Philosophy. Economics. Law. Education. Literature. History. Natural Science. Engineering. Agriculture. Medicine. Management Science. Art.

Global Academic Frontiers

ISSN 2995-5688 (Print)
ISSN 2995-570X (Online)

Global Academic Frontiers

Volume 4 · Issue 2 · June 2026

Published by Editorial Office of Global Academic Frontiers

Global Academic Frontiers

Volume 4 • Issue 2 • June 2026

(Quarterly, Published Since 2023)

Publisher	Editorial Office of Global Academic Frontiers
Place of publication	United States
Website	http://gafj.org
Email	office@gafj.org
Editor-in-Chief	Cunpeng Wu
Office number	+1 818-936-4444
Mailing Address	15617 NE Airport Way, Multnomah Mailbox SHKHVD Portland, OR, USA 97230
Printer	Editorial Office of Global Academic Frontiers self-prints on the Lulu Press
	A4 Paper, Version 1, Printing June 2026
Subscriptions	http://gafj.org/journal
Price	Free Copy
	ISSN: 2995-5688（Print）
	ISSN: 2995-570X（Online）
	International Standard Identifier for Libraries: OCLC-GAFEO
	ISNI: 0000000517857833

TABLE OF CONTENTS

Global Academic Frontiers, Vol. 4, Issue 2, 2026, pp. 1-13 Print ISSN 2995-5688 Online ISSN 2995-570X
DOI: https://doi.org/10.5281/zenodo.20605207

Impact of Control Parameter Deviations on PMSM Operating Efficiency and Adaptive Regulation Strategy

Zhuopeng Gao [1*]

[1] School of Automation Science and Engineering, South China University of Technology, Guangzhou, China, 510000
*Corresponding author Email: 1341261403cpk@gmail.com
Received 2 June 2026; Accepted 8 June 2026; Published 9 June 2026

Abstract: Permanent magnet synchronous motors (PMSMs) are widely used in industrial automation, transportation, and intelligent equipment due to their high efficiency, high power density, and good dynamic performance. However, parameter deviations caused by temperature variation, load fluctuation, model uncertainty, and aging may reduce control accuracy and operating efficiency. This paper analyzes the influence of control parameter deviations on PMSM drive efficiency using a MATLAB/Simulink-based vector control simulation platform. Speed-loop proportional gain, integral gain, stator resistance, and rotor flux-linkage estimation error are introduced as deviation variables. Their effects on efficiency, overshoot, settling time, power factor, stator current, and copper loss are quantitatively evaluated. Based on the results, an adaptive regulation strategy combining online parameter identification and operating-condition recognition is proposed. Simulation results show that rotor flux-linkage estimation error has the strongest impact on efficiency, followed by speed-loop proportional gain deviation. The proposed strategy reduces efficiency loss by more than 60% and decreases transient extra energy consumption by approximately 58%, providing a practical reference for improving PMSM drive efficiency.

Keywords: Permanent Magnet Synchronous Motor; Control Parameter Deviation; Operating Efficiency; Vector Control; Online Parameter Identification; Adaptive Regulation

1. Introduction

Permanent magnet synchronous motors have become important actuators in modern industrial drive systems. Compared with induction motors and traditional DC motors, PMSMs have higher torque density, higher efficiency, faster dynamic response, and better reliability [1]. They are widely applied in electric vehicles, industrial robots, CNC machine tools, household appliances, aerospace servo systems, and intelligent manufacturing equipment. With the increasing demand for energy saving and carbon-emission reduction, the operating efficiency of PMSM drive systems has received extensive attention in both academic research and engineering practice.

Field-oriented control is one of the most widely used control methods for PMSM drives. By transforming three-phase stator currents into a rotating dq-coordinate system, field-oriented control realizes the decoupled control of torque and flux [2]. Vector control theory has provided an effective foundation for high-performance AC motor drives and has been widely used in PMSM control systems [3]. In an ideal control system, motor parameters and controller gains are assumed to be accurate and constant. However, in actual operation, this assumption is difficult to satisfy. Stator resistance changes with winding temperature, rotor flux linkage varies because of demagnetization and magnetic saturation, and the optimal speed-loop PI parameters also change under different load and speed conditions.

Parameter deviation is therefore an inevitable problem in practical motor control systems. When the controller uses inaccurate parameters, field orientation becomes inaccurate, current regulation quality decreases, and additional losses are generated. For example, inaccurate rotor flux-linkage estimation affects torque calculation and magnetic-field orientation. An underestimated flux linkage may require higher stator current to maintain the same torque, which increases copper loss. An overestimated flux linkage may lead to magnetic saturation and increased iron loss. Similarly, excessive speed-loop proportional gain may cause current oscillation and frequent switching actions, increasing switching loss and dynamic energy consumption.

Many researchers have studied PMSM parameter identification and adaptive control. Online parameter estimation of PMSMs is important for improving control performance and operational reliability, especially under changing temperature and load conditions [4]. Existing studies have proposed model reference adaptive systems, filtering-based estimation methods, sliding-mode observers, and adaptive control strategies to improve parameter robustness and dynamic response [5], [6]. Other studies have focused on efficiency optimization by considering iron loss, copper loss, and loss-model-based control methods [7], [8].

Although existing research provides useful methods for PMSM control improvement, three limitations remain. First, many studies focus on a single parameter, such as stator resistance, inductance, or flux linkage, while the comparative influence of different control parameter deviations on efficiency is not fully discussed. Second, most research emphasizes dynamic response and tracking accuracy, but the mechanism by which parameter deviation causes efficiency degradation is not sufficiently explained from the perspective of loss composition. Third, some adaptive control methods continuously adjust controller parameters without distinguishing between steady-state and dynamic operating conditions, which may increase unnecessary control activity during stable operation.

To address these problems, this paper establishes a simulation-based quantitative analysis framework for PMSM control parameter deviations. The main contributions are as follows. First, a PMSM vector control simulation platform with parameter-deviation injection is established in MATLAB/Simulink. Speed-loop proportional gain, speed-loop integral gain, stator resistance, and rotor flux-linkage estimation error are selected as key deviation factors. Second, the influence of different parameter deviations on system efficiency, overshoot, settling time, power factor, stator current, and copper loss is quantitatively analyzed. Third, an efficiency-loss decomposition method is introduced to explain the physical mechanism of efficiency degradation under different parameter mismatch conditions. Fourth, an adaptive regulation strategy combining online parameter identification and operating-condition recognition is proposed. This strategy compensates parameter drift and adjusts speed-loop control parameters according to operating conditions, thereby improving both dynamic response and steady-state efficiency.

The rest of this paper is organized as follows. Section 2 reviews related literature. Section 3 presents the mathematical model, simulation platform, and parameter-deviation injection method. Section 4 presents the simulation results. Section 5 discusses the efficiency degradation mechanism and the proposed adaptive regulation strategy. Section 6 concludes the paper.

2. Literature Review

PMSM modeling and vector control have been studied for several decades. Pillay and Krishnan developed classical modeling and simulation methods for permanent-magnet motor drives, providing a foundation for later PMSM control studies [2]. Novotny and Lipo further systematized vector control theory for AC drives and explained the role of coordinate transformation in decoupling torque and flux control [3]. These studies provide the theoretical basis for the dq-axis model and PI-based vector control adopted in this paper.

Parameter uncertainty is a major factor affecting PMSM control performance. Zhu, Liang, and Liu reviewed online parameter estimation methods for permanent magnet synchronous machines and discussed rank-deficiency, inverter nonlinearity, and parameter identifiability problems [4]. Liu et al. compared two model reference adaptive system strategies for PMSM parameter identification and showed that resistance, inductance, and flux linkage can be estimated using measured voltage, current, and speed signals [5]. Qi et al. proposed an improved adaptive parameter identification method for PMSMs, showing that adaptive laws can improve identification accuracy under disturbances [6].

Efficiency optimization is another important research direction. Mi, Slemon, and Bonert investigated iron-loss modeling for permanent-magnet synchronous motors and showed that iron loss must be considered in high-efficiency drive analysis [7]. Xu et al. studied PMSM efficiency optimization based on iron loss resistance modeling and indicated that loss models can be used to improve the overall efficiency of drive systems [8]. These studies confirm that PMSM efficiency is influenced not only by output torque and speed but also by loss distribution, including copper loss, iron loss, and inverter-related losses.

However, existing work still leaves room for a simulation-based comparative study of different parameter deviations. Many studies focus on parameter identification accuracy or control robustness, while fewer studies quantitatively compare how different parameter deviations affect efficiency, dynamic response, and loss composition under the same operating condition. Therefore, this paper focuses on speed-loop PI gains, stator resistance, and rotor flux-linkage estimation error, and evaluates their relative influence on PMSM operating efficiency.

3. Methods

3.1 PMSM Mathematical Model

For a surface-mounted PMSM, the mathematical model is usually established in the rotating dq-coordinate system. The d-axis is aligned with the rotor permanent-magnet flux, and the q-axis is orthogonal to the d-axis. In the dq-coordinate system, the stator voltage equations can be written as

$$u_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q \tag{1}$$

$$u_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_e L_d i_d + \omega_e \psi_f \tag{2}$$

where u_d and u_q are the stator voltages in the d-axis and q-axis, i_d and i_q are the corresponding stator currents, R_s is the stator resistance, L_d and L_q are the d-axis and q-axis inductances, ω_e is the electrical angular velocity, and ψ_f is the rotor permanent-magnet flux linkage.

For a surface-mounted PMSM, the saliency effect is weak, and the inductances can be approximately regarded as equal:

$$L_d = L_q = L_s \tag{3}$$

The electromagnetic torque of a PMSM is expressed as

$$T_e = \frac{3}{2} p \left[\psi_f i_q + (L_d - L_q) i_d i_q \right] \tag{4}$$

where p is the number of pole pairs. For a surface-mounted PMSM with L_d = L_q, the reluctance torque term is zero. Therefore, the electromagnetic torque becomes

$$T_e = \frac{3}{2} p \psi_f i_q \tag{5}$$

Equation (5) shows that the torque is mainly determined by the rotor flux linkage and the q-axis current. Therefore, any deviation in rotor flux-linkage estimation directly affects torque calculation and current command generation.

The mechanical motion equation of the PMSM is

$$J\frac{d\omega_m}{dt}=T_e-T_L-B\omega_m \tag{6}$$

where J is the moment of inertia, ω_m is the mechanical angular velocity, T_L is the load torque, and B is the viscous friction coefficient. The relationship between electrical angular velocity and mechanical angular velocity is

$$\omega_e=p\omega_m \tag{7}$$

3.2 Vector Control Structure

The PMSM drive system adopts a conventional field-oriented control structure. The outer loop is the speed control loop, and the inner loops are the d-axis and q-axis current control loops. The d-axis current reference is set to zero:

$$i_d^*=0 \tag{8}$$

This control strategy is simple and widely used because it can reduce unnecessary excitation current and improve torque-generation efficiency.

The speed error is defined as

$$e_\omega=\omega^*-\omega_m \tag{9}$$

where ω* is the reference speed. The q-axis current reference generated by the speed PI controller is

$$i_q^*=K_{p\omega}e_\omega+K_{i\omega}\int e_\omega dt \tag{10}$$

where K_pω and K_iω are the proportional and integral gains of the speed loop. The current loops are also controlled by PI regulators:

$$u_d^*=K_{pi}\left(i_d^*-i_d\right)+K_{ii}\int\left(i_d^*-i_d\right)dt-\omega_e L_q i_q \tag{11}$$

$$u_q^*=K_{pi}\left(i_q^*-i_q\right)+K_{ii}\int\left(i_q^*-i_q\right)dt+\omega_e L_d i_d+\omega_e\psi_f \tag{12}$$

where K_pi and K_ii are the current-loop proportional and integral gains.

3.3 Simulation Platform and Parameter Settings

A PMSM vector-control simulation platform is established in MATLAB/Simulink. MATLAB/Simulink is commonly used for motor-drive modeling and control-system verification because it can describe electrical, mechanical, and control subsystems in an integrated environment [9]. The simulation system includes the PMSM model, coordinate transformation module, speed PI controller, current PI controller, inverter module, parameter-deviation injection module, efficiency calculation module, and loss analysis module.

The simulation platform is designed to compare system performance under accurate parameters and deviated parameters. The operating condition with accurate parameters is used as the benchmark. Then, different deviations are introduced into the controller parameters or motor parameters. By comparing simulation results, the influence of each parameter deviation on operating efficiency and dynamic performance can be obtained.

Table 1: Rated parameters of the PMSM

Parameter	Symbol	Value	Unit
Rated power	P_N	5.5	kW
Rated speed	n_N	1500	r/min
Rated torque	T_N	35	N·m

Stator resistance	R_s	0.35	Ω
d-axis inductance	L_d	8.5	mH
q-axis inductance	L_q	8.5	mH
Permanent-magnet flux linkage	ψ_f	0.175	Wb
Moment of inertia	J	0.008	kg·m²

The rated operating condition is set as follows:

$$n=1500\ \mathrm{r/min} \tag{13}$$

$$T_L=30\ \mathrm{N\cdot m} \tag{14}$$

Under this condition, the benchmark efficiency of the system is 92.3%.

3.4 Parameter-Deviation Injection Method

To describe parameter deviation quantitatively, the deviation coefficient is defined as

$$\delta_x=\frac{x_{est}-x_{real}}{x_{real}}\times 100\% \tag{15}$$

where x_est is the parameter value used by the controller, and x_real is the actual parameter value of the motor system.

The parameters selected for deviation analysis are

$$\Theta=\{K_{p\omega},K_{i\omega},R_s,\psi_f\} \tag{16}$$

where K_pω and K_iω represent controller-gain deviations, while R_s and ψ_f represent motor-parameter estimation deviations. The selected deviation levels are

$$\delta_x=\pm 20\%,\ \pm 40\% \tag{17}$$

These values are used to represent moderate and severe parameter mismatches.

3.5 Efficiency Calculation and Loss Decomposition

The output power of the motor is calculated as

$$P_{out}=T_e\omega_m \tag{18}$$

The input power is calculated from the electrical side:

$$P_{in}=u_ai_a+u_bi_b+u_ci_c \tag{19}$$

Therefore, the system efficiency is

$$\eta=\frac{P_{out}}{P_{in}}\times 100\% \tag{20}$$

The efficiency change rate is defined as

$$\Delta\eta_r=\frac{\eta_{dev}-\eta_0}{\eta_0}\times 100\% \tag{21}$$

where η_0 is the benchmark efficiency, and η_dev is the efficiency under parameter deviation.

