 DOI: 10.19601/j.cnki.issn1943 – 9903.2025.02.006

Assessment of Carbon Sink Capacity in Seawater Suspension Cage Aquaculture of Shellfish in Tianjin from 2015 to 2022

Zhiru FU[1]*, Xin QI[1], Jian LI[1], Haonan CHEN[2], Chao MA[1], Lijun SHI[1], Liwei SHI[1]

1. Tianjin Agricultural Development Service Center, Tianjin 300061, China; 2. Tianjin Animal Disease Prevention and Control Center, Tianjin 300410, China

Abstract [**Objectives**] To assess the carbon sink capacity in seawater suspension cage aquaculture of shellfish in Tianjin from 2015 to 2022. [**Methods**] The carbon sink capacity of different shellfish species was evaluated using both physical and value assessment methods. [**Results**] The shellfish cultivated in seawater suspension cages in Tianjin exhibited a significant capacity for carbon sinks. The amounts of carbon removed by suspension cage aquaculture of *Rapana venosa*, *Crassostrea gigas*, *Scapharca subcrenata*, *Scapharca broughtonii* and *Argopectens irradias* were 448.297, 403.398, 89.463, 40.657, and 106.719 t, respectively. Furthermore, the total volume of shellfish cultivated in seawater exhibited a consistent upward trend over time, correlating with an annual increase in the amount of carbon removed. Among the shellfish cultivated in seawater suspension cages, the order of carbon sink capacity was as follows: *C. gigas* > *R. venosa* > *A. irradias* > *S. subcrenata* and *S. broughtonii*. In terms of the carbon sink capacity of soft tissues, the ranking was as follows: *A. irradias* > *R. venosa* > *C. gigas* > *S. subcrenata* and *S. broughtonii*. The structural and yield factors associated with seawater suspension cage aquaculture of shellfish significantly influenced the enhancement of the total carbon sink of cultivated shellfish. Notably, structural factors had a greater impact on the increase in the carbon sink of cultivated shellfish compared to total yield factors. [**Conclusions**] The findings will serve as a reference for enhancing the carbon sink potential of fisheries and achieving sustainable development in seawater aquaculture in Tianjin.

Key words Seawater suspension cage aquaculture, Shellfish, Carbon sink, Assessment, Tianjin

0 Introduction

In China, researchers have conducted studies examining the role of carbon sinks associated with cultivated shellfish. Tang Qisheng[1] calculated and assessed the total yield and carbon sinks of seawater-cultivated shellfish in China from 1999 to 2008. The findings indicated that the total yield of seawater-cultivated shellfish during this period was 860 000 t, of which 670 000 t were in the form of shells. Qi Zhanhui *et al.*[2] conducted a quantitative assessment of the carbon absorption capacity of shellfish and the overall carbon sink value in Guangdong Province through physical and value assessment methods. Their findings indicated that in 2009, Guangdong Province removed approximately 110 000 t of carbon from seawater, which corresponds to 396 000 t of CO_2. The estimated cost associated with the sequestration and fixation of these CO_2 ranged from 59 million to 238 million USD. Li Ang *et al.*[3] conducted an estimation of the carbon sink capacity of cultivated shellfish in Hebei Province in 2010 utilizing the system synthesis method. Their findings indicated that Hebei Province had the potential to achieve a carbon sink of 27 500 t in that year, which corresponds to a reduction of 101 000 t of CO_2, valued at approximately 60.38 million yuan. Quan Wei *et al.*[4] and Ke Aiying *et al.*[5] measured the changes in annual carbon sequestration and the average annual carbon emission reduction associated with seawater-cultivated shellfish in Zhejiang Province and Wenzhou City (Zhejiang Province), from 2004 to 2013. Their findings indicated that the average annual carbon sequestration in Zhejiang Province and Wenzhou City was 62 900 and 5 732 t, respectively. Furthermore, the average annual carbon emission reduction values were estimated to be between 7 984 000 and 31 937 000 USD for Zhejiang Province, and between 860 000 and 3 440 000 USD for Wenzhou City. Yu Zuo'an *et al.*[6] conducted an assessment of the carbon sink capacity of cultivated shellfish in Liaoning Province from 2015 to 2017, focusing on both physical and value assessment. The findings indicated that, on average, Liaoning Province sequestered approximately 277 700 t of carbon annually during this period, which corresponds to the removal of 1 018 200 t of CO_2. Furthermore, the estimated cost associated with reducing these CO_2 emissions was approximately 160 million yuan.

