Carbon Sequestration by Shellfish in Yantai's Coastal Waters

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Abstract. The carbon sequestration by shellfish constitutes a significant component of marine carbon sinks. This study quantitatively analyzed their carbon sequestration potential by measuring the carbon content of cultivated Zhikong scallops *(Chlamys farreri)* and bay scallops *(Argopecten irradians)* from the coastal aquaculture areas of Yangma Island, Yantai, as well as wild blood clams *(Scapharca broughtonii)* and mirror clams *(Amusium pleuronectes)* from Tianyue Bay. Specimens were collected during April and November 2024 to assess seasonal variations in carbon fixation efficiency.The results demonstrated species-specific carbon allocation patterns: the shell carbon content ranged from 12.55% to 13.51% in bay scallops *(Argopecten irradians)*, 12.36% to 12.64% in Zhikong scallops *(Chlamys farreri),* and 12.01% to 13.52% in blood clams *(Scapharca broughtonii)*, with minimal seasonal differences (April vs. November) observed in these three species, indicating temporal stability. In contrast, mirror clams *(Amusium pleuronectes)* exhibited a significant seasonal increase in shell carbon content, rising from 11.82%~11.94% in April to 12.51%~12.64% in November ($p < 0.05$). Soft tissues consistently displayed significantly higher carbon content than shells across all species ($p < 0.01$); however, this disparity diminished with increasing individual size, showing no significant differences in larger specimens. Seasonal variations in CO_2sequestration rates were most pronounced in mirror clams, with absorption values increasing from 14.20~22.39 g•a^{-1} in April to 23.36~41.73 g•a^{-1} in November, where larger individuals exhibited amplified differences ($r = 0.82$, $p < 0.001$). Economic analysis revealed that Yantai's mariculture shellfish harvest in 2022 reduced CO_2mitigation costs by approximately 71.64 million yuan (equivalent to~10.12 million USD), highlighting the triple benefits of bivalve aquaculture in fostering social welfare, economic profitability, and ecological resilience through enhanced carbon sink services.

Keywords: Yantai;Zhikong scallop; bay scallop; blood clam; mirror clam; carbon content; carbon sequestration capacity.

1. Introduction

Mariculture significantly enhances the ocean ecosystem's capacity to absorb atmospheric CO_2 by directly or indirectly utilizing substantial marine carbon resources through the cultivation of economically valuable organisms, demonstrating remarkable carbon sink value. In China, the annual yield of mariculture exceeds 10 million metric tons. Over the past two decades, shellfish and algae cultivation has successfully removed approximately 700,000 to 990,000 metric tons of carbon from marine environments, with shellfish shells alone contributing up to 670,000 metric tons of carbon sequestration [1].According to the prediction by Academician Tang Qisheng, mariculture is projected to remove approximately 1.3 million tons of carbon annually by 2030. By 2050, the carbon sequestration achieved through shellfish and algae cultivation could reach 4 million tons.

Given the significant ecological, economic, and social values of shellfish, the carbon sequestration mechanisms of shellfish have attracted increasing attention from researchers. Zhang Jihong et al. measured that within a single aquaculture cycle, the organic carbon removed from water bodies through scallop harvesting accounts for approximately 30% of the total organic carbon utilization.[2]Additionally, approximately 40% of organic carbon is transported to the seabed through biodeposition, of which a portion is further sequestered via burial mechanisms, thereby enhancing the accumulation of seabed carbon reservoirs.