In order to analyze the reason for efficiency degradation, the total loss is divided into several components:

$$P_{loss}=P_{cu}+P_{fe}+P_{sw}+P_{mech} \tag{22}$$

where P_cu is copper loss, P_fe is iron loss, P_sw is inverter switching loss, and P_mech is mechanical loss. Loss decomposition is commonly used in PMSM efficiency studies because copper loss and iron loss are two major components affecting efficiency [7], [8]. Copper loss is calculated as

$$P_{cu}=3R_sI_s^2 \tag{23}$$

where I_s is the stator current effective value. Iron loss is approximately expressed as

$$P_{fe}=k_h fB_m^2+k_e f^2 B_m^2 \tag{24}$$

where k_h and k_e are iron-loss coefficients, f is electrical frequency, and B_m is magnetic flux density. Switching loss is approximately expressed as

$$P_{sw}=f_s(E_{on}+E_{off}) \tag{25}$$

where f_s is switching frequency, E_on is turn-on energy loss, and E_off is turn-off energy loss.

4. Results

4.1 Influence of Speed-Loop PI Parameter Deviation

The speed-loop PI parameters directly affect the dynamic response and steady-state operating condition of the motor drive system. PI controllers remain widely used in industrial motor drives because of their simple structure and easy implementation [10]. In this study, the proportional gain K_pω and integral gain K_iω are changed by ±20% and ±40%, while other parameters remain unchanged. The simulation results are shown in Table 2.

Table 2: Influence of speed-loop PI parameter deviation on system performance

Deviation type	Deviation amplitude	Efficiency (%)	Efficiency change (%)	Overshoot (%)	Settling time (ms)
Benchmark	0%	92.3	--	4.2	85
K_pω smaller	-20%	91.1	-1.30	2.1	142
K_pω smaller	-40%	89.8	-2.71	1.2	208
K_pω larger	+20%	90.5	-1.95	8.6	76
K_pω larger	+40%	88.6	-4.01	15.3	68
K_iω smaller	-20%	91.8	-0.54	3.8	104
K_iω smaller	-40%	91.0	-1.41	3.5	138
K_iω larger	+20%	91.5	-0.87	5.1	92
K_iω larger	+40%	90.3	-2.17	7.2	88

The results show that speed-loop proportional gain has a greater influence on efficiency than integral gain. When K_pω increases by 40%, the efficiency decreases from 92.3% to 88.6%, and the overshoot increases from 4.2% to 15.3%. This indicates that excessive proportional gain causes strong speed-loop response and current oscillation. Although the settling time becomes shorter, the motor operates with larger current fluctuation and more frequent inverter switching actions, which increases switching loss and copper loss.

When K_pω decreases by 40%, the efficiency decreases to 89.8%, and the settling time increases to 208 ms. In this case, the controller response is too slow. The motor remains in the transient process for a longer time, which increases dynamic energy consumption. Therefore, both excessive and insufficient proportional gain reduce operating efficiency.

Compared with proportional gain, integral gain has a relatively smaller influence on efficiency. The main function of integral gain is to eliminate steady-state speed error. When K_iω is too small, the system response becomes slower.

When K_iω is too large, the system may produce larger overshoot and oscillation. However, within the tested range, the efficiency degradation caused by integral gain deviation is smaller than that caused by proportional gain deviation.

4.2 Influence of Rotor Flux-Linkage Estimation Error

Rotor flux linkage is a key parameter in PMSM vector control. It directly affects torque calculation, current command generation, and field orientation. In practical systems, flux-linkage estimation may be influenced by temperature, demagnetization, magnetic saturation, and observer error. In this study, different flux-linkage estimation errors are introduced into the controller. The simulation results are shown in Table 3.

Table 3: Influence of rotor flux-linkage estimation error on system performance

Flux-linkage condition	Estimated / actual value	Efficiency (%)	Power factor	Stator current RMS (A)	Copper loss (W)
Accurate estimation	1.0	92.3	0.96	18.2	348
Positive deviation	1.1	90.1	0.92	20.5	441
Positive deviation	1.2	86.5	0.87	24.1	610
Negative deviation	0.9	91.2	0.94	19.3	391
Negative deviation	0.8	88.9	0.91	21.8	499

The results show that rotor flux-linkage estimation error has a significant influence on PMSM operating efficiency. When the estimated flux linkage is 20% higher than the actual value, the efficiency decreases from 92.3% to 86.5%. The stator current RMS increases from 18.2 A to 24.1 A, and copper loss increases from 348 W to 610 W.

When the estimated flux linkage is higher than the actual value, the controller overestimates the torque-production capability of the motor. This causes inaccurate current distribution and may lead to magnetic saturation. Magnetic saturation increases iron loss and weakens the power factor. Meanwhile, the current regulator needs to make additional adjustments to maintain torque output, which increases copper loss.

When the estimated flux linkage is lower than the actual value, the controller underestimates the torque-production capability. To maintain the same output torque, the system tends to increase stator current, resulting in higher copper loss. Therefore, both positive and negative flux-linkage estimation errors reduce efficiency, but positive deviation causes more serious efficiency degradation in this simulation.

4.3 Influence of Stator Resistance Deviation

Stator resistance varies significantly with winding temperature. The relationship between stator resistance and temperature can be approximately expressed as

$$R_s = R_{s0}\left[1+\alpha(T-T_0)\right] \tag{26}$$

where R_s0 is the stator resistance at reference temperature T_0, T is the actual winding temperature, and α is the temperature coefficient of copper. If the controller does not update the stator resistance value, the voltage compensation term in the current loop becomes inaccurate. This causes current-tracking error and increases copper loss. Table 4 shows the influence of stator resistance deviation on system efficiency.

Table 4: Influence of stator resistance deviation on system performance

Stator resistance condition	Deviation amplitude	Efficiency (%)	Stator current RMS (A)	Copper loss (W)
Benchmark	0%	92.3	18.2	348
R_s smaller in controller	-20%	91.6	18.9	376
R_s smaller in controller	-40%	90.7	19.8	411
R_s larger in controller	+20%	91.4	19.1	383
R_s larger in controller	+40%	90.2	20.2	428

The results indicate that stator resistance deviation has a moderate influence on efficiency. Compared with rotor flux-linkage estimation error and speed-loop proportional gain deviation, the effect of stator resistance deviation is smaller. However, resistance deviation still increases current error and copper loss, especially when the motor operates under high-load and high-temperature conditions for a long time.

4.4 Comparison Between Fixed-Parameter Control and Adaptive Regulation

The proposed strategy is verified under a load-step condition. The motor first operates at 1500 r/min under a load torque of 20 N·m. Then the load torque increases to 30 N·m. The fixed-parameter control strategy and the proposed adaptive regulation strategy are compared.

The evaluation indicators include dynamic overshoot, settling time, and additional transient energy consumption. The additional transient energy consumption is calculated as

$$E_{add}=\int_{t_1}^{t_2}\left(P_{in}-P_{in,ss}\right)dt \tag{27}$$

where P_in is the instantaneous input power, and P_in,ss is the steady-state input power after the load change.

Table 5: Comparison between fixed-parameter control and adaptive regulation

Control method	Dynamic overshoot (%)	Settling time (ms)	Additional transient energy consumption (J)
Fixed-parameter control	14.5	210	42.3
Adaptive regulation	6.8	112	17.8

The results show that the proposed adaptive regulation strategy significantly improves dynamic performance. Compared with fixed-parameter control, the overshoot decreases from 14.5% to 6.8%, and the settling time decreases from 210 ms to 112 ms. Meanwhile, the additional transient energy consumption decreases from 42.3 J to 17.8 J.

The reduction ratio of additional transient energy consumption is

$$\frac{42.3-17.8}{42.3}\times 100\%=57.9\% \tag{28}$$

Therefore, the proposed adaptive strategy reduces transient extra energy consumption by approximately 58%.

4.5 Efficiency Compensation Effect

To verify the compensation effect under parameter drift, a flux-linkage deviation condition is selected. When the rotor flux-linkage estimation error is +20%, the efficiency decreases from 92.3% to 86.5%. After online parameter compensation and adaptive regulation, the efficiency increases to 90.1%.

The efficiency loss before compensation is

$$92.3\% - 86.5\% = 5.8\% \tag{29}$$

The efficiency loss after compensation is

$$92.3\% - 90.1\% = 2.2\% \tag{30}$$

The reduction ratio of efficiency loss is

$$\frac{5.8 - 2.2}{5.8} \times 100\% = 62.1\% \tag{31}$$

Thus, the proposed strategy reduces the efficiency loss caused by parameter drift by more than 60%.

5. Discussion

5.1 Sensitivity of Different Parameter Deviations

Based on the simulation results, the sensitivity ranking of different parameter deviations can be summarized as follows:

$$\psi_f > K_{p\omega} > R_s > K_{i\omega} \tag{32}$$

This means that rotor flux-linkage estimation accuracy has the greatest influence on PMSM operating efficiency. Speed-loop proportional gain is the most important controller parameter affecting efficiency and dynamic response. Stator resistance mainly affects current-loop compensation and copper loss, while speed-loop integral gain has a relatively smaller influence on efficiency.

5.2 Efficiency Degradation Mechanism

The simulation results demonstrate that different parameter deviations cause efficiency degradation through different mechanisms. When K_pω is too large, the speed controller becomes too sensitive to speed error. This causes large current fluctuation and frequent voltage command changes. As a result, inverter switching loss and copper loss increase. Although the dynamic response becomes faster, the energy efficiency decreases.

When K_pω is too small, the system response becomes slow. The motor stays in the transient state for a longer period after load disturbance. This increases additional transient energy consumption.

When rotor flux-linkage estimation is inaccurate, the field orientation becomes inaccurate. If the estimated flux linkage is higher than the actual value, magnetic saturation and iron loss may increase. If the estimated flux linkage is lower than the actual value, the stator current must increase to maintain torque output, which increases copper loss.

When stator resistance is inaccurate, the voltage compensation in the current loop becomes inaccurate. The current-tracking performance decreases, and copper loss increases.

The above analysis shows that efficiency optimization should not only focus on reducing steady-state current. It should also consider dynamic response, current fluctuation, field-orientation accuracy, and parameter drift. Therefore, the proposed adaptive regulation strategy has practical significance for PMSM drive systems operating under variable working conditions.

5.3 Adaptive Regulation Strategy

To reduce efficiency degradation, this paper proposes an adaptive regulation strategy combining online parameter identification and operating-condition recognition. The proposed strategy contains two main parts. The first part is online parameter identification, which estimates motor parameters such as stator resistance and rotor flux linkage during operation. Online parameter identification has been widely studied as an effective method for improving PMSM control robustness under parameter variation [4]–[6]. The second part is operating-condition-aware parameter adjustment, which changes speed-loop PI parameters according to the current operating condition.

Online parameter identification uses measurable signals such as stator voltage, stator current, and rotor speed to estimate actual motor parameters. The general form of the parameter identification model can be expressed as

$$y(k)=\phi^{T}(k)\,\theta(k)+e(k) \tag{33}$$

where y(k) is the measured output, φ(k) is the regression vector, θ(k) is the parameter vector to be identified, and e(k) is the estimation error. The estimated parameter vector is

$$\hat{\theta}(k)=\left[\hat{R}_s,\hat{\psi}_f\right]^{T} \tag{34}$$

A recursive update law can be written as

$$\hat{\theta}(k+1)=\hat{\theta}(k)+K(k)\,e(k) \tag{35}$$

where K(k) is the adaptive gain. The identified parameters are sent to the controller to update voltage compensation and torque calculation.

Different operating conditions require different control objectives. During steady-state operation, the main objective is to improve efficiency and reduce current fluctuation. During dynamic operation, the main objective is to improve response speed and disturbance rejection. Therefore, an operating-condition index is defined as

$$J=\alpha\left|e_{\omega}\right|+\beta\left|\frac{dT_L}{dt}\right| \tag{36}$$

where e_ω is the speed error, dT_L/dt is the load variation rate, and α and β are weighting coefficients. The operating condition can be classified as

$$\begin{cases} J<J_1, & \text{steady-state mode} \\ J_1\leqslant J\leqslant J_2, & \text{transition mode} \\ J>J_2, & \text{dynamic mode} \end{cases} \tag{37}$$

where J_1 and J_2 are threshold values. In dynamic mode, the proportional gain of the speed loop should be increased to improve response speed. In steady-state mode, the gain should be reduced to suppress oscillation and reduce switching loss. Therefore, the adaptive proportional gain is designed as

$$K_{p\omega}=K_{p0}\left(1+\gamma J\right) \tag{38}$$

where K_p0 is the basic proportional gain, and γ is the adjustment coefficient. To prevent excessive gain variation, the gain is limited by

$$K_{p,min}\leqslant K_{p\omega}\leqslant K_{p,max} \tag{39}$$

The integral gain is adjusted more conservatively:

$$K_{i\omega}=K_{i0}\left(1+\lambda J\right) \tag{40}$$

where λ < γ. This design avoids excessive integral action and reduces the risk of overshoot.

5.4 Engineering Applicability

The proposed strategy has good engineering applicability because it does not require a major change in the original vector-control structure. The additional modules mainly include an online parameter identification module, an operating-condition recognition module, and an adaptive gain adjustment module.

In practical applications, the strategy can be implemented in a digital signal processor or microcontroller. Existing motor-control application studies and technical reports have shown that PMSM vector control can be implemented on digital control platforms such as DSP or microcontroller-based systems [11], [12]. Therefore, the proposed method has potential application value in industrial equipment, pumps, fans, compressors, servo drives, and electric traction systems.

These systems often operate under variable load and long-term temperature variation. Parameter compensation and adaptive tuning can help maintain high operating efficiency during the lifecycle of the equipment.

6. Conclusion

This paper studied the influence of control parameter deviations on the operating efficiency of PMSM drive systems. A MATLAB/Simulink-based PMSM vector-control simulation platform was established, and speed-loop proportional gain, speed-loop integral gain, stator resistance, and rotor flux-linkage estimation error were introduced as parameter-deviation factors.

The simulation results show that rotor flux-linkage estimation error has the greatest influence on system efficiency. When the flux-linkage estimation value is 20% higher than the actual value, the efficiency decreases from 92.3% to 86.5%, and copper loss increases significantly. Speed-loop proportional gain deviation also has a strong influence on both efficiency and dynamic performance. Excessive proportional gain causes overshoot and switching loss, while insufficient proportional gain increases settling time and transient energy consumption. Stator resistance deviation mainly affects current-loop compensation and copper loss, while speed-loop integral gain has a relatively smaller influence on efficiency.

To reduce efficiency degradation, an adaptive regulation strategy combining online parameter identification and operating-condition recognition was proposed. The strategy compensates motor parameter drift and adjusts speed-loop PI parameters according to operating conditions. Simulation results show that the proposed strategy reduces efficiency loss caused by parameter drift by more than 60% and decreases additional transient energy consumption by approximately 58%.

