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Mechanized Transformation in Shellfish Aquaculture: Practical Challenges and Intelligentization-Driven Breakthrough Pathways

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Abstract: Under the dual pressure of global aquatic resource constraints and the transformation to a low-carbon economy, intelligent technologies are reshaping the underlying logic of the shellfish farming industry. This paper systematically constructs a three-dimensional analysis framework of "technology - ecology - governance". Through horizontal comparisons of 12 countries and vertical analyses of 38 technological innovation cases, it reveals the three core contradictions of intelligent transformation: regional imbalance in technology supply, ambiguity of rights and responsibilities in data governance, and intergenerational conflicts in benefit distribution. Research has found that China's shellfish industry has achieved partial leadership in areas such as offshore aquaculture robots and AI disease early warning through the "scene-driven innovation" model. However, shortcomings such as a domestic sensor production rate of less than 20% and a digital skill compliance rate of only 11.3% among practitioners are restricting the overall transformation. Propose breakthrough paths such as establishing an "Intelligent Fishery innovation community", piloting a digital twin system for sea areas, and promoting carbon sink credit trading, providing a Chinese solution for the intelligentization of global shellfish farming.

Key words: Shellfish farming ; Intelligent transformation; Digital twin Carbon sink economy ; Governance innovation

1. The global shellfish industry is becoming intelligent

According to the data from the FAO in 2023, the global shellfish farming market size has reached 42 billion US dollars, with China leading the way with a 36.7% share. However, the production efficiency gap is significant: The intelligent penetration rate of scallop farming in Norway has reached 58%, and the yield per unit water body is 2.3 times that of similar projects in China. This gap stems from the technological barriers constructed by developed countries in three aspects。

1.1 Intelligent equipment:

The "AI Mussel Harvesting Vessel "of Mitsubishi Heavy Industries in Japan integrates millimeter-wave radar and fluid mechanics algorithms, and its harvesting efficiency is 17 times higher than that of traditional equipment. This vessel is mainly used in the nearshore mussel farming area and is particularly suitable for large-scale and intensive farming models. Its efficient operation capacity can meet the demands of large-scale breeding enterprises for rapid harvesting and reduction of labor costs. In addition, in areas such as the intertidal zone where traditional equipment has difficulty accessing, the AI mussel harvesting boat, with its intelligent advantages, can still maintain stable operations, expanding the boundaries of mussel harvesting.

1.2 Digitalization of Decision-making:

The aquaculture decision-making system of Blue Ocean in the United States, through the sensor network deployed in the aquaculture sea area, Real-time collection of data from over 2,000 dimensions, including water

quality parameters (dissolved oxygen, pH value, temperature, salinity, ammonia nitrogen, chlorophyll), hydrological parameters (flow rate, direction, wave height), meteorological parameters (wind speed, air pressure, rainfall), biological parameters (activity level of aquaculture organisms, feeding behavior), and bottom quality parameters (sediment composition, microbial community), is based on a deep learning box The frame is preprocessed through edge computing nodes to ensure real-time performance and accuracy. By combining satellite remote sensing data with on-site sensor data, correcting the monitoring deviation of local sea areas, and controlling the prediction error within ±3 days, a prediction model for the growth curve of aquaculture organisms was systematically constructed. Preprocessing is carried out through edge computing nodes to ensure real-time performance and accuracy. Essentially, it is to reconstruct the production function of Marine fishery through digital technology. While traditional animal husbandry still relies on "experience + trial and error", this system has achieved a paradigm shift of "data + prediction". With the popularization of 5G Marine private networks and edge AI chips, such systems may drive the global aquaculture industry into an era of "zero-error" decision-making.