Tianjin is a significant coastal city in China, characterized by its abundant marine resources. The province boasts a mainland coastline that extends for 153 km and encompasses a managed sea area of 2 500 km^2, of which 336 km^2 consist of mudflats[7]. Shellfish fishing is a traditional advantageous aquatic industry in the maritime region of Tianjin. The traditional economic shellfish species in this area include *Scapharca subcrenata*, *Sinonovacula constricta*, *Rapana venosa*, *Ruditapes philippinarum*, *Mactra veneriformis*, and *Crassostrea gigas*. Tianjin Huawei Marine Technology Co., Ltd. is the largest producer and seller of seawater shellfish aquaculture in Tianjin, with its annual production accounting for over 75% of the total shellfish aquaculture output in the region. This study evaluated the carbon sink capacity of shellfish cultivated in seawater suspension cages in Tianjin from 2015 to 2022, based on the production data of the company. The findings aim to provide a reference for improving the carbon sink potential of fisheries and promoting sustainable development in seawater aquaculture within the region.

1 Materials and methods

1.1 Data sources The data utilized in this study were sourced

Received: July 30, 2024 Accepted: November 10, 2024

Supported by Science and Technology Commissioner Project of Tianjin Science and Technology Bureau (22ZYCGSN00630).

* Corresponding author. Zhiru FU, master, senior engineer, research fields: aquaculture and biodiversity conservation research.

from the statistical records of aquaculture production provided by Tianjin Huawei Marine Technology Co., Ltd. from 2015 to 2022. Additionally, the carbon content of various shellfish species was assessed in accordance with pertinent literature.

1.2 Assessment methods

1.2.1 Physical assessment method. Seawater-cultivated shellfish primarily utilize carbon in the ocean through three mechanisms: first, absorbing bicarbonate ions (HCO_3^-) from seawater to synthesize calcium carbonate shells; second, filter feeding and assimilating plankton and particulate organic matter from the seawater to develop the soft tissue of shells; and third, utilizing particulate organic carbon present in the seawater environment, which is subsequently deposited to the seafloor through biological sedimentation.

The physical assessment of the carbon sinks associated with seawater-cultivated shellfish in Tianjin was conducted in accordance with the methods established by Qi Zhanhui *et al.* [2] and Li Ang *et al.* [3]. The calculation formulae are presented as follows:

Carbon content of cultivated shellfish (C) = Carbon content of soft tissues + Carbon content of shells

Carbon content of soft tissues (C) = Yield of cultivated shellfish × Wet and dry coefficient of soft tissues × Carbon content of soft tissues

Carbon content of shells (C) = Yield of cultivated shellfish × Wet and dry coefficient of shells × Carbon content of shells

The dry and wet coefficients, as well as the carbon content associated with the carbon sink capacity of seawater-cultivated shellfish, were derived from the experimental data reported by Tang Qisheng *et al.* [8], Zhou Yi *et al.* [9], Lu Haoze *et al.* [10], and Gu Bojun *et al.* [11]. The measured parameters are presented in Table 1.

Table 1 Estimation parameters of carbon sink capacity of seawater-cultivated shellfish

Species	Wet and dry coefficient // %		Carbon content // %	
	Soft tissue	Shell	Soft tissue	Shell
Oyster	4.00	61.10	45.89	12.68
Clam	3.66	34.33	45.86	11.29
Scallop	9.17	54.70	43.90	11.40
Abalone, snail	4.43	56.45	44.99	11.98

1.2.2 Value assessment method. According to the *Kyoto Protocol to the United Nations Framework Convention on Climate Change* (1998), the expenditure budget for CO_2 emission reduction in industrialized countries is estimated to range from 150 to 600 USD per ton. Utilizing the average annual exchange rate between USD and yuan, the economic cost of carbon emission reduction (C) was calculated. Consequently, the value of shellfish carbon sinks (V) was estimated using the following formula:

Value of carbon sinks (V) = Carbon sink capacity (C) × Economic cost per unit of carbon emission reduction (C)

2 Results and analysis

2.1 Physical assessment of shellfish carbon sinks The primary species and production data pertaining to the cultivated shellfish in seawater suspension cages in Tianjin City from 2015 to 2022 are presented in Table 2. Notably, *R. venosa* was supplemented with kelp and *R. philippinarum* (or clams) at intervals of 7 d, with the feeding volume constituting 25% – 30% of the total mass of *R. venosa*; other shellfish species were not provided with feed. The total amount of carbon sequestered from seawater through seawater suspension cage aquaculture of shellfish in Tianjin from 2015 to 2022 is detailed in Table 3 and illustrated in Figs. 1-2.

