].

The IC and MY of queen scallops observed in this research were similar to the results obtained from *P. jacobeus* from the Southern Mediterranean [20], although much higher than *P. jacobeus* from the Gulf of Antalya during all seasons [15]. Seasonal changes in the IC in this study showed a steady decrease from autumn until summer. Lower condition indices in summer indicate that scallops have allocated less energy to maintaining their body mass, which may relate to energy investments into stress defense against increased temperatures [34]. Moreover, the IC showed a statistically significant negative correlation with temperature, pH value and dissolved oxygen. Seasonal fluctuations in the seawater parameters can negatively affect the physiology, stress response and survival of the queen scallop (*A. opercularis*) in the Northern Adriatic [11], as was found in this study. Previous research showed that, in addition to environmental parameters such as temperature, salinity and food availability, gametogenesis represents an important factor for morphological growth, since it requires a lot of energy [40]. Gametogenesis can occur once there is enough food available for the energetically demanding process of reproduction. However, when food becomes limited, gametogenesis turns to the catabolism of reserve tissue, such as the adductor muscle [41]. Sexual maturation also requires significant mobilization of energy resources for the synthesis of gonads, tissue and vitellogenesis [42]. Gametogenesis is under the influence of internal factors such as age and external factors such as seasonal changes in the environment. In this study, the GSI increased from autumn 2020 to spring 2021, after which it decreased during summer. Similar patterns were observed in mussel bivalves from Trieste bay, with peak values recorded in spring [43]. Marčeta et al. [14] noted that *F. glaber* scallops, sampled from the northwest Adriatic, had their lowest GSI values from October to December, in the period when their sexual organs are dormant. The scallop species' reproduction period starts from April to September in the Mediterranean Sea. Most reproduction occurs in mid-summer in the Adriatic Sea, especially in July and August [11,14].

Furthermore, the GSI and MY are in relation to the reproduction period due to the area covered by the muscle tissue being relatively less by the enlargement of the gonads [8]. In scallops, glycogen from the adductor muscle is used as an energy source to build up gonads, and thus reproduction significantly influences adductor muscle mass [11,15,44]. The relative effect of the adductor muscle in the process of scallop gametogenesis is directly connected to food availability in the environment. In this research, the MI showed an increase from autumn to winter and a decrease from spring to summer. Furthermore, the rates of increase and decrease are highly correlated to the GSI and to the CI, which has already been documented in previous research [8,18,45]. As the adductor muscle in scallops reached maximum mass before the period of gonad development and in the process of gametogenesis [46,47], the winter period could be a suitable time for harvesting and human consumption because of the scallops' high nutritional values [48]. A monthly approach to protective measures with respect to the period of reproduction for *A. opercularis*, both in aquaculture and in the wider marine–land interfaces, will provide relevant information on whether there is a closed reproduction season of this species in the Northern Adriatic. It could therefore be affirmed that the assessed biological indices are important factors for these organisms in terms of both commercial quality and nutritional value.

Furthermore, the biochemical content in scallops was influenced by the seasonal changes in environmental factors, as was found in many previous studies [11,33,39,41–49]. The biochemical composition of many bivalves indicates annual accumulation patterns and reserve uses as a consequence of a complex interaction between food availability, growth and reproduction [8]. In this research, the water content in *A. opercularis* tissue did not significantly change, remaining between 86 and 88%. These results are similar to the results obtained for other marine bivalves [15,50]. In research conducted in the Adriatic Sea, the water content of the scallop *F. glaber* amounted to approximately 83% and higher [51]. The average water content in *A. opercularis* tissue samples from the British islands was 82.2% [52]. In research conducted on the west coast of the Istrian peninsula, the water content in scallops *Chlamys varia* and *F. glaber* amounted to 84 and 87%, respectively [49]. Water content in the tissue is considered a good indicator of scallop freshness and meat quality [53] and depends on the physical structure of meat, since water is fundamental in chemical reactions such as the transport of nutrients, the deposition of waste products, neural impulse transition and muscle contraction [50]. In this research, ash content varied from 2.58% in summer up to 2.79% in spring, showing comparable variation to the queen scallops sampled from the Northern Adriatic [49]. The protein content of queen scallops in this study exhibited a similar composition to the scallops from the Ionian Sea [18] and Tunisian Sea [54]. The species *C. varia* and *F. glaber* from the Adriatic Sea had slightly higher protein concentrations [11]. Protein content ranged from minimum values in the winter to maximum values in the summer and was nearly identical to the average yearly protein content of the scallop *F. glaber* in the Mediterranean [19]. Lipids in queen scallops had the same values as those found in *F. glaber* [51] and *P. jacobeus* [15]. Variations from spring and summer to the highest values in autumn in this study can be compared with the same pattern observed for the scallop *C. varia* sampled from the Mediterranean; however, for the species *F. glaber* the concentrations showed a reverse pattern—the highest concentrations were measured in spring (1.07%), while the lowest were measured in autumn (0.3%) [49]. The main biological functions of lipid are as a structural organization of the cellular membrane and for signalisation and energy storage during stress events; lipids represent an effective energy resource and are an important component of human seafood demand [18]. Scallop lipid content research in the various areas of the Mediterranean is very limited [18,55], and none of the existing studies cover seasonal variations in the scallop lipid content. The carbohydrate content in queen scallops in this study was very low, with less than 0.1 g/100 g in autumn, winter and spring. According to the literature, carbohydrate content in this research is lower in comparison to other research [52,56]; however, in the study of Biandolino et al. [18], their sugar content is very similar to our findings.

Besides biochemical content, *A. opercularis* from the Northern Adriatic showed a fleshy texture with great flavor, which could be attractive to consumers interested in seafood with nutritional and health benefits [39]. In Croatia, individuals are sold fresh; however, in recent years, they have been thermally processed and placed vacuum-packed, frozen as pure meat on the market, in accordance with consumer requests. The thermally processed scallops had a ten times higher price and positively influenced the profitability of fishermen.

To conclude, the results of this study showed that *A. opercularis* is an important seafood source with commercial parameters in ideal proportions. Scallop weight exponentially increased with shell height, resulting in constant fineness during the study period. The highest values of commercial quality (CI and MY) in the studied scallops occurred in autumn, and the lowest were recorded in summer. The peak in the MI was in winter, while that in GSI was in spring, which could be related to their physiological functions.

In addition, queen scallop tissue has nutritional properties that are better or identical to those of other scallops. The moisture content accounted for the greatest proportion of the weight component throughout the whole study period, with the highest value occurring in summer. The highest values of protein and lipid contents were observed in scallop tissues in winter, while the peak in the carbohydrate content in scallop tissues occurred in summer. Although a decrease in the condition index and meat yield during the study period was observed, scallops were still evaluated as being quite nutritious, especially in spring and winter. Therefore, wild-caught species could be suitable for higher human consumption. Until now, few data have been reported in the literature on the reproduction period of the queen scallop, so protective measures with respect to the period of reproduction will require additional research.

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