1.3 Blockchainization of Certification:

The COQUILLES project in France has achieved full-chain traceability of shellfish from breeding to the dining table through blockchain technology, with a product premium of up to 40%. This innovative model provides a new paradigm for the sustainable development of the global fishery industry. This project takes the Saint-Jacques scallops from Normandy, France as the core carrier, and has established a digital trust system covering the entire life cycle of the fishery. This network integrates Marine monitoring data from the French Institute for Marine Development (Ifremer), production records from fishery associations, certification information from third-party testing institutions, and sales data from retail terminals, forming an unalterable data chain. Each Saint-Jacques scallop is assigned a unique digital identity. More than 200 environmental parameters of its growth area, such as salinity, temperature and microbial indicators, as well as operation records of each link from breeding, farming, fishing, processing to logistics, are all uploaded to the Internet of Things device in real time. At the data collection end, the project deployed an underwater sensor network to collect hydrological data of the aquaculture area at a frequency of once every 15 minutes, and established a scallop growth model through AI algorithms. When scallops reach the legal fishing size of 11 centimeters, the system automatically generates an electronic fishing license to ensure that all onshore products meet sustainable fishing standards. In the processing stage, the blockchain is connected to the factory's ERP system, recording the operators, equipment numbers and environmental parameters of 12 processes such as cleaning, shelling and quick-freezing, achieving transparency in the processing process. This model is of reference significance for China's fishery. Data from the Chinese Academy of Fishery Sciences shows that by introducing blockchain traceability, the brand value of Zhoushan cuttlefish has increased by 28%, and the customs clearance time for exports to the European Union has been shortened by 60%. In the future, with the integration of 5G Marine private networks and an independently controllable blockchain underlying system, China is expected to establish a blue food certification system "from tidal flats to dining tables", reshaping the global aquatic product trade pattern.

2. Intelligence of the domestic shellfish industry

At present, domestic shellfish farming mainly adopts various models such as tidal flat pond farming, cement clam farming ponds, fish and shellfish relay recilatory water farming in seawater ponds, and open water tidal flat shellfish farming [1]. The in-depth development of mechanization and intelligence in the shellfish industry has fully permeated every key link such as breeding, farming, fishing and processing [2].

2.1 Breeding Stage:

The traditional molshellfish breeding process is highly dependent on manual intervention. This approach is not only time-consuming and labor-intensive, but also relatively inefficient [3]. With the introduction of mechanization and intelligent technologies, the field of shellfish breeding has witnessed a revolutionary change. The team from Ocean University of China has developed the "Intelligent Editing Platform for Shellfish Genes", breaking through

three major technical bottlenecks: target prediction, using graph neural networks (GNN) to analyze 100,000 sets of genomic data, and increasing the localization efficiency of genes associated with excellent traits by 80%; Off-target control and quantum annealing algorithm optimization of sgRNA design enabled the gene editing accuracy of Pacific oyster to reach 99.2%. Phenotypic simulation and digital twin systems predict the effect of gene expression, reducing the breeding cycle from 5 years to 18 months. By performing precise cutting, insertion, replacement and other modification operations on these sequences, researchers can change the expression patterns of genes, thereby achieving targeted improvement of specific traits in shellfish. This improvement not only enhanced the disease resistance of shellfish but also significantly increased their key economic traits such as growth rate [4], making the cultivated shellfish seedlings more competitive in the market. These studies not only provide solid technical support for the sustainable development of the shellfish industry, but also are expected to completely change the situation where traditional artificial breeding methods are time-consuming, labor-intensive and inefficient.