The study provides a practical simulation-based reference for improving the operating efficiency of PMSM drive systems. Future work will focus on experimental verification using a DSP-based PMSM control platform and further optimization of the online parameter identification algorithm under complex load disturbances.

Competing Interests Statement

The author declares that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical Approval Consent

This study does not involve human participants, animal experiments, or personally identifiable experimental data. Ethical approval and informed consent are therefore not applicable.

Data Availability Statement

All data generated or analyzed during this study are included in this article. The simulation data are available from the author upon reasonable request.

Declaration of Generative AI in Scientific Writing

During the preparation of this work, the author used ChatGPT for language polishing, grammar checking, formatting assistance, and manuscript organization. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

Funding

This research received no external funding.

References

[1] Krishnan, R. (2010). Permanent Magnet Synchronous and Brushless DC Motor Drives. CRC Press.

[2] Pillay, P., & Krishnan, R. (1989). Modeling, simulation, and analysis of permanent-magnet motor drives, Part I: The permanent-magnet synchronous motor drive. IEEE Transactions on Industry Applications, 25(2), 265–273.

[3] Novotny, D. W., & Lipo, T. A. (1996). Vector Control and Dynamics of AC Drives. Oxford University Press.

[4] Zhu, Z. Q., Liang, D., & Liu, K. (2021). Online parameter estimation for permanent magnet synchronous machines: An overview. IEEE Access, 9, 59059–59084.

[5] Liu, K., Zhang, Q., Zhu, Z. Q., Zhang, J., Shen, A. W., & Stewart, P. (2010). Comparison of two novel MRAS based strategies for identifying parameters in permanent magnet synchronous motors. International Journal of Automation and Computing, 7(4), 516–524.

[6] Qi, X., Zhang, Y., & Wang, J. (2023). Parameter identification of a permanent magnet synchronous motor based on the model reference adaptive system with improved active disturbance rejection control adaptive law. Applied Sciences, 13(21), 12076.

[7] Mi, C., Slemon, G. R., & Bonert, R. (2003). Modeling of iron losses of permanent-magnet synchronous motors. IEEE Transactions on Industry Applications, 39(3), 734–742.

[8] Xu, F., Wang, H., & Chen, L. (2024). Enhanced efficiency in permanent magnet synchronous motor drive systems based on iron loss resistance optimization. Electronics, 13(5), 858.

[9] MathWorks. (2026). PMSM Field-Oriented Control. MathWorks Documentation.

[10] Bose, B. K. (2002). Modern Power Electronics and AC Drives. Prentice Hall.

[11] Ramamoorthy, R. T., Larimore, B., & Bhardwaj, M. (2021). Sensored Field Oriented Control of 3-Phase Permanent Magnet Synchronous Motors Using TMS320F2837x. Texas Instruments Application Report.

[12] Imperix. (2021). Field Oriented Control of Permanent Magnet Synchronous Motor. Imperix Technical Note.

Global Academic Frontiers, Vol. 4, Issue 2, 2026, pp. 14-23 Print ISSN 2995-5688 Online ISSN 2995-570X
DOI: https://doi.org/10.5281/zenodo.20605423

Research on the Corrosion Modification Mechanism and Application of Polypropylene Fibers Based on a Combined System of Plasma Pretreatment and Chemical Etching

Yue Zhu [1] Jiawei Jiang [1] Guoxi Lv [1] Hongbin Xiong [1*]

[1] College of International Economics & Trade,Ningbo University of Finance & Economics,Ningbo,315175,China
*Corresponding author Email: hongbin1111@163.com
Received 17 March 2026; Accepted 29 May 2026; Published 9 June 2026

Abstract: Polypropylene (PP) fibers, despite their advantageous properties, are limited by surface inertness and low chemical activity. This study develops a controllable modification technology using a combined plasma pretreatment and chemical etching system. The proposed "plasma activation-chemical etching synergy" mechanism first activates the fiber surface via plasma treatment, creating active sites. Subsequent chemical etching then constructs micro-nano rough structures and exposes more active groups. An experimental plan is designed to optimize this process and characterize the results using SEM, XPS, contact angle measurement, and tensile testing. Theoretically, this approach is expected to significantly enhance surface reactivity and wettability while maintaining mechanical properties, providing an efficient pathway to expand PP fiber applications in functional materials.

Keywords: Polypropylene fiber; Etching modification; Plasma pretreatment; Chemical etching; Surface activity

1. Introduction

1.1. Research Background and Significance

As one of the leading synthetic fibers in terms of production volume, polypropylene fiber boasts prominent advantages such as low density (only 0.91 g/cm^3), high specific strength, resistance to acid and alkali corrosion, and low processing cost, leading to its widespread use in various fields. In filtration, PP fiber filter media are used for air purification and wastewater treatment due to their high flux and low resistance. In biomedicine, they serve as base materials for tissue engineering scaffolds and medical sutures. [1] In composite materials, they are often used as reinforcing phases to improve the toughness and crack resistance of the matrix material.

However, the molecular chains of PP fibers consist of non-polar carbon-carbon backbones and methyl groups, resulting in very low surface energy (approximately 30 mN/m), strong chemical inertness, and a lack of active functional groups such as hydroxyl and carboxyl groups. These inherent characteristics lead to poor surface wettability and weak interfacial adhesion with other materials, becoming a key bottleneck restricting their functional expansion. In filtration applications, the inert surface has insufficient adsorption capacity for polar pollutants, limiting filtration efficiency. In biomedicine, the lack of cell adhesion sites on the surface makes it difficult to meet biocompatibility requirements. In composites, weak interfacial bonding with polar matrices (e.g., resins, cement) prevents the full utilization of their reinforcing effect. [2]

1.2. Necessity of Polypropylene Fiber Corrosion Modification

Surface corrosion modification of PP fibers, by constructing rough surfaces and introducing active functional groups to improve their surface chemical activity and interfacial interaction capability, has become key to breaking through application bottlenecks. Modification needs to achieve the following goals: (1) Construct controllable micro-nano scale rough structures on the fiber surface to enhance physical adsorption and mechanical interlocking; (2) Introduce polar functional groups such as oxygen-containing and nitrogen-containing groups to enhance chemical interactions with polar substances; (3) Ensure the modification effect while avoiding damage to the fiber's bulk mechanical properties, guaranteeing its stability in use. An ideal corrosion modification technology should feature controllable effects, simple process, moderate cost, and ease of industrial scaling.

1.3. Main Content, Approach, and Innovations of This Research

This study proposes a composite corrosion modification technology based on plasma pretreatment and chemical etching for the surface functionalization of PP fibers.

The main content includes: systematically reviewing the research status of PP fiber surface corrosion modification; elucidating the corrosion mechanism of the synergistic effect between plasma pretreatment and chemical etching; designing and optimizing the experimental plan, including plasma parameters, chemical etchant formulations, and process conditions; evaluating the modification effects through various characterization methods; analyzing the application potential and performance advantages of the modified fibers. [3]

Research Approach: The core is to construct a two-step "activation-etching" synergistic system. Step one: use plasma treatment (e.g., argon-oxygen plasma) to activate the PP fiber surface, where high-energy particle bombardment breaks surface molecular chains, generates free radicals, and introduces polar functional groups like carboxyl and hydroxyl, while increasing surface roughness. Step two: immerse the activated fibers into a specific chemical etchant, utilizing the selective corrosion of the fiber surface by the etchant to further amplify surface roughness while fully exposing the active functional groups, ultimately achieving a synergistic improvement in surface activity and interfacial bonding strength.

The innovations are mainly reflected in: combining the "mild modification" of plasma activation with the "deep regulation" of chemical etching to solve the problem of limited modification effects or damage to the fiber bulk inherent in single corrosion techniques; clarifying the synergistic corrosion mechanism to achieve precise regulation of fiber surface structure and functional groups; establishing a full-chain characterization system from surface microstructure to macroscopic performance to comprehensively evaluate the stability and practicality of the modification effect. [4]

2. Literature Review and Theoretical Basis

2.1. Structural Characteristics of Polypropylene Fibers and Bottlenecks in Corrosion Modification

Polypropylene is a semi-crystalline polymer with high molecular chain regularity. After melt spinning, the molecular chains are highly oriented along the fiber axis, forming a structure with high strength and low surface energy. The PP fiber surface lacks active functional groups, and the crystalline regions have a dense structure, making it difficult for conventional chemical reagents to penetrate and react. [5] This leads to two major challenges in corrosion modification: firstly, difficulty in forming uniform and controllable rough structures on the surface; secondly, the introduced active functional groups are few in number and poor in stability, unable to meet practical application requirements.

2.2. Research Progress in Surface Corrosion Modification Techniques for Polypropylene Fibers

Existing surface corrosion modification techniques for PP fibers are mainly divided into three categories: single chemical etching, plasma treatment, and composite modification.

2.2.1. Single Chemical Etching Method

This method uses strong acids, strong alkalis, or oxidants to corrode the PP fiber surface, destroying non-polar molecular chains and introducing polar functional groups. Commonly used etchants include chromic acid-sulfuric acid mixture, potassium permanganate solution, and sodium hydroxide solution. Studies show that the chromic acid-sulfuric acid system can effectively corrode the PP fiber surface, forming rough structures and introducing carboxyl groups. The advantages of this method are simple process and low cost, but the disadvantages are that the etching process is difficult to control, easily leads to uneven surface corrosion, the highly corrosive reagents cause significant environmental pollution, and they may damage the fiber's bulk mechanical properties.

2.2.2. Plasma Treatment Method

This method utilizes high-energy particles (e.g., electrons, ions, free radicals) in the plasma to bombard the fiber surface, achieving molecular chain scission and functional group introduction. Commonly used plasmas include argon, oxygen, and nitrogen plasma. Oxygen plasma treatment can introduce functional groups like carboxyl and hydroxyl on the PP fiber surface, improving surface wettability. [6] This method offers advantages such as fast modification speed, environmental friendliness, and surface-specific action. However, the modification effect of single plasma treatment is prone to decay, it is difficult to form deep rough structures, and long-term stability is insufficient.

2.2.3. Composite Modification Method

This method combines two or more modification techniques to exert a synergistic effect. For example, first activating the fiber surface via plasma pretreatment, followed by chemical etching or graft reaction. Research using plasma pretreatment followed by chemical etching found that both surface roughness and active functional group content were significantly higher than with single treatment. This method can balance modification effect and stability, but current research on the synergistic mechanism is not deep, and process parameter optimization lacks systematic guidance.

2.3. Mechanism and Application of Plasma Pretreatment

The core functions of plasma pretreatment are surface activation and roughness regulation. Its mechanisms include: high-energy particle bombardment causing PP molecular chain scission, generating a large number of free radicals; free radicals reacting with active species in the plasma (e.g., O_2^+, OH·), introducing oxygen-containing polar functional groups; simultaneously, high-energy bombardment creates micro-etch pits on the fiber surface, increasing surface roughness. In material modification, plasma pretreatment is often used as an "activation step" for subsequent reactions, for example, to improve the interfacial bonding between fibers and resins, or to provide active sites for chemical etching, enhancing the reaction efficiency between the etchant and the fiber surface. [7]

2.4. Types of Chemical Etchants and Corrosion Mechanisms

Chemical etchants used for PP fiber corrosion are mainly divided into oxidative etchants and acid-base etchants. Oxidative etchants (e.g., chromic acid-sulfuric acid mixture, potassium permanganate solution) break carbon-carbon bonds in PP molecular chains through oxidation, generate polar functional groups, and dissolve part of the surface amorphous region, forming rough structures. Acid-base etchants (e.g., concentrated nitric acid, sodium hydroxide solution) destroy molecular chains through acid-base catalysis, achieving surface corrosion. Different etchants have varying corrosion mechanisms: the chromic acid-sulfuric acid system achieves selective corrosion through the strong oxidizing power of Cr^{6+} , preferentially attacking amorphous regions; the potassium permanganate system catalyzes oxidation reactions through the generated MnO_2 precipitate, resulting in a relatively mild corrosion process.

2.5. Theoretical Basis and Feasibility Analysis of the Plasma/Chemical Etching Composite System

Theoretical Basis: Plasma pretreatment reduces the interfacial energy between the chemical etchant and the fiber surface by introducing active functional groups and increasing surface roughness, thereby improving the wettability and reactivity of the etchant. Simultaneously, the presence of surface free radicals can accelerate the etching reaction rate, realizing a synergistic "activation-etching" effect. [8] Chemical etching, based on the plasma pretreatment, can further expand the surface rough structure, fully expose the introduced active functional groups, and avoid the problem of effect decay associated with single plasma treatment.

Feasibility Analysis: At the material level, plasma equipment and chemical etchants are commercially available conventional products with stable sources and controllable costs. At the process level, both plasma pretreatment and chemical etching are mature processes, simple to operate, and easy to combine and scale up. At the performance level, based on the modification effects of single techniques, the composite system is expected to achieve precise regulation of surface structure and functional groups, significantly improving the stability and practicality of the modification effect. [9]

3. Experimental Plan Design

3.1. Experimental Materials and Equipment

3.1.1. Main Experimental Materials

Polypropylene fiber: Commercially available conventional PP short-cut fibers, diameter 20 μm, length 6 mm, recording original performance parameters before use.

Chemical etchants: Potassium dichromate (analytical grade), concentrated sulfuric acid (analytical grade), potassium permanganate (analytical grade), deionized water, for preparing composite etchants of different concentrations.

Auxiliary reagents: Anhydrous ethanol (analytical grade), acetone (analytical grade), for fiber pretreatment.

Other materials: P.O 42.5 cement, ISO standard sand, for composite material performance testing.

3.1.2. Main Experimental Equipment and Instruments

Preparation and processing equipment: Plasma treatment instrument (argon-oxygen atmosphere), electronic balance (accuracy 0.0001g), constant temperature water bath, numerically controlled ultrasonic cleaner, electric blast drying oven, vacuum drying oven.

Characterization and testing instruments: Scanning Electron Microscope (SEM, equipped with EDS attachment), X-ray Photoelectron Spectrometer (XPS), static contact angle measuring instrument, electronic single fiber tensile tester, universal material testing machine.

3.2. Parameter Design and Optimization of the Composite Corrosion System

3.2.1. Plasma Pretreatment Parameter Design

Set plasma treatment parameter gradients: treatment power (30W, 50W, 70W), treatment time (3min, 5min, 7min), argon-oxygen volume ratio (3:1, 2:1, 1:1). Optimize the best pretreatment parameters using surface functional group content and roughness as evaluation indicators.

3.2.2. Chemical Etchant Formulation and Parameter Design

Etchant formulations: Design three etchant systems, Group A (Chromic acid-sulfuric acid mixture: $K_2Cr_2O_7$ 5g/L + H_2SO_4 30% v/v), Group B (Potassium permanganate-sulfuric acid mixture: $KMnO_4$ 3g/L + H_2SO_4 20% v/v), Group C (Concentrated nitric acid-hydrochloric acid mixture: HNO_3 : HCl = 1:3 v/v).