In recent years, a growing number of scholars have conducted research on the economic valuation of shellfish carbon sequestration.Yu Jinkai[6] calculated the indirect carbon sequestration costs of mariculture shellfish in Shandong Province by referencing the pricing methodology of forestry carbon sequestration, and applied wastewater treatment pricing to estimate the water purification value of shellfish;Fang Lei [7] estimated the economic value of carbon sequestration by shellfish aquaculture in China in 2008 to be between 129 million and 516 million USD, referencing the market price of CO2 emission reduction. Shen Jinsheng [6] and others, drawing on the principles of foreign forestry carbon sequestration benefit accounting, successfully constructed a pricing model for blue carbon sequestration in marine ranching based on the cost-benefit method, calculating the minimum carbon sequestration price that stakeholders are willing to invest in marine ranching operations. Research results on the economic value of shellfish carbon sequestration show that in Guangdong Province, shellfish aquaculture generated an average annual economic value of 86 to 343 million USD from 2016 to 2020 through carbon removal [8]. Additionally, the carbon sequestration capacity and economic value of shellfish and algae aquaculture in Zhejiang Province play a significant role in achieving China's "dual carbon" goals [9]. This study will use these findings as a basis to analyze the economic value of carbon sequestration in offshore shellfish aquaculture in Yantai.

2. Materials and Methods

2.1 Samples and Data Sources

Experimental samples of *Chlamys farreri* and *Argopecten irradians* were freshly purchased from Beicui Market in Muping District, Yantai City in April and November 2024, consisting of uniformly sized cultured individuals from the Yangma Island aquaculture area in Yantai. Experimental samples of *Scapharca broughtonii* and *Amusium pleuronectes* were wild individuals collected from Tianyuewan Beach in Yantai.Since organisms attached to shellfish surfaces can also sequester carbon, surface attachments were removed as much as possible during experiments to minimize errors and avoid affecting experimental results [10].The shells and soft tissues to be tested were separately rinsed with distilled water, surface moisture was drained, and wet weights were measured. Samples were then dried at 60 °C for 48 hours, after which dry weights, dry-to-wet ratios, and mass ratios were recorded.The dried shellfish soft tissues and shells were finely ground, and particles of appropriate diameter were selected using a 100-mesh sieve. The C, H, and N contents of both soft tissue and shell samples were measured using an Elementar Vario CHN elemental analyzer [11].According to sample loading requirements, samples were embedded, with three replicates taken for each sample. The average value was calculated to determine carbon content.

The 2022 marine aquaculture shellfish production data for Yantai City were obtained from the "2022 Shandong Fishery Statistical Yearbook."

2.2 Carbon sequestration capacity assessment method

This study follows the methodology of the National Marine Environmental Monitoring Center (2023) and references the methods of Yu Zuoan [5], Shao Guilan[12], and Liu Dahai et al. [13] to divide shellfish carbon sequestration capacity into two parts for calculation: the carbon sequestration capacity of shells (1) and the carbon sequestration capacity of soft tissues (2), thereby calculating the biomass carbon of shellfish and their carbon sequestration capacity (in terms of carbon) (3). This study does not currently consider the carbon sequestration capacity of shellfish biodeposits.

2.2.1 Methods for assessing shellfish carbon sequestration capacity

Carbon sequestration capacity of bivalve shells:

$$C_j^B = W_j \times R_j^S \times wc_j^S \tag{1}$$

In the equation:

C_j^B represents the carbon sequestration amount of the shells of the j-th bivalve species;

W_j represents the yield (wet weight) of the j-th bivalve species;

R_j^s represents the proportion of dry shell mass to the total mass (wet weight) of the bivalve;

wc_j^s represents the percentage of carbon in the dry shell mass of the j-th bivalve species (%).

Carbon sequestration capacity of bivalve soft tissues:

$$C_j^{ST} = W_j \times R_j^{ST} \times wc_j^{ST} \tag{2}$$

In the equation:

C_j^{ST} represents the carbon sequestration amount of the soft tissues of the j-th bivalve species;

W_j represents the yield (wet weight) of the j-th bivalve species;

R_j^{ST} represents the proportion of dry soft tissue mass to the total mass (wet weight) of the bivalve;

wc_j^{ST} represents the percentage of carbon in the dry soft tissue mass of the j-th bivalve species.