2.2 Breeding Stage:

In the practice of shellfish farming, the introduction of an intelligent farming management system has significantly improved the farming efficiency and enhanced the environmental sustainability. This system can monitor the growth status of shellfish and the surrounding environmental parameters in real time, and dynamically adjust the breeding density and feeding strategy accordingly, thereby effectively avoiding resource waste and reducing the adverse impact on the environment. In addition, the intelligent system has also achieved the recycling and efficient purification treatment of aquaculture water, significantly reducing water consumption and pollution risks. The intelligent breeding management system can also precisely calculate and automatically adjust the feed dosage based on the specific growth stage and quantity of shellfish. This not only avoids feed waste but also ensures that the nutritional needs of shellfish are met, promoting their healthy growth [5]. The application of the water change device for shellfish seedling raising still effectively reduced the impact of water change on the growth of shellfish and increased the survival rate [6]. Through the continuous efforts of these seedling raising machines and the research and development institutions behind them, the shellfish seedling raising industry has achieved remarkable optimization and upgrading in multiple aspects such as environmental control and water change guarantee, effectively promoting the development of the shellfish seedling raising industry towards a more scientific and efficient direction.

Table 1. Advancements in Mechanized Applications for Shellfish Cultivation

Aquaculture Machinery	Actors	Scope of Application
Indoor shellfish nursery systems	• Technology enterprises & research institutes • Yellow Sea Fisheries Research Institute, Chinese Academy of Fishery Sciences	• Indoor shellfish larvae rearing with optimized environmental conditions
Liquid feed delivery systems for shellfish larvae	• Equipment manufacturers & research institutions	• Precise control of feed quantity and timing during seedling cultivation
Automated nursery environment control & feeding devices	• Equipment manufacturers & research institutions	• Environmental regulation (light/temperature) and feeding management tailored to species-specific nursery requirements
Automated water exchange systems for shellfish nursery	• Marine economy research institutes (e.g., Yantai Marine	• Water renewal operations minimizing physiological stress

	Economic Research Institute)	on larvae [Survival rate improvement: 15-25%]

The data is sourced from the China Fisheries Statistical Yearbook

2.3 Fishing Stage:

Today, with the accelerated advancement of the mechanization process in the shellfish industry, advanced fishing equipment has undoubtedly become an important symbol in this process[7]. Compared with the traditional manual fishing method, the "Qianlong" series of scallop harvesting robots developed by the Shenyang Institute of Automation, Chinese Academy of Sciences, have achieved bionic grippers: drawing on the principle of the adductor muscle of scallops, the adaptive adjustment range of the grasping force is 0.1-50N; Innovations such as developing swarm intelligence, establishing a self-organizing network communication with 100 robots, and increasing dynamic coverage efficiency by 300%[8]. More importantly, this equipment can carry out fishing operations around the clock and without interruption, and is not restricted by natural conditions such as weather and tides, thus ensuring the stability and continuity of the fishing work. In addition, the application of intelligent management systems and big data analysis has also provided scientific basis for industrial decision-making, promoted the intelligent upgrade of the entire industrial chain, and laid a solid foundation for the sustainable development of the shellfish industry.

2.4 Processing Stage:

The application of shellfish mechanization in the deep processing stage has achieved remarkable results, demonstrating distinct characteristics of diversity, refinement and high efficiency. A number of research institutions, universities and enterprises, represented by the Institute of Fishery Machinery and Instruments of the Chinese Academy of Fishery Sciences, have successfully developed a series of automated and intelligent equipment. These devices have demonstrated outstanding processing capabilities in complex processing tasks such as cleaning, grading, shelling and packaging of shellfish, greatly enhancing processing efficiency[9]. Meanwhile, the introduction of sensors and control systems has elevated the accuracy and controllability of shellfish processing to an unprecedented level. These advanced technological devices can monitor key parameters such as temperature, humidity and pressure in real time during the processing, ensuring that every step of operation strictly complies with the established standards and requirements, thereby guaranteeing the stability and consistency of product quality[10]. In addition, Zhanjiang Guolian Aquatic Products has built the world's first AI processing line for shellfish. The three-dimensional model of shellfish was reconstructed through structured light scanning, with a classification accuracy of 99.7%. Laser-induced Breakdown spectroscopy (LIBS) : Heavy metal residue detection is completed in 0.1 seconds; Digital label printing: Nano-scale inkjet coding technology records 117 traceability information items.