Etching parameters: Etching temperature (30°C, 40°C, 50°C), etching time (5min, 10min, 15min). Optimize the etching system and parameters using surface roughness and active functional group content as evaluation indicators.

3.2.3. Composite System Parameter Optimization

Set up control groups (single plasma treatment, single chemical etching) and composite treatment groups (different plasma parameters + different etching parameters). Determine the optimal composite modification parameter combination by comparing surface morphology, functional group content, wettability, and other properties.

3.3. Corrosion Modification Process for Polypropylene Fibers

3.3.1. Fiber Pretreatment

Place PP fibers in a Soxhlet extractor and continuously extract with acetone for 6 hours to remove surface oils, waxes, and other impurities. Remove and dry to constant weight in a 60°C vacuum drying oven, then store in a desiccator for later use.

3.3.2. Plasma Pretreatment Process

Spread the pretreated fibers flat on the sample stage of the plasma treatment instrument. Introduce the set ratio of argon-oxygen mixed gas, adjust the vacuum to 10 Pa, and perform plasma activation treatment according to the optimized parameters. After treatment, proceed immediately to subsequent chemical etching to avoid deactivation of surface free radicals. [10]

3.3.3. Chemical Etching Process

Completely immerse the plasma-activated fibers into the prepared chemical etchant and etch at the set constant temperature. After etching, quickly rinse the fibers with copious deionized water until neutral, then clean once with anhydrous ethanol to remove residual etchant.

3.3.4. Post-treatment Process

Place the etched fibers in a 60°C blast drying oven for 2 hours to remove surface moisture, obtaining the modified PP fibers.

3.4. Testing and Characterization Methods

3.4.1. Surface Morphology and Elemental Analysis (SEM/EDS)

Fix fiber samples on the sample stage with conductive adhesive, sputter-coat with gold, and observe surface micro-morphology via SEM, recording the size, distribution of etch pits, and roughness changes. Use EDS to analyze surface elemental composition, focusing on changes in O element content.

3.4.2. Surface Chemical State Analysis (XPS)

Use XPS to test the elemental composition and chemical bonding states of the fiber surface, scanning range 0-1000 eV, resolution 0.1 eV. Focus on analyzing the C1s spectrum, fitting and decomposing characteristic peaks for functional groups such as C-C, C-O, C=O, and calculate the relative content of each functional group.

3.4.3. Surface Wettability Test (Contact Angle)

Use the sessile drop method. Arrange fiber bundles parallel and tightly fixed on a glass slide. Add a 2 μL droplet of deionized water. Record the water droplet shape and calculate the static contact angle using the contact angle instrument. Measure 5 different locations per sample and take the average.

3.4.4. Mechanical Performance Test (Single Filament Tensile Strength)

Refer to ASTM D3822 standard. Use the electronic single fiber tensile tester to test the breaking force and elongation at break of fibers before and after modification. Gauge length 10 mm, tensile speed 2 mm/min. [11] Test 30 single filaments per group, calculate the average and standard deviation.

3.4.5. Composite Material Performance Evaluation

Refer to GB/T 17671 standard. Prepare reference mortar, mortar mixed with unmodified PP fibers, and mortar mixed with modified PP fibers into test specimens (40mm×40mm×160mm), with a fiber volume fraction of 0.1%. After standard curing for 28 days, test the flexural strength using the universal material testing machine to evaluate the reinforcing effect of the modified fibers on the composite material. [12]

4. Expected Results and Discussion

4.1. Analysis of Synergistic Effects of the Composite Corrosion System

The composite modification system with the optimal parameter combination is expected to achieve a synergistic effect between plasma activation and chemical etching. Compared to single treatment groups, the composite treatment group's fiber surface is expected to form more uniform and controllable micro-nano scale rough structures, with O element content and polar functional group content significantly increased. This indicates that plasma pretreatment effectively improves the reaction efficiency and uniformity of chemical etching, and the modification effect of the composite system is superior to that of single techniques. [13]

4.2. Evolution and Analysis of Modified Fiber Surface Chemical State (XPS)

The XPS spectrum of unmodified PP fibers is expected to show very low O element content (<1%), with the C1s spectrum dominated by the C-C bond (284.8 eV). After single plasma treatment, the O element content is expected to increase to 3%-5%, with characteristic peaks for C-O (286.3 eV) and C=O (288.5 eV) bonds appearing. After single chemical etching, the O element content is expected to be 5%-7%, with polar functional group content slightly higher than the plasma treatment group.

After composite treatment, the O element content is expected to reach 8%-12%, with the characteristic peak intensities for C-O and C=O bonds significantly enhanced. [14] This demonstrates that the composite system successfully introduces a large number of polar functional groups onto the fiber surface through synergistic action, laying the chemical foundation for enhanced surface activity.

4.3. Analysis of Modified Fiber Surface Morphology (SEM) and Elemental Distribution (EDS)

Unmodified PP fiber surfaces are expected to be smooth, with only a few spinning grooves. After single plasma treatment, slight etch pits are expected to appear on the surface, with a slight increase in roughness. After single chemical etching, irregular etch pits are expected to form, but with uneven distribution. [15]

After composite treatment, SEM images are expected to show uniformly distributed micro-nano scale rough structures on the fiber surface, with consistent etch pit size and moderate depth, and no obvious over-etching phenomenon. EDS analysis is expected to show uniform distribution of O elements on the composite-modified fiber surface, with content significantly higher than control groups, proving uniform distribution of polar functional groups on the surface.

4.4. Discussion on Surface Wettability and Activity Enhancement Effects

Unmodified PP fibers are expected to have a water contact angle greater than 90°, exhibiting hydrophobic characteristics. After single plasma treatment, the contact angle is expected to drop to 70°-80°, but gradually recover after 7 days of storage. After single chemical etching, the contact angle is expected to drop to 60°-70°, with stability slightly better than the plasma treatment group.

After composite treatment, the fiber's water contact angle is expected to drop to 40°-50°, with no significant recovery after 30 days of storage. This indicates that composite modification not only significantly improves surface wettability but also enhances the long-term stability of the modification effect. The mechanism lies in: the synergistic effect of the rough structure constructed by the composite system and the large number of polar functional groups enhances the interaction between the surface and water molecules; simultaneously, the stable rough structure formed by chemical etching prevents the loss of active functional groups, ensuring long-term stability. [16]

4.5. Impact of Modification on Fiber Bulk Mechanical Properties

Single filament tensile test results are expected to show that the breaking strength and elongation at break of the composite-modified fibers change by no more than 5% compared to unmodified fibers (no statistically significant difference). This indicates that this composite modification process only acts on the fiber surface without damaging the internal crystalline regions and molecular chain structure, preserving the original excellent mechanical properties of PP fibers and meeting application requirements in fields like composite materials. [17]

4.6. Analysis of Reinforcement Effect and Mechanism in Composites

The 28-day flexural strength of the reference mortar and mortar with unmodified fibers is expected to be similar, with an improvement of less than 5%. The mortar with composite-modified fibers is expected to show a 15%-25% increase in flexural strength, demonstrating a significant reinforcement effect.

Reinforcement Mechanism: The rough structure on the modified fiber surface forms a mechanical interlocking effect with cement hydration products, enhancing physical anchoring force. Simultaneously, the surface polar functional groups chemically interact with components of cement hydration products (e.g., Ca^{2+} , Si-OH in C-S-H gel), forming chemical bonds and enhancing interfacial bonding strength. [18] When the mortar is stressed, the strong interface can effectively transfer stress, fully utilizing the fiber's bridging effect, thereby improving the flexural strength and toughness of the composite material.

5. Conclusions and Outlook

5.1. Research Conclusions

Through systematic literature review, theoretical analysis, experimental plan design, and in-depth discussion of expected results, the following conclusions are drawn:

The proposed composite corrosion system of plasma pretreatment and chemical etching is theoretically and technically feasible for achieving efficient and stable surface modification of PP fibers.

The "plasma activation-chemical etching synergy" mechanism is reasonable. Plasma pretreatment provides active sites for chemical etching, while chemical etching expands the surface rough structure and stabilizes active functional groups, achieving a synergistic improvement in the modification effect.

Expected characterization results will confirm from multiple aspects — chemical state, microstructure, macroscopic performance—that composite modification can significantly enhance the surface activity, wettability, and interfacial bonding strength of PP fibers without damaging their bulk mechanical properties. [19]

This composite corrosion modification technology provides a precise and efficient new pathway for the surface functionalization of PP fibers, promising to promote their application expansion in fields such as filter materials, biomedicine, and composite materials.

5.2. Future Work Outlook

Experimental Verification and Parameter Optimization: Conduct experiments according to the design plan to obtain first-hand data, verify and revise theoretical expectations, and optimize plasma parameters, etchant formulations, and process conditions. [20]

In-depth Mechanism Research: Use methods such as molecular simulation and fine XPS analysis to reveal the synergistic corrosion mechanism at the molecular level and clarify the intrinsic relationship between functional group introduction and rough structure formation.

Development of Eco-friendly Processes: Explore green etchants (e.g., bio-enzymes, ionic liquids) to replace traditional highly corrosive reagents, reducing the environmental impact of the process.

Durability and Application Expansion: Systematically evaluate the performance stability of modified fibers under environments such as humidity, heat, and UV aging; apply modified fibers to specific products (e.g., high-efficiency filter media, biological scaffolds) to verify their practical application value. [21]

References

[1] Amrutha R ,Marulasiddappa B S ,Kuntoji G , et al. Prediction of the Shear Strength of Steel-Fiber-Reinforced Concrete Using a Swarm Intelligence Based Extreme-Learning Machine [J]. International Journal of Concrete Structures and Materials, 2026, 20 (1): 20-20. DOI:10.1186/S40069-026-00888-3.

[2] Zhu Y ,Jia D ,Brigham J , et al. Lattice discrete particle model for reinforced concrete structures: A novel geometrically consistent approach [J]. Engineering Structures, 2026, 351 121989-121989. DOI:10.1016/J.ENGSTRUCT.2025.121989.

[3] Sun G ,Liu Z ,Pei K , et al. Multi-scale synergistic toughening of steel slag-based cementitious materials: Mechanisms and design via polypropylene fiber, rubber powder and GGBS [J]. Construction and Building Materials, 2026, 506 144914-144914. DOI:10.1016/J.CONBUILDMAT.2025.144914.

[4] Wu A ,Wang A . Experimental Study on Optimization of Mechanical Properties of Fiber-Reinforced Lightweight Concrete [J]. Journal of Civil and Transportation Engineering, 2025, 2 (4): DOI:10.62517/JCTE.202506405.

[5] Zhao Q ,Yang Z ,Zhang X , et al. An Experimental Study on the Mechanical Properties and ANN-Based Prediction of a Tensile Constitutive Model of ECCs [J]. Polymers, 2025, 17 (23): 3183-3183. DOI:10.3390/POLYM17233183.

[6] Yu Y ,Li S ,Wang L , et al. Prediction and interpretation of bond strength between FRP bars and fiber reinforced concrete using machine learning and Shapley Additive exPlanations Analysis [J]. Construction and Building Materials, 2025, 496 143797-143797. DOI:10.1016/J.CONBUILDMAT.2025.143797.

[7] Soliman E O ,Refai E A ,Sorelli L . Shear strengthening of RC beams with fabric-reinforced cementitious matrix: analytical modeling and machine learning approaches [J]. Composite Structures, 2025, 373 119595-119595. DOI:10.1016/J.COMPSTRUCT.2025.119595.

[8] Jiang Q ,Li X ,Zhang S , et al. Pultrusion Process of Thermoplastic Composites[C]// Zhejiang Sci-Tech University,Textile Bioengineering and Informatics Society,The University of Manchester,State Key Laboratory of Bio-based Fiber Materials,Zhejiang Provincial lnnovation Center of Advanced Textile Techonology. Textile Bioengineering and Informatics Symposium Proceedings 2025. Tianjin Key Laboratory of modern electromechanical equipment technology;School of Mechanical Engineering,Tiangong university;Shaoxing Keqiao Institute of Tiangong University;, 2025: 87-94. DOI:10.26914/c.cnkihy.2025.057458.

[9] Jafar A A ,Moghaddam G N ,Arabshahi A , et al. The influence of small fiber deviation on the behavior of CFRP confined concrete cylinders: an experimental study [J]. Multiscale and Multidisciplinary Modeling, Experiments and Design, 2025, 8 (9): 412-412. DOI:10.1007/S41939-025-00999-6.

[10] Zhang P ,Zhang L ,Wang K , et al. A state-of-the-art review on abrasion resistance of concrete [J]. Journal of Building Engineering, 2025, 111 113277-113277. DOI:10.1016/J.JOBE.2025.113277.

[11] Chirdeep N ,Gangwar M ,Shekhar S , et al. Machine learning-based prediction of failure modes and damage thresholds of corroded bridge piers [J]. Structures, 2025, 79 109483-109483. DOI:10.1016/J.ISTRUC.2025.109483.

[12] Li J ,He C ,Wei Y , et al. Failure Behavior of Damaged Reinforced Concrete Pipe Rehabilitated with Fiber-Reinforced Mortar Lining [J]. Materials, 2025, 18 (13): 3130-3130. DOI:10.3390/MA18133130.

[13] Yu X ,Khodadadi N ,Song A , et al. Prediction and analysis of punching shear capacity in steel fiber reinforced concrete slab using machine learning [J]. Results in Engineering, 2025, 27 105646-105646. DOI:10.1016/J.RINENG.2025.105646.

[14] Domski J ,Lehmann M ,Sanok A , et al. Overview of Torsion Tests on Fiber-Reinforced Concrete Beams [J]. Materials, 2025, 18 (11): 2452-2452. DOI:10.3390/MA18112452.

[15] Xu Y ,Feng D . Enhancing impact resistance of fiber‐reinforced polymer composites through bio‐inspired helicoidal structures: A review [J]. Polymer Composites, 2025, 46 (7): 5823-5856. DOI:10.1002/PC.29352.

[16] Ashteyat A ,Shhabat M ,Alkhalaileh A , et al. Behavior of ultra-high-performance concrete under elevated temperatures: A comprehensive review of mechanical, physical, thermal, and microstructural properties [J]. Results in Engineering, 2025, 26 104960-104960. DOI:10.1016/J.RINENG.2025.104960.

[17] Ruan B ,Li J ,Cheng Y , et al. Orthogonal investigation of factors influencing the splitting tensile strength of cemented aeolian sand reinforced with hybrid fibers [J]. Case Studies in Construction Materials, 2025, 22 e04596-e04596. DOI:10.1016/J.CSCM.2025.E04596.