Carbon sequestration capacity of bivalves:

$$C_j^{\text{shellfish}} = \sum\ (\ C_j^B + C_j^{ST}\ ) \tag{3}$$

2.2.2 Carbon Sequestration (i.e., Biomass Carbon) Assessment Method

The carbon sequestration (i.e., CO_2absorption) of each bivalve species was calculated based on the Carbon Accounting Methodology for Cultivated Macroalgae and Bivalves—Carbon Stock Change Approach (Zhang et al., 2021[14]). The total production of bivalves was used instead of production per unit farming area to estimate the carbon sequestration (i.e., biomass carbon) from harvested adult bivalves.

$$C_{BH} = W_{by} \times R_{adw} \times (R_{ash} \times C_{ash} + R_{am} \times C_{am}) \times 3.67 \tag{4}$$

In the equation:

C_{BH} represents the carbon content of harvested adult farmed bivalves, in tons per hectare;

W_{by} represents the production yield per unit culture area, in kilograms per hectare;

R_{adw} represents the dry-to-wet weight ratio of adult bivalves;

R_{ash} represents the shell mass ratio of adult bivalves;

C_{ash} represents the carbon content percentage in bivalve shells;

R_{am}represents the soft tissue mass ratio of adult bivalves;

C_{am} represents the carbon content percentage in bivalve soft tissues.

3.67 is the molecular weight ratio of carbon (C) to carbon dioxide (CO_2).

2.3 Carbon Sequestration Value Assessment Method

The Kyoto Protocol issued by the United Nations in 1997 is commonly used as a reference standard by domestic scholars when assessing the carbon sequestration value of marine bivalve aquaculture. According to the Kyoto Protocol, the cost for industrialized countries to reduce CO_2 emissions was projected to range between 150 to 600 USD per ton, equivalent to approximately 1,028 to 4,110 CNY per ton. However, from 1997 to 2017, due to technological advancements, steady economic growth, shifts in energy consumption patterns, and demographic changes, the cost of CO_2 emission reduction has shown significant evolution. Consequently, the applicability and accuracy of continuing to use this outdated metric for carbon sequestration valuation have been called into question.Based on a comprehensive review of multiple scholarly studies on carbon sequestration valuation methods, this study adopts the 227 CNY/ton value for Cc (carbon price) reported by Cao Qingren [15] for Shandong Province.

With reference to the carbon sequestration valuation approach for bivalves and macroalgae proposed by Li Ang et al. [16], the formula is as follows:

$$\mathrm{V}_c = C_t + C_C$$

In the equation:

V_c represents the carbon sequestration value;

C_t denotes the carbon sequestration capacity;

C_C represents the unit economic cost of carbon emission reduction.

3. Results and Analysis

3.1 Dry-to-wet weight ratio and carbon content rate in bivalve shells and soft tissues

The dry-to-wet weight ratio and carbon content rate are two important coefficient indicators for bivalve carbon sequestration accounting. The test results of dry-to-wet weight ratio and carbon content rate of bivalve samples in this study (Table 1) show that: among different bivalve species, the razor clam (Laternula anatina) had the highest dry-to-wet ratio (64.12-64.71%), while the bay scallop (Argopecten irradians) (44.32-45.79%) and zhikong scallop (Chlamys farreri) (47.25-47.36%) showed the lowest ratios; the blood clam (Nuttallia olivacea) had the highest soft tissue carbon content rate (41.59-42.27%), while the bay scallop had the lowest (33.72-37.95%); the shell carbon content rates showed little difference, with bay scallop at 12.55-13.51%, zhikong scallop at 12.36-12.64%, and blood clam at 12.01-13.52%; the three bivalve species showed small differences in shell carbon content rates between April and November, demonstrating relative temporal stability, while the razor clam's shell carbon content rate was 11.82-11.94% in April and 12.51-12.64% in November.

One-way ANOVA was performed on the test results of dry-to-wet weight ratio and carbon content rate of bivalve samples using SPSS. The results (Table 2) show that: although there were differences in individual size and collection time (April and November, respectively), the dry-to-wet ratios of the same bivalve species showed no significant differences; the bay scallop, zhikong scallop, and blood clam showed no significant differences in shell and soft tissue carbon content rates; however, the razor clam showed significant differences in both shell and soft tissue carbon content rates.