Table 2. Mechanization Progress in Shellfish Processing Stages

Process	Actors	Advantages	Disadvantages
Cleaning	• Fishery Machinery and Instrument Research Institute, CAFS	• High cleaning efficacy with <2% damage rate • Adaptive to 80%+ common shellfish species	• Customized solutions required for non-standard species/sizes
Grading	• Fishery Machinery and Instrument Research Institute, CAFS	• 30x efficiency gain over manual sorting • 95%+ accuracy in size/weight classification	• Limited adaptability to mixed-species batches
Shell Removal	• Hebei Agricultural University • Dalian Zhengshui	• Throughput: 1,200-1,500 units/hour • Freshness	• Potential protein denaturation and bioactive compound

	Equipment Factory	preservation (ATP >5.0 μmol/g) • Real-time monitoring of critical parameters (e.g., oxygen levels, seal integrity) • ⩽0.5% packaging defect rate	loss
Packaging	• Food processing equipment manufacturers		• High upfront costs (equipment + training) • Requires specialized maintenance teams

The data is sourced from the China Fisheries Statistical Yearbook

3. The realization path of mechanization in the shellfish industry

3.1 Build a mechanized platform system for shellfish and improve the technical usage support system

Strengthen the independent research and development of high-end mechanical equipment and enhance the ability to break through key technologies. Promote cooperation between shellfish aquaculture enterprises and relevant research institutes or universities related to the sea and equipment [11]. Focus on key technologies such as shellfish rope traction, rope material separation, raw material grading, net county development, shellfish trapping, and fresh product shelling. Develop mechanized aquaculture and harvesting equipment, sorting equipment, and supporting control systems. Build oyster, scallop, mussel, abalone, clam, snail and other important economic shellfish real-time monitoring and early warning, intelligent farming, automated harvesting, sorting integration platform system, continuously improve the production simplification and mechanization level of shellfish farming. Optimize the breeding structure, promote large-scale and intensive breeding models, and reduce the impact on the environment; Improve fishing techniques, utilize mechanized means to enhance fishing efficiency and accuracy, and reduce the waste of fishery resources; Deepen the processing chain, utilize mechanization and automation technologies to increase the added value of shellfish products and meet the diversified demands of the market. At the same time, further improve the technical usage support system for practitioners, including establishing a fast-response technical service team to provide immediate answers and on-site guidance for fishermen when they encounter problems during the use of new equipment. Customized development of scenario-based technology packages for intelligent equipment combinations adapted to different sea areas

Table 3 Customization of Scenario-based Technology Packages

Sea area type	Technical package configuration	Cost optimization
mudflat aquaculture	Unmanned plowing and harrowing vehicle +AI seedling planter	Reduce costs by 42%
Deep-sea suspension	Autonomous navigation feeding vessel + optical fiber monitoring network	Increase efficiency by 35%

3.2 Strengthen the relevant skills training for shellfish farming practitioners and enhance the efficiency of socialized services

In order to effectively promote the wide popularization of shellfish farming technology and enhance the overall efficiency of the mechanical socialized service system in the shellfish industry [12], we must strengthen the training of shellfish farming practitioners on the operation and maintenance skills of modern advanced equipment. We can organize systematic training courses regularly to ensure that each user can master the latest mechanical operation skills. This includes knowledge about the daily maintenance and troubleshooting of equipment, etc., to enhance

their autonomous maintenance capabilities. Meanwhile, efforts should be made to actively promote the application of new and efficient shellfish farming and processing equipment [13]. By introducing and demonstrating advanced equipment, small and medium-sized fishermen can directly feel the improvement in production efficiency and product quality brought about by technological progress, thereby stimulating their enthusiasm for adopting new technologies. During this process, the government, industry associations and research institutions should form a joint force to provide policy guidance, financial support and technical consultation services for fishermen, and lower the threshold and risks for them to apply new technologies.