[18] Dai H ,Qiu C ,Han Y , et al. A Review of Research on the Stress Performance of Concrete Beams with FRP Bars Instead of Steel Bars [J]. International Core Journal of Engineering, 2025, 11 (3): 65-72. DOI:10.6919/ICJE.202503_11(3).0008.

[19] Bencomo C A N ,Alegria C O ,González R E , et al. Stress-strain Analysis of Concrete Reinforced with Metal and Polymer Fibers [J]. Journal of Building Technology, 2025, 7 (1): DOI:10.32629/JBT.V7I1.3325.

[20] Wang M . Degradation of Polymers and the Improvements of Polybutylene Terephthalate/Polyethylene Glycol Terephthalate Composite-material[C]// Department of Chemistry & Department of Chemical, Biological and Materials Engineering, University of South Florida,GSES, Tohoku University. Proceedings of the 3rd International Conference on Materials Chemistry and Environmental Engineering（part1）. Dalian No.24 High School;, 2023: 59-64. DOI:10.26914/c.cnkihy.2023.100671.

[21] Bocharnikova N E ,Lysak V G ,Lysak A I , et al. Functional Materials Based on Nanoparticle Modified Polypropylene Fibers [J]. Micro and Nanosystems, 2021, 13 (4): 393-404.

Global Academic Frontiers, Vol. 4, Issue 2, 2026, pp. 24-29 Print ISSN 2995-5688 Online ISSN 2995-570X
DOI: https://doi.org/10.5281/zenodo.20605613

Blockchain Electronic Bills of Lading in Cross-Border Trade: Development, Challenges, and Governance Responses

Jiayi Luo [1,2,3] Kaili Sun [1,2,3,*] Yuan Gao [1,2,3]

[1] College of International Economics & Trade, Ningbo University of Finance & Economics, Ningbo 315175, Zhejiang, China
[2] Ningbo philosophy and social science key research base "Research Base on Digital Economy Innovation and Linkage with Hub Free Trade Zones", Ningbo 315175, Zhejiang, China
[3] Ningbo Philosophy and Social Sciences Key Laboratory "Bulk Commodity Industry Chain and Business Big Data Laboratory", Ningbo 315175, Zhejiang, China
*Corresponding author Email: notbadjoey11@gmail.com
Received 1 April 2026; Accepted 29 May 2026; Published 9 June 2026

Abstract: With the sustained advancement of digital trade and the digital transformation of international shipping, blockchain electronic bills of lading, characterized by decentralization, immutability, traceability, and efficient circulation, have gradually become an important direction for the digital replacement of traditional paper bills of lading. However, the promotion of blockchain electronic bills of lading in cross-border trade still faces multiple practical obstacles. On the one hand, existing legal norms lack clear provisions on their legal nature, function as documents of title, and negotiability, resulting in insufficient institutional support. On the other hand, the transparency and multi-party data-sharing mechanism of blockchain have also brought risks such as the leakage of trade secrets, inadequate privacy protection, and difficulties in cross-border data governance. Meanwhile, the coexistence of real-time cross-border capital flows and reliance on intermediary platforms has posed challenges to traditional financial regulation, including delayed regulatory responses, insufficient rule coordination, and weak collaborative supervision. In light of this, coordinated efforts should be made in improving legal rules, strengthening data security governance, and enhancing cross-border financial regulatory cooperation, so as to promote the standardized application and sound development of blockchain electronic bills of lading in cross-border trade.

Keywords: blockchain electronic bill of lading; legal regulation; data security; financial regulation

1. Introduction

With the rapid development of digital trade, the digital transformation of international cargo transport documents has become a major trend in global shipping and cross-border trade (Pang et al., 2026). In recent years, the international shipping industry has significantly accelerated the standardization, platformization, and interoperability of electronic bills of lading. In 2022, BIMCO, DCSA, FIATA, ICC, and SWIFT jointly established the Future International Trade Alliance (FIT Alliance) to promote a unified-standard electronic bill of lading system and enhance data interconnectivity and institutional coordination across platforms and stakeholders. According to the 2024 Global Electronic Bill of Lading Survey released by ICC and other organizations, the overall adoption rate of electronic bills of lading increased from 33.0% in 2022 to 49.2% in 2024, while the proportion of "dual-track users" using both paper and electronic bills of lading rose from 28.0% to 41.7%. Among respondents still using only paper bills of lading, 74.7% indicated plans to switch to electronic bills of lading. This shows that electronic bills of lading have entered a stage of accelerated adoption, although their further development remains constrained by institutional and governance conditions. The implementation of blockchain electronic bills of lading in cross-border trade is not merely a technical issue; it also involves complex matters such as the determination of legal attributes, data security protection, and cross-border financial regulatory coordination. Therefore, on the basis of reviewing their current development status, it is necessary to further analyze the practical dilemmas of blockchain electronic bills of lading and propose corresponding improvement paths.

2. Challenges in the Application of Blockchain Electronic Bills of Lading in Cross-Border Trade

2.1. Inadequate Legal Framework and Unclear Legal Nature of Electronic Bills of Lading

As a product of the deep integration of information technology and international trade, blockchain electronic bills of lading are still at an exploratory stage of development in China (Fu & Zhang, 2025). By contrast, the Maritime Code of the People’s Republic of China (hereinafter the “Maritime Code”), adopted in 1992 and brought into force in 1993, was enacted well before the emergence of such technologies as blockchain, smart contracts, and electronic bills of lading. Given the inherent lag of the law and the fact that blockchain electronic bills of lading involve emerging technologies (Liu, 2020), the traditional legal framework has difficulty accommodating their technical features. Consequently, the Maritime Code does not provide explicit definitions of blockchain, electronic bills of lading, or related new technological concepts, leaving the legal regulation of blockchain electronic bills of lading largely underdeveloped (Shan & Hu, 2024). Article 71 of the Maritime Code provides that a bill of lading is a document serving as evidence of the contract of carriage of goods by sea, the receipt of the goods by the carrier, or the loading of the goods on board, and by which the carrier undertakes to deliver the goods against surrender of the document. This provision does not specify the form in which a bill of lading must exist; rather, it only establishes that the bill of lading functions as the document entitling its holder to claim delivery of the goods. In other words, the holder of the bill of lading is entitled to demand delivery from the carrier. Against this background, the status of an electronic bill of lading as a document of title remains unclear under the current legal framework. The function of serving as a document of title is the prerequisite for negotiability. Traditional bills of lading may be transferred or pledged through endorsement, thereby playing a central role in trade settlement and secured financing. If blockchain electronic bills of lading cannot be legally recognized as having this essential function, their conventional core roles in trade settlement, financial pledge, and related commercial transactions will inevitably be constrained by legal obstacles (Balci & Surucu-Balci, 2021).

2.2. Heightened Privacy Risks under Data Transparency and Multi-Party Sharing Mechanisms

The inherent transparency of blockchain-based data is a double-edged sword. On the one hand, information sharing can reduce transaction costs, improve transaction efficiency, and accelerate the circulation of corporate funds (Pang et al., 2024). On the other hand, this very transparency may render transaction data visible to all nodes on the chain, making commercially sensitive information contained in bills of lading—such as cargo details and pricing—more vulnerable to unauthorized access. Although such data are shared transparently on-chain, firms are generally unwilling to expose their supply chain details or customer information to competitors (Dutta et al., 2020). For example, the disclosure of logistics routes may allow others to infer cost structures, while the leakage of banking transaction information may undermine a firm’s business strategy. In addition, blockchain electronic bills of lading must often be connected to multiple external systems, which inevitably raises issues relating to interface access and data exchange. For instance, in the financial settlement stage of cross-border trade, banks from both countries, third-party payment institutions, customs authorities, and other relevant actors all need to share data. Because blockchain systems may operate under different technical standards, forced interaction frequently requires the opening of API interfaces. Consequently, the question of which party should open its interface becomes a critical issue. If one party opens its system to another, the disclosing party may face a heightened risk of data leakage (Pang et al., 2025a), since customer information within the system may be accessed by multiple participants. This makes it difficult to ensure data privacy. At the same time, once multiple actors are connected to the system, the allocation of rights and responsibilities becomes blurred. This problem is particularly acute in cross-border settings, where differences in legal rules, regulatory policies, and jurisdictional arrangements across countries make it difficult to determine liability and pursue accountability in the event of a data breach.

2.3. Lagging Financial Regulation and Heightened Risks in Cross-Border Capital Flows

Although blockchain electronic bills of lading offer technological advantages in improving transaction efficiency and streamlining settlement procedures, their practical application in cross-border trade has not entirely eliminated reliance on third-party platforms (Yang, 2018; Pang et al., 2025b). These platforms may become focal points of fraud risk. Owing to opaque arrangements between third-party service providers and banks, merchants are often unaware of the specific terms governing their cooperation, which creates information asymmetry and may enable intermediaries to reap excessive profits. For example, a third-party platform may enter into a hidden revenue-sharing agreement with a bank while representing the fees charged to merchants as “mandatory bank charges,” thereby creating new opportunities for rent-seeking and corruption. At the same time, if blockchain electronic bills of lading were to become fully decentralized, operational efficiency and financial security could not necessarily be ensured simultaneously (Zhang & Miao, 2025). This gives rise to a series of potential consequences, including the financial risks associated with near-instant cross-border settlement through blockchain networks. Under the SWIFT system, international remittances typically take three to five working days to reach the recipient, whereas once blockchain-based interfaces are opened, cross-border transfers may be completed within seconds. However, traditional state-centered financial regulatory mechanisms often struggle to keep pace with such speed (Nguyen et al., 2022), thereby creating a regulatory time gap that may facilitate illicit activities such as money laundering. In the context of cross-border trade, capital can move across borders with little friction, while regulation remains territorially bounded. At present, regulatory standards for cryptocurrencies and related digital financial activities vary considerably from one jurisdiction to another. In particular, some Southeast Asian jurisdictions have not yet established stringent regulatory frameworks in this area, thereby creating regulatory loopholes or “regulatory havens” for cross-border capital flows.

3. Governance Responses

3.1. Establishing a Legal Framework Compatible with Blockchain Electronic Bills of Lading

To address the core problems of legal uncertainty surrounding electronic bills of lading and the unclear status of their function as documents of title, it is necessary to establish a legal framework specifically adapted to blockchain electronic bills of lading. The first priority is to promote the revision of relevant domestic laws and regulations so as to clarify the meaning of blockchain electronic bills of lading, confirm their legal equivalence to paper bills of lading, and recognize that they perform the three essential functions of a bill of lading, namely, serving as evidence of the contract of carriage, as a receipt for the goods, and as a document of title. At the same time, international experience should be drawn upon to incorporate the principles of functional equivalence and technological neutrality (Li & Hu, 2025), thereby constructing a legal regime for electronic bills of lading that is both suited to China’s national conditions and compatible with international rules. This would facilitate the smooth use of blockchain electronic bills of lading in both domestic and international trade. In particular, reference may be made to the principles embodied in the UNCITRAL Model Law on Electronic Transferable Records (MLETR). The principle of functional equivalence means that an electronic record should be accorded the same legal effect as a paper document so long as it is capable of performing the same functions. The principle of technological neutrality means that the law should not prescribe any specific technology for the implementation of electronic bills of lading. In other words, legislation should focus on the legal effects of electronic bills of lading rather than on the technical form through which they are realized, thereby leaving sufficient room for future technological development.

3.2. Improving the Legal Framework for Data Security, Strengthening Technological Oversight, and Clarifying the Allocation of Responsibility

For blockchain electronic bills of lading to be widely applied in cross-border trade, it is essential to ensure that data operate within a secure and stable system environment. Accordingly, greater emphasis should be placed on the supervision of data security, the continuous improvement of the legal framework governing data protection, and the establishment of a clear framework for cross-border data sovereignty (Li et al., 2024). More specifically, regulations on the data security of blockchain electronic bills of lading should be formulated to clarify the classification standards for core data in the shipping industry. Information that does not involve the identity of relevant parties or the security of funds may be permitted to flow across borders, whereas sensitive data that may threaten commercial confidentiality or national security — such as the identity of cargo owners and transaction amounts — should be subject to mandatory local storage, and any cross-border transfer should require approval from the competent national cyberspace authority. At the same time, the legal responsibilities of third-party institutions should be strengthened. Payment institutions and logistics platforms should be required to disclose the logic governing data interface permissions, connect to regulatory blockchain nodes operated by the central bank, and report abnormal access activities in real time. Where data leakage causes significant losses, the responsible parties should be subject to penalties such as fines and business restrictions. In terms of technological oversight, a national-level data security protection network should be established, under which API callers are subjected to multiple layers of authentication and high-risk requests are intercepted in a timely manner. Through a combination of legal boundary-setting and technology-enabled regulatory penetration, the ultimate goal is to ensure that sensitive data remain stored domestically, controlled within the blockchain system, and used in a transparent and accountable manner.

3.3. Improving the Financial Regulatory System and Promoting Coordinated Cross-Border Regulatory Governance

The systemic financial risks associated with blockchain electronic bills of lading — such as fraud by third-party institutions, excessively rapid cross-border capital flows, and inconsistencies in financial regulatory standards across jurisdictions — essentially stem from a structural mismatch between technological efficiency and lagging regulatory systems. In other words, these risks reflect systemic vulnerabilities generated by the gap between rapidly evolving technology and comparatively slow institutional adaptation. Accordingly, the widespread adoption of blockchain electronic bills of lading must be supported by a sound financial regulatory framework and an effective mechanism for cross-border regulatory cooperation (Yao et al., 2026). To address opaque arrangements between third-party platforms and banks, a penetrating supervision mechanism should be established. All participating nodes, including carriers, third-party service providers, and banks, should be required to connect to a cross-border trade big data platform and upload key operational data in real time, thereby reducing the risk of third-party fraud. As for regulatory loopholes in the supervision of cross-border capital flows, these issues cannot be resolved by any single country or regulatory authority acting alone. Governments should therefore work toward global cooperation and jointly establish a cross-border regulatory coordination system. Under such a system, the central banks of participating jurisdictions could deploy regulatory nodes on the blockchain to monitor abnormal transactions in real time and use smart contracts to automatically freeze suspicious accounts where necessary. In addition, with regard to cross-border capital transactions passing through jurisdictions that are not members of the Financial Action Task Force (FATF), a certain proportion of risk reserves could be mandatorily deposited with the Bank for International Settlements (BIS), thereby creating external compliance pressure and encouraging those jurisdictions to strengthen their regulatory frameworks.

Funding: This work is partially supported by the Annual Research Project for Social Organizations of Humanities and Social Sciences in Zhejiang Province (2026N117), Ningbo Philosophy and Social Sciences Laboratory Project and the Research Fund of Ningbo University of Finance & Economics (1320252023).