The yield of shellfish through seawater suspension cage aquaculture in Tianjin exhibited a consistent annual increase (Table 2). The ranking of shellfish yield, from highest to lowest, was as follows: *R. venosa*, *C. gigas*, *S. subcrenata*, *Argopectens irradians*, and *S. broughtonii*.

Table 2 Species and yield of shellfish through seawater suspension cage aquaculture in Tianjin from 2015 to 2022 t

Year	*Rapana venosa*	*Crassostrea gigas*	*Scapharca subcrenata*	*Scapharca broughtonii*	*Argopectens irradias*	Total
2015	230	155	175	65	250	875
2016	240	185	180	75	160	840
2017	270	300	180	64	200	1 014
2018	320	600	190	70	165	1 345
2019	880	480	230	115	75	1 780
2020	1 050	400	210	125	65	1 850
2021	1 100	490	220	108	65	1 983
2022	1 030	1 600	230	110	60	3 030
Total	5 120	4 210	1 615	732	1 040	12 717

In seawater suspension cage aquaculture of shellfish in Tianjin, the carbon sinks removed by shells were larger than those by soft tissues (Table 3); under the same condition of yield (10 000 t), the order of the total amount of carbon removed by shells was: *C. gigas* > *R. venosa* > *A. irradias* > *S. subcrenata* and *S. broughtonii*; and the order of the total amount of carbon removed by soft tissues was: *A. irradias* > *R. venosa* > *C. gigas* > *S. subcrenata* and *S. broughtonii*.

The total amount of carbon sequestered from seawater by shellfish cultivated in seawater suspension cages in Tianjin was ranked as follows: *R. venosa* > *C. gigas* > *A. irradias* > *S. subcrenata* > *S. broughtonii* (Fig. 1). Furthermore, the overall carbon removal from seawater was found to be associated with both the structural characteristics of the cultivated shellfish species and the scale of the aquaculture operations.

The carbon sink capacity of various shellfish species was ranked as follows: *C. gigas* > *R. venosa* > *A. irradias* > *S. subcrenata* and *S. broughtonii* (Fig. 2). In contrast, the carbon sink capacity of soft tissues was ranked as *A. irradias* > *R. venosa* > *C. gigas* > *S. subcrenata* and *S. broughtonii*. The carbon content transported by the shells of *R. venosa* was found to be 3.39 times greater than that by the soft tissues. Similarly, the carbon content removed by the shells of *C. gigas* was 4.22 times greater than that by the soft tissues. Furthermore, the carbon content removed by the shells of *S. subcrenata* and *S. broughtonii* was 2.31 times greater than that by the soft tissues, while the carbon content removed by the shells of *A. irradians* was 1.55 times greater than that by the soft tissues.

Table 3 Total carbon removal from seawater by seawater suspension cage aquaculture shellfish in Tianjin from 2015 to 2022 t

Year	*Rapana venosa*		*Crassostrea gigas*		*Scapharca subcrenata*		*Scapharca broughtonii*		*Argopectens irradias*		Total carbon removal
	Soft tissue	Shell	Soft tissue	Shell	Soft tissue	Shell	Soft tissue	Shell	Soft tissue	Shell	
2015	4.584	15.554	2.845	12.009	2.697	6.783	1.091	2.519	10.064	15.590	73.736
2016	4.783	16.231	3.396	14.333	3.021	6.977	1.259	2.907	6.441	9.977	69.325
2017	5.381	18.259	5.507	23.242	3.021	6.977	1.074	2.481	8.051	12.472	86.465
2018	6.378	21.641	11.014	46.484	3.189	7.364	1.175	2.713	6.642	10.289	116.889
2019	17.539	59.512	8.811	37.188	3.860	8.915	1.930	4.457	3.019	4.677	149.908
2020	20.927	71.009	7.342	30.990	3.525	8.139	2.098	4.845	2.617	4.053	155.545
2021	21.924	74.390	8.944	37.963	3.693	8.527	1.813	4.186	2.617	4.053	168.110
2022	20.529	69.656	29.370	123.960	3.860	8.915	1.846	4.263	2.415	3.742	268.556
Total	102.045	346.252	77.229	326.169	26.866	62.597	12.286	28.371	41.866	64.853	1 088.534
Total carbon removal *	199.306	676.271	183.560	774.748	167.848	387.586	167.848	387.586	402.563	623.580	–

NOTE * denotes the total amount of carbon removed under identical yield conditions, specifically at a scale of 10 000 t.