3.3 Promote the synchronization of mechanization and informatization in the shellfish industry and establish a digital service platform

Accelerate the establishment of a big data monitoring platform for Marine fishery, integrate advanced data analysis and processing technologies, and by collecting and analyzing massive amounts of Marine environmental data (such as water temperature, salinity, dissolved oxygen content, etc.), fish migration and distribution patterns, fishing operation dynamics and other key information, provide fishermen with accurate and real-time reports on the status of Marine resources. On this basis, explore the application of cutting-edge technologies such as artificial intelligence and machine learning in the shellfish industry. For instance, use AI algorithms to predict the growth cycle of shellfish and the probability of disease occurrence, providing fishermen with more scientific decision support [14]. Introduce Internet of Things (iot) technology to build an intelligent management system covering the entire process of shellfish production. The Internet of Things (iot) technology can achieve remote monitoring and automatic control of aquaculture facilities, intelligent feeding systems, online water quality monitoring and regulation systems, etc., significantly improving the accuracy and efficiency of aquaculture management. Meanwhile, Internet of Things (iot) technology can also be applied to the real-time positioning and status monitoring of fishing vessels, ensuring the safety and efficiency of offshore operations. In addition, a shellfish industry information and service platform should be established to integrate market information, technical training, policy interpretation and other contents, providing one-stop services for fishermen and helping them better integrate into the digital age.

3.4 Strengthen financial support for the mechanization of the shellfish industry and improve the subsidy policy for the purchase of agricultural machinery

Comprehensively strengthen financial support for the mechanization development of the shellfish industry and optimize the subsidy policy for the purchase of agricultural machinery. The government should increase its investment in subsidies for the purchase of shellfish machinery to ensure that the subsidy policy is widely covered. In particular, it should target small and medium-sized fishermen and cooperatives, lower the threshold for them to purchase advanced shellfish machinery and equipment, and stimulate their enthusiasm for investment. Meanwhile, the design of subsidy policies should pay more attention to guidance and motivation, encouraging fishermen to purchase energy-saving, environmentally friendly, efficient and intelligent fishery machinery, such as electric or solar-driven fishing equipment, automated aquaculture systems, etc., so as to promote the green upgrading of shellfish machinery [15]. In addition, policies should also encourage and support the research and development innovation of shellfish machinery and equipment, especially to develop more applicable and efficient green shellfish machinery and equipment for specific Marine environments and farmed species, achieving a win-win situation for the development of shellfish mechanization and Marine ecological protection [16]. During the implementation process, it is necessary to enhance policy promotion, ensure the transparency and fairness of the subsidy policy, establish and improve the application, approval and distribution mechanisms for subsidies, ensure that subsidy funds can be distributed to fishermen in a timely and accurate manner, and guarantee that the policy dividends can be fully released.

4. Conclusion

The intelligence of the shellfish industry is an inevitable trend in the development of modern fishery. It is not only

an effective means to improve production efficiency, solve the problem of labor shortage and reduce the labor intensity of practitioners, but also a key engine driving the transformation and upgrading of China's shellfish industry from the traditional model to modern, efficient and sustainable. The intelligent transformation is deconstructing and reconstructing the value network of shellfish farming. Decentralized production, distributed intelligent equipment clusters independently manage the million-mu breeding area. The proportion of carbon sink benefits from value diversification will exceed the profits from traditional aquaculture. Participation in democratization will make every fisherman a data sovereign owner. This transformation is not only a technological revolution but also a leap in the paradigm of Marine civilization. Only by building an intelligent fishery system that is technologically controllable, ecologically friendly and distributionally fair can we safeguard the sustainable development of the blue granary in the digital wave. The wide application of these innovative technologies and mechanical equipment will greatly enhance the efficiency of breeding, reduce labor costs, and at the same time improve product quality and safety. In the future, with the continuous advancement of information technology and the continuous expansion of the market, the mechanization of the shellfish industry will demonstrate a more vigorous development trend.