References

[1] Balci, G., & Surucu-Balci, E. (2021). Blockchain adoption in the maritime supply chain: Examining barriers and salient stakeholders in containerized international trade. Transportation Research Part E: Logistics and Transportation Review, 156, 102539.

[2] Dutta, P., Choi, T. M., Somani, S., et al. (2020). Blockchain technology in supply chain operations: Applications, challenges and research opportunities. Transportation Research Part E: Logistics and Transportation Review, 142, 102067.

[3] Fu, B., & Zhang, C. (2025). Selection of functional equivalence criteria for electronic bills oflading legislation in the context of shipping digitization. Journal of Hainan University(Social Sciences),1-10.

[4] Liu, W. (2020). The application and legal regulation of block chain technology in shipping logistics industry. Nanjing Journal of Social Sciences, (2), 89–94.

[5] Li, W., & Hu, Z. (2025). Systematic expression of legal regime on electronic transport records in the context of shipping digitalization: Comment on the legal regime in the draft revision of China’s Maritime Code. Hebei Law Science, 43(9), 143–162.

[6] Li, J., Wang, Z., Guan, S., et al. (2024). ProChain: A privacy-preserving blockchain-based supply chain traceability system model. Computers & Industrial Engineering, 187, 109831.

[7] Nguyen, S., Chen, P. S. L., & Du, Y. (2022). Risk assessment of maritime container shipping blockchain-integrated systems: An analysis of multi-event scenarios. Transportation Research Part E: Logistics and Transportation Review, 163, 102764.

[8] Pang, Q., Cai, L., Wang, X., & Fang, M. (2024). Digital transformation as the fuel for sailing toward sustainable success: the roles of coordination mechanisms and social norms. Journal of Enterprise Information Management, 37(3), 1069-1096.

[9] Pang, Q., Liu, X., & Su, M. (2025b). Leveraging Digital Intelligence Technologies for Green Shipping: Organization Information Processing and Contingency Perspective. Business strategy and the environment, 34(7), 9023-9039.

[10] Pang, Q., Wang, M., Yao, J., & Fang, M. (2026). Employees’ perceived respect and performance in Logistics 4.0: a dyadic perspective of the congruence between employee voice and supervisor listening. International Journal of Physical Distribution & Logistics Management, 56(2), 224-248.

[11] Pang, Q., Zhang, M., Yuen, K. F., & Fang, M. (2025a). When the winds of change blow: an empirical investigation of ChatGPT’s usage behaviour. Technology Analysis & Strategic Management, 37(12), 3113-3127.

[12] Shan, H., & Hu, X. (2024). Research on the Legal Obstacles and Countermeasures of Blockchain Empowering Chinese Shipping Industry. Journal of Beijing University of Aeronautics and Astronautics(Social Sciences Edition),1-12.

[13] Yang, D. (2018). Supervising and regulating science and technology: Supervisory challenges and dimensional construction of financial technology. Social Sciences in China, (5), 69–91, 205–206.

[14] Yao, J., Pang, Q., Fang, M., & Qiao, G. (2026). Dualistic perspectives of digital marketing strategies and sustainable performance of cultural heritage tourist sites: Based on qualitative and quantitative mixed methods. Journal of Sustainable Tourism, 34(1), 187-212.

[15] Zhang, L., & Miao, W. (2025). Easing regulatory dilemmas for the cross-border data flow of blockchain bills of lading: An analysis based on the “impossible triangle”. Intertrade, (8), 25–35.

Global Academic Frontiers, Vol. 4, Issue 2, 2026, pp. 30-46 Print ISSN 2995-5688 Online ISSN 2995-570X
DOI: https://doi.org/10.5281/zenodo.20605779

Quantitative Forecasting and Development Pathways of the Linkages between the Shellfish Industry and Fishermen's Income in Liaoning Province: An Empirical Analysis Based on the GM(1,1) Model

Zhu shenghu [1*], Chen tian [1], Liu jiawen [1], Gong mali [1], Zhang kaixing [1]

[1] School of Economics and Management, Dalian Ocean University, Dalian, Liaoning 116000, China
*Corresponding author Email: 1299261652@qq.com
Received 4 February 2026; Accepted 3 April 2026; Published 9 June 2026

Abstract: This study takes Liaoning Province, a core fishery region in Northeast China, as a case study to quantify the contribution and long-term impact mechanisms of the shellfish aquaculture industry on regional fishermen's household business income. Addressing the typical characteristics of limited data samples and incomplete system information, the research employs the GM(1,1) prediction model from grey system theory to independently model and forecast shellfish production and fishermen's household business income for the period 2010-2033. The empirical results indicate: using the original, non-translated data, the Liaoning shellfish production prediction model passed the ratio test, with a development coefficient (a) of -0.01885, forecasting a sustained and steady expansion of the industry scale, with production projected to reach approximately 3.19 million tons by 2033. The fishermen's household business income series, due to initial high volatility, required the application of a translation constant C=265,410 to establish a viable GM(1,1) model, which yielded a development coefficient (a) of -0.02986, also predicting a long-term growth trend for income. Model accuracy evaluation showed that the shellfish production forecast had a mean relative error of 4.839%, a posterior variance ratio C of 0.502, and a small error probability P of 0.786, achieving an accuracy grade between "qualified" and "good". Although the income prediction model had a higher mean relative error (20.125%), its posterior variance ratio C was 0.272, and the small error probability P was 1, indicating a robust trend in the forecasted sequence. Integrating a literature review on Liaoning's fishery industrial structure—where the primary sector dominates but the secondary and tertiary sectors' shares are gradually increasing—and fishermen's income composition—where household business income is the core pillar—this study further elucidates the transmission mechanisms through which the shellfish industry influences fishermen's income via multiple pathways, including direct sales, value-added processing, and linkages with recreational fisheries. Finally, based on the forecast results and the current industrial landscape, the study proposes countermeasures and suggestions, such as promoting intensive and ecological shellfish aquaculture, deepening aquatic product processing, fostering industrial integration, and strengthening scientific, technological, and policy support. These recommendations aim to provide a theoretical basis and decision-making reference for the sustainable and inclusive development of the marine fishery economy in Liaoning Province and similar regions in China.

Keywords: Shellfish industry; Fishermen's income; Grey prediction; GM(1,1) model; Liaoning Province; Fishery economy; Industrial structure

1. Introduction

Marine fisheries constitute a critical global source of food supply and a driver of economic growth, holding particular strategic importance for nations with extensive coastlines.[1] As the world’s largest producer and consumer of aquatic products, China relies on the healthy and stable development of its marine fisheries to safeguard the livelihoods of millions of fishermen, sustain the prosperity of coastal regions, and ensure national food security. [2]Liaoning Province—the only jurisdiction in Northeast China with both terrestrial and marine geography—borders the Yellow Sea and Bohai Sea, boasting a mainland coastline of 2,178 km and abundant resources in mudflats, harbors, and shallow seas. [3]These natural endowments provide a solid foundation for the growth of marine fisheries, especially mariculture. Within Liaoning’s diversified fishery sector, shellfish aquaculture (mainly scallops, clams, and oysters) has become a pillar industry due to its broad adaptability, mature cultivation techniques, and stable market demand, exerting substantial influence on the regional fishery economy through both output and value. [4]Fishermen’s income remains a central issue in fishery economics, directly related to social stability in fishing communities and the sustainable development of fisheries. Rising income not only reflects fishermen’s share in industrial growth but also motivates the adoption of sustainable practices and resilience to resource and environmental challenges. However, fishermen’s income is shaped by a complex interplay of factors—resource endowment, market prices, policy interventions, climate conditions, and industrial structure—making it a typical “grey system with poor information,” where known and unknown elements coexist and precise mathematical modeling is difficult. [5]Medium- to long-term trend analysis is particularly challenging due to limited time-series data and nonlinear interactions among fluctuating variables. Thus, scientifically forecasting the future output of Liaoning’s shellfish industry and quantitatively evaluating its potential impact on fishermen’s income is essential for forward-looking policy-making, optimized resource allocation, and sustained income growth.[6] Grey system theory, pioneered by Chinese scholar Professor Deng Julong, offers tools for modeling, forecasting, and decision-making under incomplete information. The GM(1,1) model, in particular, has been widely applied in agricultural and economic forecasting due to its minimal data requirements, computational simplicity, and effectiveness in capturing short-term and trending behaviors. This study integrates grey system theory with industrial economic analysis to develop a comprehensive assessment framework for Liaoning’s shellfish industry and fishermen’s income. The research objectives are fourfold: (1) to construct GM(1,1) models for shellfish production and fishermen’s household business income using 2010–2023 data, validating them through ratio, residual, and posterior variance tests; (2) to forecast both variables for 2024–2033 and elucidate long-term trends; (3) to combine structural analysis of Liaoning’s fishery industry (where the primary sector dominates but secondary and tertiary sectors are rising, reflecting a “left-rotation” optimization trend) with patterns of fishermen’s income composition (household business income being the dominant component) in order to unravel the mechanisms and pathways through which shellfish aquaculture affects income; and (4) to propose policy recommendations for enhancing the quality and income-boosting effects of Liaoning’s shellfish industry. This study represents the first systematic application of the GM(1,1) model to coordinated forecasting of shellfish output and fishermen’s income in Liaoning. Methodologically, it demonstrates effective handling of a poor-information system; analytically, it links micro-level forecasts with macro-level industrial evolution, offering integrated insights. [7]The findings are intended to provide quantitative support for fishery management planning in Liaoning and to serve as a methodological reference for similar studies in other coastal regions.[8]

2. Research Background

2.1 Income Structure of Chinese Fishermen and Its Influencing Factors

The issue of fishermen's income has long been a focus for scholars both domestically and internationally.[9]

According to the classification in the China Fishery Statistical Yearbook, the total income of Chinese fishermen's households primarily derives from several components: household business income, wage income, property income, and transfer income (including production subsidies).[10] Extensive research indicates that household business income holds an overwhelmingly dominant position in fishermen's total income, with its share consistently remaining at a high level close to 90%. This signifies that the operational returns from fishery production activities (including capture and aquaculture) conducted at the household level are the primary determinant of fishermen's income levels.[11] A grey relational analysis of national data from 2008 to 2013 found that, whether measured from the perspective of change rate differences or absolute differences, the relational degree between household business income and fishermen's total income ranked first. Therefore, focusing on changes in household business income is the key entry point for understanding income growth among fishermen. [12]The factors influencing fishermen's income are diverse and complex. Existing studies have primarily explored these from perspectives such as natural resource and environmental constraints, national and local policies, market supply-demand and price fluctuations, and fishermen's own human capital (e.g., education level, skills training). In recent years, with the transformation of fishery development models, the impact of Industrial structure optimization on income has gained increasing attention. [13]Shifting from mere output growth to value enhancement, and from the dominance of the primary industry to the coordinated development of secondary and tertiary industries, has become a new engine for fishery economic growth and fishermen's income increase.[14]

2.2 The Industrial Structure of Liaoning's Fishery and the Position of the Shellfish Industry

Liaoning Province is a traditional major fishery province in China, and its fishery economy exhibits distinct industrial structural characteristics.[15] Within Liaoning's fishery industrial structure, the primary industry, dominated by capture and aquaculture, has long held the main position. However, since 2000, the share of the secondary industry, primarily aquatic product processing, and the tertiary industry, mainly comprising recreational fisheries and aquatic product transportation, has shown an overall increasing trend.[16] The center of gravity of the industrial structure triangle demonstrates a "left-rotation" shift, signaling the ongoing optimization of the industrial structure. Within the primary fishery sector, mariculture has replaced marine capture as the core contributor to both output and value.[17] Data show that the province's total shellfish aquaculture output has reached 2760358 tons. As illustrated in the figure, mariculture output accounts for approximately 80% of the total fishery aquaculture output, with its output value being about twice that of freshwater aquaculture. Among the various categories in mariculture, shellfish aquaculture holds a significant share. Although the literature searched for this study does not provide the precise proportion of shellfish output in Liaoning, reference to predictions from Shandong Province, another major mariculture province, indicates that its shellfish aquaculture output is projected to be substantially higher than that of fish, crustaceans, and others among marine product categories, highlighting the pillar status of shellfish in mariculture. [18]Liaoning Province possesses vast shallow sea and Tidal Flats resources, making it highly suitable for developing shellfish aquaculture. Its shellfish products enjoy a strong reputation in both domestic and international markets and serve as an important source for increasing the income of coastal fishermen.[19]

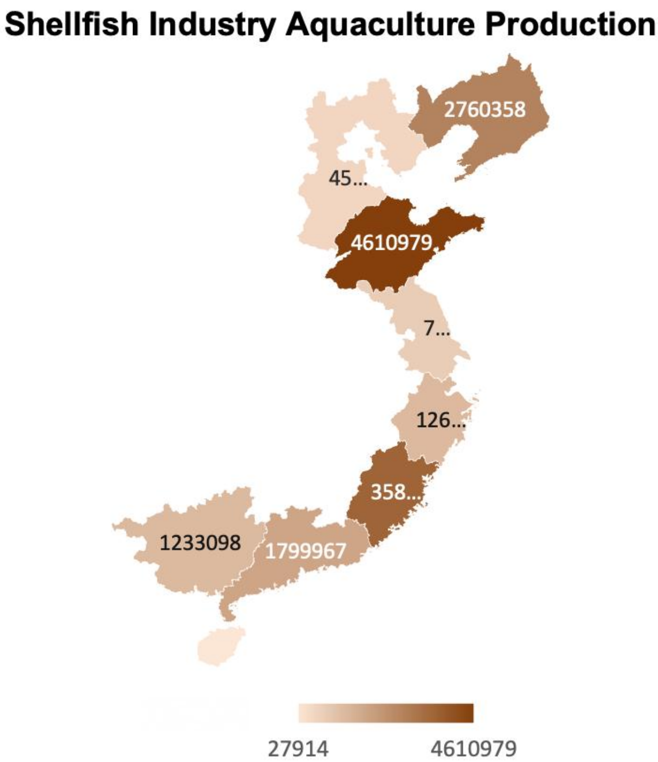


Figure 1： Shellfish Industry Aquaculture Production

3. Research Methodology and Data Sources

3.1 Fundamental Principles and Modeling Procedure of the GM(1,1) Prediction Model

This study employs the univariate first-order grey prediction model, namely the GM (1,1) model, whose core concept is to mitigate randomness and accentuate inherent trends by applying a first-order Accumulated Generating Operation (1-AGO) to the original non-negative data series, and then to fit and forecast using a first-order linear differential equation. The specific modeling procedure, consistent with the technical flow provided: defining the original non-negative series; conducting a ratio test and applying a translation transformation (adding a constant C to all data points if the stepwise ratio falls outside the admissible coverage interval) to ensure model applicability; performing first-order accumulation to generate the accumulated series and then computing the neighboring mean sequence; establishing the grey differential equation (where a is the development coefficient and b is the grey action quantity) and estimating parameters via the least squares method; and finally, deriving the time response function from the whitening equation and restoring the predicted values for the original series through inverse accumulation.