According to reference values for bivalve carbon sequestration capacity calculation coefficients, the carbon content rates for scallops were 42.84% for soft tissues and 11.4% for shells, while for clams they were 44.9% for soft tissues and 11.52% for shells [13], which differ from the measured values in this study. In this study, the measured shell carbon content rates of scallops were slightly higher than the reference values, while the soft tissue carbon content rates were slightly lower than the reference values, which may be because the accurate calculation of bivalve carbon sequestration is affected by factors such as bivalve species, individual size, and tissue mass ratio (commonly considered as condition index) [17].

Table 1 Dry weight, wet weight, dry-to-wet ratio, and carbon content of mollusks in the coastal waters near Yantai

Species	Number	Project	Wet weight/g	dry weight/g	dry-to-wet ratio/%	carbon content rate/%
Argopecten irradians(April)	Large size	Shell	30.94	28.70	45.02	12.66
		soft body	39.52	3.02		34.09
	medium size	Shell	24.34	21.26	44.61	12.61
		soft body	29.19	2.62		34.03
	small size	Shell	19.72	17.94	44.32	12.55
		soft body	25.36	2.04		33.72
Argopecten irradians(November)	Large size	Shell	27.30	25.40	44.97	12.62
		soft body	38.30	4.10		37.95
	medium size	Shell	19.6	18.5	45.17	12.63
		soft body	29.1	3.50		37.86
	small size	Shell	15.8	13.4	45.79	12.61
		soft body	17.61	1.9		39.86
Chlamys farreri(April)		Shell	19.94	17.76	47.35	12.44

	Large size	soft body	24.41	3.24		40.31
	medium size	Shell	15.30	13.56	47.25	12.48
		soft body	18.86	2.58		40.23
	small size	Shell	10.42	9.50	47.36	12.41
		soft body	13.31	1.74		40.15
Chlamys farreri(November)	Large size	Shell	21.38	19.15	47.34	12.50
		soft body	26.38	3.46		40.41
	medium size	Shell	17.57	15.87	47.27	12.44
		soft body	22.22	2.94		40.21
	small size	Shell	12.52	11.26	47.29	12.41
		soft body	15.12	1.81		40.18
Scapharca broughtonii(April)	Large size	Shell	6.11	5.96	55.80	13.14
		soft body	6.11	0.97		42.25
	medium size	Shell	4.54	4.41	54.07	13.08
		soft body	5.39	0.96		42.06
	small size	Shell	3.65	3.57	53.84	13.00
		soft body	4.69	0.92		41.59
Scapharca broughtonii(November)	Large size	Shell	7.22	7.11	54.44	13.13
		soft body	7.86	1.10		42.27
	medium size	Shell	5.43	5.36	53.64	12.94
		soft body	6.39	0.98		41.60
	small size	Shell	4.61	4.55	53.95	13.17
		soft body	5.62	0.97		41.72
Amusium pleuronectes(April)	Large size	Shell	41.3	39.8	64.27	11.94
		soft body	26.09	3.51		38.56
	medium size	Shell	36.80	33.70	64.64	11.86
		soft body	19.40	2.63		38.29
	small size	Shell	28.7	27.1	64.71	11.82
		soft body	15.9	1.76		37.96
Amusium pleuronectes(November)	Large size	Shell	78.2	77.6	64.56	12.64
		soft body	50.67	5.6		28.01
	medium size	Shell	65.4	64.1	64.21	12.59
		soft body	41.59	4.6		27.87
	small size	Shell	45.3	43.6	64.12	12.51
		soft body	27.84	3.3		27.79

Table2 ANOVA test of dry weight, wet weight, dry-to-wet ratio, and carbon content rate of shellfish in the offshore area of Yantai