Data availability statement: The data used in this study are sourced from public domain resources. The specific data were obtained from China Fishery Statistical Yearbook, which can be accessed through the official website of the Ministry of Agriculture and Rural Affairs of the People's Republic ofChina at：
http://www.moa.gov.cn/sj/tjnj/yynj/yyztj/202412/t20241219_6449421.htm.

Since these data are publicly accessible, they can be easily obtained by other researchers. By using publicly available data, we aim to enhance the reproducibility of our research and contribute to the open - science movement in the global academic context.

References

[1] E. Nurmianto,A. Pamungkas. "Food processing industry and ergonomics handicraft creation from shellfish." IOP Conference Series: Materials Science and Engineering(2019).

[2] Wang Yu, Yuan Haihong, Shen Langzi, et al. Vulnerability Analysis of Typhoon Disasters in Island Aquaculture: Case Studies of Zhoushan and Wenzhou [J]. Tropical Geography, 2024, 44(06): 1127-1138. (in Chinese)

[3] Hangqi Li,Gang Mu,Hanbing Zhang,Hao Wu,Fawei Liu. "Design and testing of a mechanized brush-screen cooperative vibration harvester for mudflat-buried shellfish based on the discrete elem1ent method." Frontiers in Marine Science(2023).

[4] Adhering to Metrological Innovation for Continuous Improvement in Product Quality and Reliability [J]. China Quality Supervision, 2020, (08): 74-75. (in Chinese)

[5] General Office of the Ministry of Agriculture and Rural Affairs. Notice on Designating the First Batch of National Long-Term Fixed Observation Stations for Agricultural Green Development [J].

[6] Gazette of the Ministry of Agriculture and Rural Affairs of the People’s Republic of China, 2020, (11): 63-64. (in Chinese)

[7] Daomin Peng,Xiaomei Hou,Yang Li,Yongtong Mu. "The difference in development level of marine shellfish industry in 10 major producing countries." Marine Policy(2019).

[8] Chen Xinjun, Zhang Zhong. Recommendations for Developing New Quality Productive Forces in Pelagic Fisheries [J/OL]. Journal of Shanghai Ocean University, 1-9 [2024-12-09]. (in Chinese)

[9] Zhu Fuqiang, Li Tao, Duan Xueli, et al. Current Status and Strategies for the Development of the Shellfish Industry in Binzhou [J]. Agricultural Engineering, 2023, 13(11): 151-154. (in Chinese)

[10] SOLAR FLUPSY Project Update: Design and Construction Report [EB/OL]. (2012-02-12).

[11] Xu Hao, Ni Qi, Liu Huang. Research on the Development of Aquaculture Facility Models in China [J]. Fishery Modernization, 2007, (06): 1-6.

[12] Guo Yunyun, Guan Shixin, Pang Bo. Rapid Development and Full Industrial Chain Optimization of Marine Shellfish Aquaculture [J]. China Food, 2024, (09): 107-113. (in Chinese)

[13] Goulletquer P,Heral M,Prou J. "Interface between French shellfish industry and research." Journal of Shellfish Research 1(2005).

[14] Bonnet Marc,Troadec Jean-paul. "The shellfish industry in France.".

[15] Dong Jingming, Liu Zifei, Chen Limei. Policies, Practices, and Prospects of Marine Carbon Sink Trading in China [J]. Bulletin of the Chinese Academy of Sciences, 2024, 39(03): 519-527. (in Chinese)

[16] Lu Kun, Sun Juan, Pierre Failler, et al. Identification and Practical Responses to Production Stages in China’s Marine Shellfish Aquaculture [J]. China Ocean Economy, 2020, (02): 1-18. (in Chinese)

[17] Liu Zifei, Li Fei, Xia Jiajia. Current Status, Challenges, and Strategies for Ecological Fishery Development in Large Water Bodies [J]. Ecological Economy, 2022, 38(03): 142-148. (in Chinese)