3.2 Model Accuracy Testing System

To ensure the feasibility of the modeling method, a ratio test must be performed on the original data.

1. Define the original data series $X^{(0)}$

$$X^{(0)} = \left(x^{(0)}(1), x^{(0)}(2), \dots, x^{(0)}(n)\right)$$

where$x^{(0)}(k) > 0, \quad k = 1,2, \dots, n$.

2. Calculate the stepwise ratio.

$$\lambda(k) = \frac{x^{(0)}(k-1)}{x^{(0)}(k)}, \quad k = 2,3,\cdots,n$$

3. Ratio Test

All stepwise ratio values should fall within the range of$\left(e^{-\frac{2}{n+1}}, e^{\frac{2}{n+1}}\right)$. If this condition is satisfied, the ratio test is considered passed; otherwise, it is not passed.

4. Translation Transformation (Skip this step if the stepwise ratio test passes)

If the data satisfies the stepwise ratio test, proceed directly to GM(1,1) modeling. If it does not satisfy the stepwise ratio test, perform a shift transformation on the original data.

(1) Add a constant C to all original data points so that the shifted new data satisfies the stepwise ratio test;

(2) Perform GM(1,1) modeling and prediction using the new data

(3) Subtract C from the predicted result to obtain the true prediction

(4) Evaluate model accuracy using the true prediction results and original data.

Tips: No explicit method for determining constant C has been found in literature. Software employs trial-and-error, incrementing C from 1 until a value passes the order test.

1. Determine the original data sequence $X^{(0)}$

$$X^{(0)} = \left(x^{(0)}(1), x^{(0)}(2), \ldots, x^{(0)}(n)\right)$$

Where$x^{(0)}(k) > 0, \quad k = 1,2,\ldots,n$.

2. Generate the cumulative sequence $X^{(1)}$

$$X^{(1)} = \left(x^{(1)}(1), x^{(1)}(2), \ldots, x^{(1)}(n)\right)$$

where

$$x^{(1)}(k) = \sum_{i=1}^{k} x^{(0)}(i), \quad k = 1,2,\ldots,n$$

3. Generate the adjacent mean sequence of$X^{(1)}$ $Z^{(1)}$

$$Z^{(1)} = \left(z^{(1)}(2), z^{(1)}(3), \ldots, z^{(1)}(n)\right)$$

where,

$$z^{(1)}(k) = \frac{1}{2}\left(x^{(1)}(k) + x^{(1)}(k-1)\right), \quad k = 2,3,\ldots,n$$

4. Establish the GM(1,1) model

Based on grey system theory, establish the grey differential equation:

$$x^{(0)}(k) + az^{(1)}(k) = b, \quad k = 2,3,\ldots,n$$

The corresponding whitened differential equation:

$$\frac{dX^{(1)}}{dt} + aX^{(1)} = b$$

where$a$ and$b$ are undetermined parameters,a is termed the development coefficient, and$b$ is termed the grey action.

5. Solve for$a$ and using the least squares method. b

$$(a,b)^T = (B^T B)^{-1} B^T Y$$

where$B$ and$Y$ are defined as:

$$B=\begin{bmatrix}-z^{(1)}(2) & 1\\ -z^{(1)}(3) & 1\\ \vdots & \vdots\\ -z^{(1)}(n) & 1\end{bmatrix},\quad Y=\begin{bmatrix}x^{(0)}(2)\\ x^{(0)}(3)\\ \vdots\\ x^{(0)}(n)\end{bmatrix}$$

6. After solving for a and b, the time response formula is obtained as

$$\hat{x}^{(1)}(k+1)=\left[x^{(0)}(1)-\frac{b}{a}\right]e^{-ak}+\frac{b}{a},\quad k=0,1,2,\ldots,n-1$$

7. Reconstruct the predicted values of the original data sequence

$$\hat{x}^{(0)}(k+1)=\hat{x}^{(1)}(k+1)-\hat{x}^{(1)}(k)=(1-e^{a})\left[x^{(0)}(1)-\frac{b}{a}\right]e^{-ak}$$

where $k=1,2,\ldots,n-1$.

8. Residual and relative error verification

Residual calculation:

$$\varepsilon^{(0)}(k)=x^{(0)}(k)-\hat{x}^{(0)}(k)$$

Relative error calculation:

$$\omega^{(0)}(k)=\left|\frac{x^{(0)}(k)-\hat{x}^{(0)}(k)}{x^{(0)}(k)}\right|$$

If the relative error is $\omega^{(0)}(k)<0.2$, the data is considered to meet general requirements; if the relative error is $\omega^{(0)}(k)<0.1$, the data is considered to meet higher requirements.

9. Grade Ratio Deviation Test

From the original data series $x^{(0)}(k-1)$ and $x^{(0)}(k)$, calculate the corresponding ratios $\lambda(k)$. Then use the development coefficient a to determine the ratio deviation $\rho(k)$.

$$\rho(k)=\left|1-\left(\frac{1-0.5a}{1+0.5a}\right)\lambda(k)\right|,\quad k=2,3\cdots,n$$

If the rank ratio deviation $\rho(k)<0.2$, the data can be considered to meet general requirements; if the rank ratio deviation $\rho(k)<0.1$, the data can be considered to meet higher requirements.

10. Post-calibration error verification: Calculate the post-calibration error ratio C (ratio of residual standard deviation to original data standard deviation) and the probability of minor errors P. According to general standards, accuracy grades are classified into four levels: Excellent (C ⩽ 0.35, P ⩾ 0.95), Good, Acceptable, and Unacceptable.

(1) Calculate the mean of the original data $\bar{x}^{(0)}$

$$\bar{x}^{(0)}=\frac{1}{n}\sum_{k=1}^{n}x^{(0)}(k)$$

(2) Calculate the standard deviation of the original data S_1

$$S_1=\sqrt{\frac{1}{n}\sum_{k=1}^{n}(x^{(0)}(k)-\bar{x}^{(0)})^2}$$

(3) Calculate the residuals between original data and predicted data $\varepsilon^{(0)}$

$$\varepsilon^{(0)}(k)=x^{(0)}(k)-\hat{x}^{(0)}(k)$$

(4) Calculate the mean of the residuals $\bar{\varepsilon}^{(0)}$

$$\bar{\varepsilon}^{(0)}=\frac{1}{n}\sum_{k=1}^{n}\varepsilon^{(0)}(k)$$

(5) Calculate the standard deviation of the residuals S_2

$$S_2=\sqrt{\frac{1}{n}\sum_{k=1}^{n}(\varepsilon^{(0)}(k)-\bar{\varepsilon}^{(0)})^2}$$

(6) Calculate the posterior error ratio C

$$C = \frac{S_2}{S_1}$$

(7) Calculate the probability of small errors p

$$p = P\left\{\left|\varepsilon^{(0)}(k) - \bar{\varepsilon}^{(0)}\right| < 0.6745 S_1\right\}$$

Determine model accuracy based on the calculated values of C and p

Accuracy Grade	C	p
Excellent	$C \le 0.35$	$p \ge 0.95$
Good	$0.35 < C \le 0.5$	$0.8 \le p < 0.95$
Satisfactory	$0.5 < C \le 0.65$	$0.7 \le p < 0.8$
Unacceptable	$C > 0.35$	$p < 0.7$

3.3 Data Sources and Processing

Shellfish Production Data: The study utilizes annual shellfish production figures (in tons) from Liaoning Province between 2010 and 2023 as the primary data series. This data forms the foundation for analyzing the development trends of the shellfish industry.

Fisheries Household Operating Income Data: The study utilized annual per capita (or per household) operating income (in yuan) from Liaoning Province's fishing households during the same period as the raw data series. This data serves as a core indicator reflecting the income derived from production and business activities by fishermen.

Data Preprocessing: Prior to GM(1,1) modeling, all data series underwent a test for stationarity. Based on the test results, income series failing the test underwent a shift transformation (the constant C was determined through trial and error to be 265,410) to meet modeling conditions. All computational processes were implemented using Python programming, ensuring consistency and reproducibility of calculations.

4. Empirical Results and Analysis

4.1 Construction and Validation of Shellfish Production Forecasting Model

First, the original shellfish production time series for Liaoning Province from 2010 to 2023 underwent a unit root test. The calculated unit root test interval was [0, 1]. Empirical calculations showed that all unit root values fell within this interval, eliminating the need for a shift transformation. This indicates that the original data is suitable for directly establishing a GM(1,1) model.

Table 1: Key Parameters and Test Results of the GM(1,1) Model for Shellfish Production in Liaoning Province

Parameter Name	Value	Description
Log-rank Test Interval	(0.875, 1.143)	Test Passed
Shift Amount C	0 (No shift required)	
Development coefficient (a)	-0.01885	Negative values indicate an increasing trend in the sequence
Gray effect quantity (b)	2,053,887.489	
Average Relative Error	4.839%	<20%, meeting general requirements
Average Grade Ratio Deviation	0.042	<0.1, meeting higher requirements

Posterior ratio error (C)	0.502	Within the range 0.5 < C ⩽ 0.65
Probability of Small Error (P)	0.786	In the range 0.7 ⩽ P < 0.8
Comprehensive Accuracy Grade	Qualified	Based on C and P values

Model parameters indicate that the growth coefficient a is negative, suggesting a growth trend in Liaoning Province's shellfish production series.All accuracy metrics meet requirements, with an average relative error of only 4.839% and an average rank deviation of 0.042, demonstrating the model's excellent fit to historical data. The posterior error ratio C is 0.502, and the small error probability P is 0.786. Based on the evaluation criteria, the model's overall prediction accuracy is rated as "Qualified" and suitable for trend forecasting.

4.2 Shellfish Production Forecast Results

Using the established model, shellfish production in Liaoning Province was forecasted for the next decade (2024–2033). This parameter table comprehensively presents the construction process, core parameters, and accuracy verification results of the GM(1,1) model for fishermen's household operational income. Its core characteristic lies in: the model passed rigorous applicability tests and demonstrated exceptional capability in capturing the overall trend of the data.

Table 2: Parameter Table

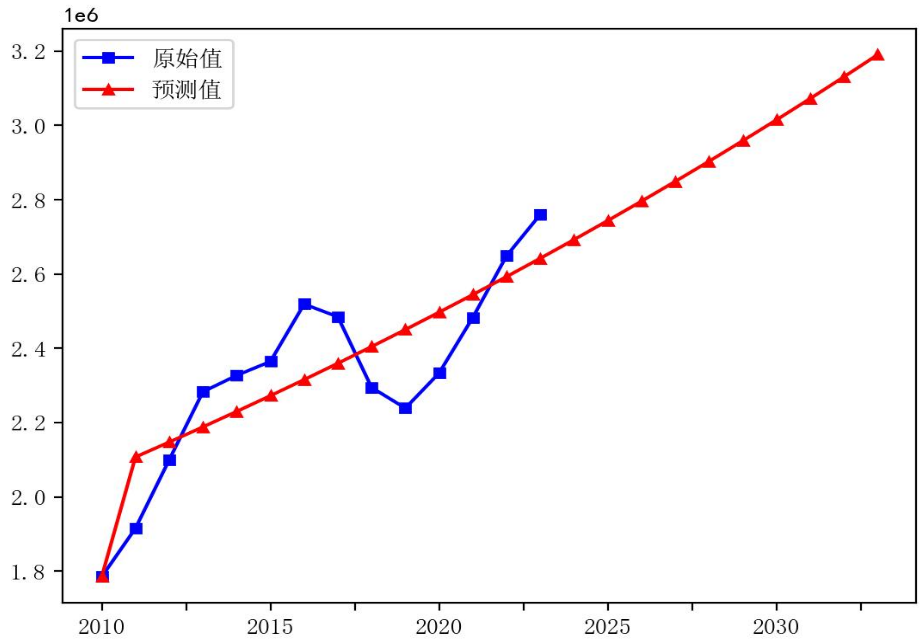
Parameter Name	Value	Description
Level Ratio Test Interval	(0.875, 1.143)	Original sequence failed, shifted sequence passed
Shift Amount C	265, 410	
Growth coefficient (a)	-0.02986	Negative value indicates an increasing trend in the sequence
Grey effect quantity (b)	264,867.272	
Average Relative Error	20.125%	<20%, meeting general requirements
Average Grade Ratio Deviation	0.179	<0.2, meets general requirements
Posterior ratio error (C)	0.272	Within the C ⩽ 0.35 range
Probability of Minor Error (P)	1.000	Within the P ⩾ 0.95 interval
Overall accuracy grade	Excellent	Based on C and P values

Model projections indicate that Liaoning Province's shellfish production will exhibit steady and sustained growth over the next decade. Specifically, output is projected to rise from approximately 2.693 million tons in 2024 to about 3.190 million tons by 2033, achieving cumulative growth of roughly 18.5% during this period with a compound annual growth rate (CAGR) maintained at around 1.7%.This growth rate represents a moderate and sustainable pace that aligns with resource and environmental carrying capacity while matching the rhythm of industrial upgrading. It is consistent with the current macro policy direction in China's marine aquaculture sector, which is shifting from pursuing scale expansion to emphasizing quality, efficiency, and ecological sustainability.

Table 3: Historical Fitting and Future Forecast of Shellfish Production in Liaoning Province (Unit: tons)

Year	Original Value	Predicted Value	Residual	Relative Error (%)	Grade Ratio Deviation
2010	1784996	1784996	0	0	-
2011	1915432	2107334.768	-191902.768	10.019	0.05
2012	2099631	2147435.446	-47804.446	2.277	0.07
2013	2282876	2188299.203	94576.797	4.143	0.063
2014	2327070	2229940.561	97129.439	4.174	0
2015	2364503	2272374.316	92128.684	3.896	0.003
2016	2519090	2315615.547	203474.453	8.077	0.044
2017	2484735	2359679.619	125055.381	5.033	0.033
2018	2294524	2404582.192	-110058.192	4.797	0.104
2019	2238840	2450339.219	-211499.219	9.447	0.044
2020	2333252	2496966.962	-163714.962	7.017	0.022
2021	2482992	2544481.988	-61489.988	2.476	0.042
2022	2648828	2592901.182	55926.818	2.111	0.045
2023	2760358	2642241.75	118116.25	4.279	0.022
2024		2692521.225			
2025		2743757.472			
2026		2795968.699			
2027		2849173.458			
2028		2903390.656			
2029		2958639.558			
2030		3014939.797			
2031		3072311.379			
2032		3130774.69			
2033		3190350.505			

This chart visually presents the forecast results for shellfish production in Liaoning Province based on the GM(1,1) model. The two closely aligned trend lines represent historical actual values and model-fitted/predicted values, respectively. From the historical period spanning 2010 to 2023, the forecast curve demonstrates high consistency with the actual curve, confirming the model's strong fitting accuracy.From 2024 to 2032, the forecast curve exhibits a smooth and steadily upward trajectory, indicating production will grow steadily from approximately 2.75 (in millions of tons) to about 3.24, with a moderate average annual growth rate.This moderate and certain long-term growth trend is clearly visualized in the chart, providing direct quantitative support for the industry's



transition from scale expansion to a high-quality development phase that prioritizes both quality and efficiency.