	Species	Large size(April)	medium size(April)	small size(April)	Large size(November)	medium size(November)	small size(November)
dry-to-wet ratio/%	Argopecten irradians	44.97±0.40	44.60±0.28	44.69±0.34	44.82±0.39	44.68±0.47	45.25±0.47
	Chlamys farreri	47.35±0.12	47.25±0.02	47.36±0.05	47.34±0.02	47.27±0.12	47.29±0.02
	Scapharca broughtonii	54.53±1.89	53.87±0.18	53.17±0.74	54.44±0.86	53.43±0.32	53.82±1.58
	Amusium pleuronectes	64.27±0.13	64.64±0.86	64.71±0.52	64.56±0.82	64.21±0.43	64.12±0.67
Shell carbon content rate/%	Argopecten irradians	12.66±0.09	12.61±0.07	12.55±0.09	12.62±0.04	12.63±0.03	12.61±007
	Chlamys farreri	12.44±0.09	12.48±0.09	12.41±0.02	12.50±0.04	12.44±0.05	12.41±0.02
	Scapharca broughtonii	13.14±0.27	13.08±0.03	13.00±0.01	13.13±0.03	12.94±0.15	13.17±0.09
	Amusium pleuronectes	11.94±0.53^{abc}	11.86±0.61^{bc}	11.82±0.28^{c}	12.64±0.17^{a}	12.59±0.04^{ab}	12.51±0.17^{abc}
soft tissue carbon content rate/%	Argopecten irradians	34.09±0.01	34.03±0.53	33.75±0.05	33.95±0.04	33.82±0.04	34.13±0.23
	Chlamys farreri	40.31±0.15	40.23±0.22	39.82±0.83	40.41±0.06	40.21±0.17	40.18±0.22
	Scapharca broughtonii	42.25±0.11	42.06±0.02	41.59±0.01	42.27±0.42	41.60±0.86	41.75±0.52
	Amusium pleuronectes	38.56±1.44^{a}	38.29±0.53^{a}	37.96±1.77^{a}	28.01±0.28^{b}	27.87±0.23^{b}	27.79±0.56^{b}
CO_2 Absorption amount/$g\cdot a^{-1}$	Argopecten irradians	17.11±0.10^{a}	13.11±0.11^{c}	10.79±0.06^{e}	16.87±0.05^{b}	12.92±0.03^{d}	8.58±0.03^{f}
	Chlamys farreri	12.90±0.08^{b}	10.02±0.07^{d}	6.87±0.06^{f}	13.92±0.04^{a}	11.58±0.05^{c}	7.80±0.03^{e}
	Scapharca broughtonii	4.38±0.06^{b}	3.60±0.01^{e}	3.11±0.01^{f}	5.13±0.03^{a}	4.04±0.06^{c}	3.99±0.04^{d}
	Amusium pleuronectes	22.41±0.96^{c}	18.36±0.81^{d}	14.21±0.40^{e}	41.75±0.55^{a}	34.32±0.14^{b}	23.38±0.34^{c}

3.2 Carbon Sequestration Estimation

According to survey results, in the aquaculture area of Yangma Island, Yantai, bay scallops *(Argopecten irradians)* and zhikong scallops *(Chlamys farreri)* are typically seeded in May each year and harvested around October, with a growth cycle of approximately 6 months. According to relevant standards, growth cycles less than one year are calculated as one year. In this study, bivalve samples purchased in April and November may originate from the following two scenarios: April samples may be temporarily cultured bivalves before seeding, while November samples may be from secondary harvests.

The blood clam (Nuttallia olivacea) and razor clam (Laternula anatina) have growth cycles less than one year (calculated as 1 year). The calculated carbon sequestration capacities of bivalve samples are shown in Table 2. Results show differences in CO_2absorption between April and November for all species, with the razor clam exhibiting the most significant variation (April: 14.20-22.39 g•a^{-1}; November: 23.36-41.73 g•a^{-1}), where larger individuals showed more pronounced differences. Although the carbon content rate of soft tissues was significantly higher than that of shells, the carbon sequestration capacity of shells was markedly greater than that of soft tissues, and this capacity increased significantly with larger bivalve size.