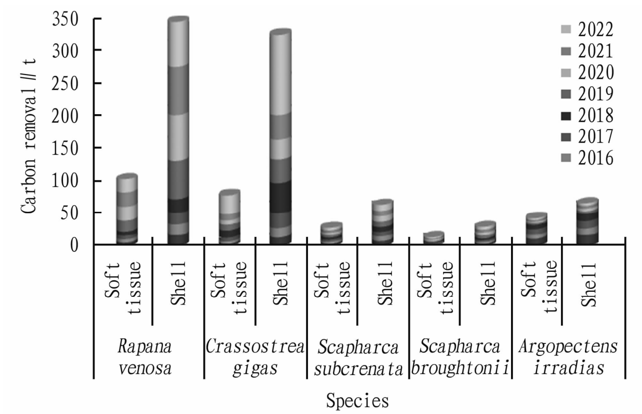

Fig. 1 Carbon removal from seawater by soft tissues and shells of different shellfish species cultivated in seawater suspension cages in Tianjin from 2015 to 2022

2.2 Value assessment of shellfish carbon sinks The carbon sink value of shellfish cultivated in seawater suspension cages in Tianjin from 2015 to 2022 is presented in Table 4. It is evident from the data that the total amount of carbon sequestered by shellfish cultivated in these cages from 2015 to 2022 was 1 088.534 t, which corresponds to a reduction of 3 918.722 t of CO_2 emissions. According to the *Kyoto Protocol to the United Nations Framework Convention on Climate Change* (1998), the estimated budgeted cost for CO_2 emission reduction in industrialized countries ranges from 150 to 600 USD per ton. Based on the average exchange rate between USD and yuan for the current year, the value of carbon sinks associated with shellfish cultivated in seawater suspension cages in Tianjin was estimated to be between 163 280 and 653 120 USD, which corresponds to approximately 1 091 990 to 4 417 260 yuan. Furthermore, the average annual value of carbon sinks from 2015 to 2022 varied between 20 410 and 85 390 USD, equivalent to approximately 136 500 to 552 160 yuan. The carbon sink potential of aquaculture shellfish not only offers consumers access to high-quality seafood, thereby enhancing the diversity of the public's food supply, but also plays a significant role in augmenting carbon sink capacity. This dual benefit presents substantial economic, ecological, and social advantages in the context of reducing greenhouse gas emissions, particularly CO_2.

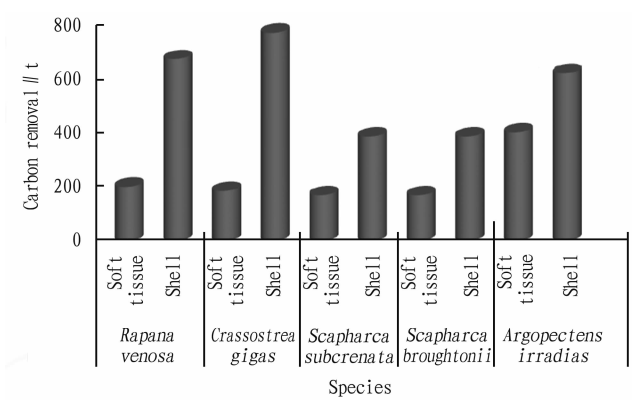

Fig. 2 Carbon removal from seawater by soft tissues and shells of different shellfish species under the same yield conditions

Table 4 Assessment of carbon sink value of shellfish cultivated in seawater suspension cages in Tianjin from 2015 to 2022