Significant differences existed in carbon sequestration capacity among species. The razor clam demonstrated significantly higher carbon sequestration than the other three species. Monthly variations most significantly affected the razor clam's carbon sequestration capacity, with November-collected specimens showing substantially greater capacity than April-collected ones, particularly among larger individuals. Wang Zheng et al. (2024) found in their study of oysters, scallops and mussels in Yantai waters that the Pacific oyster (Crassostrea gigas) had significantly higher carbon sequestration capacity than scallops and mussels ($P<0.01$), with capacity increasing significantly with individual size [17]. Results indicate a significant correlation between bivalve carbon sequestration capacity and individual size ($P<0.05$), with capacity increasing significantly with larger size.

Table 3 Carbon fixation and CO_2 absorption by mollusks in the coastal waters near Yanta

Species	Number	Project	Carbon sequestration amount/g·a^{-1}	CO_2 Absorption amount/g·a^{-1}
Argopecten irradians(April)	Large size	Shell	3.63	17.09
		soft body	1.03	
	medium size	Shell	2.68	13.09
		soft body	0.89	
	small size	Shell	2.25	10.78
		soft body	0.69	
Argopecten irradians(November)	Large size	Shell	3.21	17.16
		soft body	1.56	
	medium size	Shell	2.34	13.46
		soft body	1.33	
	small size	Shell	1.69	8.98
		soft body	0.76	
Chlamys farreri(April)	Large size	Shell	2.21	12.91
		soft body	1.31	
	medium size	Shell	1.69	10.02
		soft body	1.04	
	small size	Shell	1.18	6.86
		soft body	0.69	
Chlamys farreri(November)	Large size	Shell	2.39	13.90
		soft body	1.40	
		Shell	1.97	11.55

	medium size	soft body	1.18	
	small size	Shell	1.40	7.81
		soft body	0.73	
Scapharca broughtonii(April)	Large size	Shell	0.78	4.37
		soft body	0.41	
	medium size	Shell	0.58	3.59
		soft body	0.40	
	small size	Shell	0.46	3.08
		soft body	0.38	
Scapharca broughtonii(November)	Large size	Shell	0.93	5.10
		soft body	0.46	
	medium size	Shell	0.69	4.00
		soft body	0.41	
	small size	Shell	0.60	3.67
		soft body	0.40	
Amusium pleuronectes(April)	Large size	Shell	4.75	22.39
		soft body	1.35	
	medium size	Shell	4.00	18.39
		soft body	1.01	
	small size	Shell	3.20	14.20
		soft body	0.67	
Amusium pleuronectes(November)	Large size	Shell	9.81	41.73
		soft body	1.57	
	medium size	Shell	8.07	34.28
		soft body	1.28	
	small size	Shell	5.45	23.36
		soft body	0.92	

3.3 Assessment of Carbon Sequestration Capacity of Major Mariculture Shellfish in Yantai

3.3.1 Assessment of Carbon Sequestration Material Quantity

According to data from the 2022 Shandong Fishery Statistical Yearbook, the total mariculture production in Yantai City in 2022 was 1,379,717 tons, with shellfish accounting for the vast majority at 1,240,896 tons, representing 89.94% of the total mariculture output. Among the shellfish, oysters, mussels, scallops, and clams had the highest production (Table 4), contributing approximately 98.39% of the total shellfish yield.

Table 4 Major marine aquaculture shellfish production in Yantai City in 2022

Species	*Crassostrea gigas*	*Mytilus edulis*	*Chlamys farreri*	*Meretrix meretrix)*
Production(t)	397882	23424	630885	168766

The main cultured species in Yantai City are the Crassostrea gigas, Mytilus edulis, Argopecten irradians, and Ruditapes philippinarum. Therefore, this study uses relevant data from Pacific oysters, blue mussels, bay scallops, and Manila clams for estimation (Tables 5 and 6), thereby calculating the total amount of carbon removed from seawater by the main cultured shellfish in Yantai City (Table 7). In contrast, the production of other shellfish such as abalone, conch, and razor clam is relatively low, at 1,417 t, 80 t, and 5,643 t respectively, accounting for only about 0.6% of the total mariculture production in Yantai City. Consequently, these species are not included in the scope of this study.

Table 5 Proportion of dry mass of soft tissue and shell mass of major aquaculture bivalves

Species	Dry mass proportion of soft tissue(R_i^{ST})/%	Dry mass proportion of shell(R_i^{S})/%	References
Crassostrea gigas	1.29	63.54	Tang[19]
Mytilus edulis	4.63	70.65	Tang[19]
Argopecten irradians	3.72	36.22	MAO Yuzhe et al [18]
Ruditapes phlippinarum	7.54	45.01	Tang et al. [19]

Table 6 Carbon content in soft tissue and shell of major bivalves

Species	Soft tissue carbon content(wc_i^{ST})/%	Shell carbon content(wc_i^{S})/%	References
Crassostrea gigas	44.90	11.52	Zhou Yi et al. [20]
Mytilus edulis	45.98	12.68	Zhou Yi et al. [20]
Argopecten irradians	44.00	12.00	Qi Zhanhui et al. [21]
Ruditapes phlippinarum	42.84	11.40	Zhou Yi et al. [20]

Table 7 Carbon exported from seawater through harvesting of marine aquaculture shellfish in Yantai City in 2022

Species	Total carbon removal amount/t	Carbon removal amount per unit production (1t)/t
Crassostrea gigas	31428.77	0.0790
Mytilus edulis	2577.13	0.1109
Argopecten irradians	37747.11	0.0598
Ruditapes phlippinarum	14110.99	0.0836
Total	85864.00	

3.3.2 Carbon Sequestration Value Assessment

In 2022, the annual carbon removal by maricultured shellfish in Yantai City was approximately 85,864.00 t, equivalent to reducing CO_2emissions by 315,619.95 t. Based on the equivalent value creation cost of CO_2emission reduction in Shandong Province at 227 yuan/t [21], the estimated cost savings from CO_2emission reduction through harvesting maricultured shellfish in Yantai City in 2022 was about 71.64 million yuan.

Among the species, the Mytilus edulis exhibited the highest total carbon removal per unit production (1t), followed by the Ruditapes philippinarum, Crassostrea gigas, and Argopecten irradians. Therefore, considering only species differences and carbon removal per unit production, the blue mussel demonstrated the strongest carbon sequestration capacity. In addition to shell carbon sequestration, the blue mussel also exhibits strong carbon sequestration through biodeposits, with shell carbon sequestration and biodeposit carbon sequestration accounting for 49.6% of the total utilized carbon [23]. Furthermore, the fecal carbon excretion of blue mussels constitutes 46.61% of their ingested carbon, higher than the 42.76% observed in Pacific oysters [23]. From a carbon sequestration potential perspective, adjusting appropriate cultured species and proportions could maximize carbon sequestration value.

4. Conclusions

This study quantitatively assessed the carbon content rate and carbon sequestration capacity of offshore shellfish species in Yantai—Argopecten irradians, Chlamys farreri, Scapharca broughtonii, and Amusium pleuronectes—using the dual-shell shellfish carbon sequestration measurement method (carbon stock change approach). The carbon sequestration capacity and value of Yantai's major maricultured shellfish were analyzed. The conclusions are as follows:

(1) The carbon content rate in the soft tissue of the studied shellfish was significantly higher than that in their shells, but the shells exhibited substantially greater carbon sequestration capacity than the soft tissue. Additionally, carbon sequestration capacity increased significantly with larger shellfish body sizes.

(2) Carbon sequestration capacity was closely related to shellfish species. Amusium pleuronectes demonstrated the strongest carbon sequestration capacity, followed by Argopecten irradians and Chlamys farreri, while Scapharca broughtonii had significantly lower carbon sequestration capacity than the other three species.

(3) In 2022, the annual carbon removal by maricultured shellfish in Yantai City was approximately 85,864.00 t, equivalent to reducing CO_2 emissions by 315,619.95 t, resulting in cost savings of about 71.64 million yuan. Among Yantai's major maricultured shellfish, the blue mussel (Mytilus edulis) exhibited the most significant carbon sequestration potential, followed by the Manila clam (Ruditapes philippinarum), Pacific oyster (Crassostrea gigas), and bay scallop (Argopecten irradians).

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