Year	Carbon removal // t	Carbon sink value // 10^4 USD	Average exchange rate between USD and yuan dollar and the Chinese yuan	Carbon sink value // 10^4 yuan
2015	73.736	1.106 – 4.424	1 USD = 6.493 4 yuan	7.182 – 28.727
2016	69.325	1.040 – 4.160	1 USD = 6.969 7 yuan	7.248 – 28.994
2017	86.465	1.297 – 5.188	1 USD = 6.511 8 yuan	8.446 – 33.783
2018	116.889	1.753 – 7.013	1 USD = 6.866 3 yuan	12.037 – 48.153
2019	149.908	2.249 – 8.994	1 USD = 6.964 5 yuan	15.663 – 62.639
2020	155.545	2.333 – 9.333	1 USD = 6.540 7 yuan	15.259 – 65.976
2021	168.110	2.522 – 10.087	1 USD = 6.451 5 yuan	16.271 – 65.076
2022	268.556	4.028 – 16.113	1 USD = 6.726 1 yuan	27.093 – 108.378
Total	1 088.534	16.328 – 65.312	–	109.199 – 441.726

2.3 Carbon sink potential of shellfish From 2015 to 2022, a total of 1 088.534 t of carbon were removed by shellfish cultivated in seawater suspension cages in Tianjin. Of this total, 260.292 t were removed by soft tissues, while 828.242 t were shifted by shells. Notably, the amount of carbon removed by shells was 3.18 times greater than that by soft tissues. Carbon storage in shells refers to the process by which bicarbonate ions (HCO_3^-) from seawater are utilized to synthesize the calcium carbonate ($CaCO_3$) structures of various organisms, commonly known as shells. The carbon incorporated into these shells is not readily released into the environment, thereby functioning as a long-term carbon sink over extended periods.

3 Conclusions and discussion

3.1 Conclusions The shellfish cultivated in seawater suspension cages in Tianjin exhibited a significant capacity for carbon sequestration. From 2015 to 2022, the carbon removal attributed to the species *R. venosa*, *C. gigas*, *S. subcrenata*, *S. broughtonii*, and *A. irradias*, cultivated in these suspension cages, amounted to 1 088.534 t. This amount corresponds to a reduction of approximately 3 918.722 t of CO_2. The carbon sink capacity of various shells was ranked as follows: *C. gigas* > *R. venosa* > *A. irradias* > *S. subcrenata* and *S. broughtonii*. In contrast, the carbon sink capacity of soft tissues was ranked as *A. irradias* > *R. venosa* > *C. gigas* > *S. subcrenata* and *S. broughtonii*. Shellfish serve as the drivers of material circulation and energy flow in offshore ecosystems, and the harvesting of seawater-cultivated shellfish can lead to the establishment of significant carbon sinks.

3.2 Discussion Under conditions of equivalent yield, among the shellfish species utilized in mariculture, the highest capacity for carbon removal was observed in the cultivation of *C. gigas*, followed by *R. venosa* and *A. irradians*. Conversely, the lowest capacity for carbon removal was associated with the cultivation of *S. subcrenata* and *S. broughtonii* in mariculture. Consequently, in light of the potential of carbon sinks, it is advantageous to modify the structure and composition of seawater-cultivated shellfish species in Tianjin. This includes the promotion of aquaculture for *C. gigas* and *R. venosa*, both of which possess a greater capacity for carbon sequestration.

Seawater suspension cage aquaculture of shellfish necessitates the installation of numerous culture facilities, including floating rafts, cables, suspension cages, floaters, and various other equipment. These structures offer an extensive array of attachment surfaces for attached organisms, thereby significantly enhancing the population of attached organisms. *Ciona intestinalis* and *Styela clava*, similar to shellfish, are filter feeders characterized by their robust filter-feeding capabilities. When water temperatures decrease, these organisms tend to detach from their attachment substrates and descend to the sea bottom. In addition, *Bugula neritina*, *Balanus*, *Hydrordes*, and *Nais communis* possess calcareous shells that contribute to carbon sequestration. Although the biomass of these attached organisms is substantial, they were excluded from the assessment of carbon sink capacity in this study and were not subjected to statistical analysis regarding their carbon sink contributions.

When *R. venosa* was cultured in suspension cages, it was fed kelp and *R. philippinarum* (clams) once every 7 d at a rate of 25% – 30% of the total mass of *R. venosa*. However, the biomass provided to *R. venosa* was not quantified in this study and was not subtracted from the assessment.

This study neither evaluated the amount of particulate organic carbon in the seawater environment utilized by cultured shellfish, nor assessed the carbon sink capacity associated with biological deposition, due to limitations such as inadequate test data. Conditions will be established to facilitate pertinent research in the future.

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