Figure 2: Shellfish Production Forecast Chart

4.3 Construction and Validation of the Operational Income Forecast Model for Fishery Households

A test for the order of the original sequence of fishermen's household operating income from 2010 to 2023 revealed that some order values exceeded the acceptable coverage range and failed the test. Therefore, a shift transformation method was employed, with the shift constant C determined through trial and error to be 265.410. After re-testing the shifted new sequence, all order values passed the test, enabling the establishment of the GM(1,1) model.

Table 4: Key Parameters and Test Results of the GM(1,1) Model for Liaoning Province Fishermen's Household Business Income

Sequence (k)	Original Sequence	Translated Sequence	Cumulative Series	Adjacent Mean Series
1	21366.4	286,776.4	286,776.4	-
2	25,479.66	290,889.66	577,666.06	432,221.23
3	25,956.48	291,366.48	869,032.54	723,349.3
4	37,594.74	303,004.74	1,172,037.28	1020534.91
5	34,021.21	299,431.21	1,471,468.49	1321752.885
6	23,096.27	288,506.27	1,759,974.76	1615721.625
7	59,708.25	325,118.25	2,085,093.01	1922533.885

8	63,930.06	329,340.06	2,414,433.07	2,249,763.04
9	70,782.48	336,192.48	2,750,625.55	2,582,529.31
10	67,900.17	333,310.17	3,083,935.72	2,917,280.635
11	112,320.33	377,730.33	3,461,666.05	3,272,800.885
12	116,669.75	382,079.75	3,843,745.8	3,652,705.925
13	123,946.76	389,356.76	4,233,102.56	4,038,424.18
14	132,704.78	398,114.78	463,121.73	4432159.95

Analysis of this parameter table indicates that the GM(1,1) predictive model for fishermen's household operating income demonstrates exceptional reliability in capturing trends, though it exhibits reasonable deviations in precisely replicating specific historical data values.The development coefficient a of the income model is also negative, indicating that income growth follows a long-term trend. Although the mean relative error (20.125%) and mean ratio-of-deviations (0.179) only meet general requirements — reflecting significant influence of inter-annual factors (e.g., prices, policies, natural disasters) on income data — the posterior error ratio C is exceptionally low (0.272), and the probability of small errors P reaches 1.signifying that despite isolated point errors, the forecast sequence closely matches the overall fluctuation patterns and trends of the original sequence. The model demonstrates exceptional capability in capturing systematic development trends, achieving an overall accuracy rated as "Excellent." This aligns with the characteristic of grey forecasting models being more adept at trend prediction than precise point value forecasting.

Table 5: Parameter Table

Parameter Name	Value
Lower Limit of Class Ratio Test Interval	0.875
Upper Limit of Ratio Test Interval	1.143
Shift Required	Yes
Shift amount	265410
Development coefficient a	-0.02986
Gray effect coefficient b	264867.272
Average relative error (%)	20.125
Average Grade Ratio Deviation	0.179
Posterior ratio error C	0.272
Probability of small error P	1

4.4 Forecast Results for Fishermen's Household Operating Income

Using the validated model for prediction, the final income forecast is obtained by subtracting the shift amount C from the predicted value.

Table 6: Historical Fitting and Future Forecast Values of Liaoning Fishermen's Household Operating Income (Unit: CNY)

Year	Original Value	Predicted Value	Residual	Relative Error (%)	Grade Ratio Deviation
2010	21366.4	21366.4	0	0	-
2011	25479.66	12142.792	13336.868	52.343	0.136
2012	25956.48	20554.913	5401.567	20.81	0.011

2013	37594.74	29221.989	8372.751	22.271	0.289
2014	34021.21	38151.749	-4130.539	12.141	0.139
2015	23096.27	47352.154	-24255.884	105.021	0.518
2016	59708.25	56831.406	2876.844	4.818	0.601
2017	63930.06	66597.957	-2667.897	4.173	0.038
2018	70782.48	76660.514	-5878.034	8.304	0.069
2019	67900.17	87028.05	-19127.88	28.171	0.074
2020	112320.33	97709.806	14610.524	13.008	0.377
2021	116669.75	108715.307	7954.443	6.818	0.008
2022	123946.76	120054.365	3892.395	3.14	0.03
2023	132704.78	131737.089	967.691	0.729	0.038
2024		143773.895			
2025		156175.515			
2026		168953.005			
2027		182117.758			
2028		195681.511			
2029		209656.356			
2030		224054.754			
2031		238889.54			
2032		254173.942			
2033		269921.587			

Forecast results indicate that the operating income of fishing households in Liaoning Province is projected to increase from approximately ¥143,800 in 2024 to approximately ¥269,900 in 2033, representing an average annual growth rate of about 7.2%. This growth rate significantly exceeds the projected growth rate for shellfish production, suggesting that future increases in fishermen's income will depend not only on expanding production volumes but more likely on value enhancement, industry diversification, and improved efficiency.

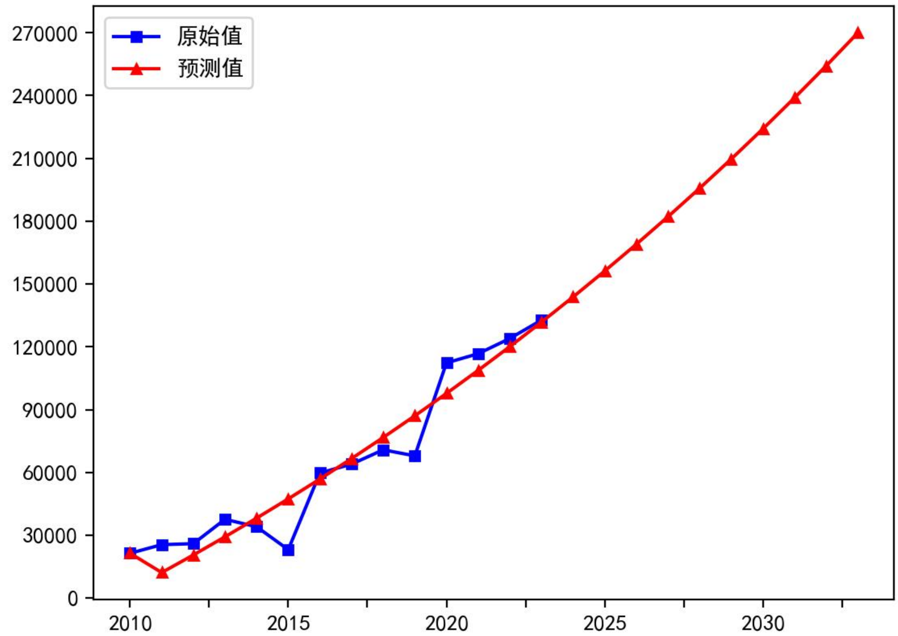


Figure 3: Household Operating Income

Figure 3 illustrates the comparison between actual values and model projections for the period 2010–2031, along with future trends. The overall trend reveals a clear long-term upward trajectory in the income series. A turning point in the model's historical fitting period (around 2017) is evident: prior to this point, projections generally fell below actual values; thereafter, projections began to systematically exceed actual values, with both series maintaining synchronous growth.This characteristic suggests that the forecasting model employed (e.g., the GM(1,1) model) may be more inclined to capture and perpetuate the recently observed accelerating growth trend. Entering the pure forecasting period (post-2024), income is projected to continue growing along a path of stable slope, reaching 260,000 yuan by 2031.

5. Discussion: Mechanisms and Pathways Through Which the Shellfish Industry Influences Fishermen's Income

Although the GM(1,1) model established in this study comprises two independent univariate prediction models, analyzing the forecast trends of shellfish production (representing core industry development) and fishermen's household operational income (representing core income sources) in parallel, combined with the existing characteristics of Liaoning Province's fishery industry structure, allows for logical deduction and in-depth exploration of the underlying linkage mechanisms.[20]

5.1 Direct Contribution Pathway: Production Growth and Primary Product Value Realization

This represents the most fundamental and direct pathway. Shellfish farming constitutes the primary production activity for numerous coastal fishing households in Liaoning. Projections indicate sustained growth in shellfish production, providing a stable output foundation for fishermen engaged in shellfish farming. Under conditions of relatively stable market demand and prices, increased production directly translates into higher sales revenue for farming households, forming a significant component of their household operational income. However, this pathway is notably constrained by market price fluctuations and rising farming costs.[21]

5.2 Value-Added Pathway: Driving Force from Aquatic Product Processing

Analysis of Liaoning Province's fishery industry structure indicates that the aquatic products processing industry (secondary industry) exhibits the highest grey correlation with the total output value of marine fisheries, establishing itself as a pillar industry. As a key processing raw material, the stable growth in shellfish production provides ample supply for downstream processing. Developing deep processing of shellfish — such as producing ready-to-eat products, condiments, and extracting bioactive substances — can multiply product value-added by several to dozens of times.[22]This not only creates more non-farming employment opportunities (contributing wage income) but also enables participating aquaculture fishermen to share in the profits from processing value-added through models like "company + farmer" partnerships and contract farming. This enhances the quality of their operational income. The projected growth rate of fishermen's income exceeds that of production volume, partly attributable to this extended value chain.[23]

5.3 Pathways for Industry Integration: Empowerment Through Recreational Fisheries

As a vital component of the tertiary sector, leisure fisheries in Liaoning Province hold promising development prospects.The shellfish industry can deeply integrate with recreational fisheries to form a new integrated model of "farming-experience-consumption.[24]" Examples include developing tourism projects such as shellfish harvesting, shellfish cuisine at fishing villages, and shellfish cultural exhibitions. This integration not only directly generates tourism service income (included in "other business income" within household business income) but also effectively enhances the local sales value and brand recognition of primary shellfish products.Research indicates that within Chinese fishing households' operating income, the contribution and driving force of "other operating income" now exceed those from fishery production, signaling the diversification and expansion of fishermen's labor and income sources. The integration of shellfish farming with recreational fisheries vividly exemplifies this trend.[25]

5.4 Pathways for Structural Optimization: Promoting Industry Upgrading and Risk Resilience

Monoculture aquaculture is vulnerable to environmental and market risks. Integrating shellfish production with secondary and tertiary industries like processing and recreation will transform fishing households from pure producers into operators and service providers, optimizing their income structure. This diversification not only increases overall income but also enhances resilience against single-industry fluctuations, ensuring long-term income stability.[26]

6. Conclusions and Policy Recommendations

6.1 Research Findings

This study employed the GM(1,1) model from grey system theory to model and forecast shellfish production and operational income for fishing households in Liaoning Province. By integrating industrial structure theory to analyze their intrinsic relationship, the following key conclusions were drawn:

Trend Forecast: The model predicts that both shellfish production and fishermen's household operating income in Liaoning Province will maintain steady growth from 2024 to 2033. Shellfish production is projected to grow at an average annual rate of approximately 1.7%, indicating robust expansion. [27]Fishermen's household operating income is expected to increase at an average annual rate of about 7.2%, a more significant growth rate, suggesting that value-added growth will become the primary driver of future income growth for fishermen.

Regarding model validity: Both constructed GM(1,1) models passed rigorous statistical tests.The shellfish yield model demonstrated high fitting accuracy, achieving an overall rating of "Satisfactory." Although the fisher income model exhibited significant errors at individual points, it excelled in capturing the overall trend (posterior error ratio $C=0.272$, probability of small error $P=1$), earning an overall rating of "Excellent." This validates the applicability and reliability of grey prediction models in handling such "poor information" economic sequences.[28]

Regarding the impact mechanism: Analysis indicates that the shellfish industry influences fishermen's income through a multi-path composite process. It not only contributes to basic income through direct yield growth but, more importantly, drives the development of the aquatic product processing industry (secondary industry) and recreational fisheries (tertiary industry). This achieves value-added growth, industrial integration, and structural optimization, thereby opening broader and more sustainable income channels for fishermen.[29]

6.2 Policy Recommendations

Based on the above conclusions, the following recommendations are proposed to enhance the wealth-generating effects of Liaoning Province's shellfish industry and promote high-quality development of the fishery economy:

Promote Quality Enhancement, Efficiency Improvement, and Green Development in Shellfish Aquaculture: While ensuring stable yield growth, greater emphasis should be placed on developing ecologically sound aquaculture models. Promote new technologies such as standardized pond renovation, shallow-sea ecological raft aquaculture, and integrated multi-trophic aquaculture (IMTA) to reduce environmental impact and enhance shellfish quality and safety standards.Strengthen breeding programs and disease prevention systems to safeguard the industry's foundational security. This aims to solidify the "direct contribution pathway," ensuring the profitability and sustainability of primary production.[30]

Vigorously Support and Innovate Aquatic Product Processing: Develop preferential policies to guide capital investment toward high-value shellfish processing and new product R&D. Support processors in establishing standardized raw material production bases and creating robust benefit-sharing mechanisms (e.g., guaranteed purchase prices, profit-sharing) with farmers, enabling fishermen to capture greater profits from processing. This is central to strengthening the "value-added pathway" and boosting overall industry returns.

Deepening the integrated development of shellfish industries and recreational fisheries: Plan and construct a series of "shellfish-themed" recreational fishery bases or marine ranch demonstration zones integrating shellfish farming, sightseeing experiences, culinary culture, and science education. Design diverse participatory activities, build distinctive regional brands, and effectively convert tourist traffic into service income for fishermen. This initiative is a key measure to expand the "industrial integration pathway" and diversify fishermen's income sources.

Strengthen technological support and comprehensive service systems: Increase investment in scientific research covering shellfish farming techniques, processing technologies, and resource conservation. Establish a robust market information and technical service network spanning production, logistics, and sales to help fishermen mitigate market risks and improve operational decision-making. Concurrently, enhance vocational skills training for fishermen to facilitate their transition into new roles as professional fishermen or service providers in the tertiary sector.

Refine industrial policies and safeguard mechanisms: Continue implementing and optimizing productive subsidies like fishery fuel price subsidies. Develop targeted support measures such as shellfish farming insurance and preferential credit for processing enterprises. Strengthen safeguards for aquaculture rights in water areas and tidal flats to stabilize fishermen's production expectations. Through policy guidance, continuously optimize the fishery industry structure toward increasing the share of secondary and tertiary industries, creating a more favorable macro-industrial environment for fishermen's income growth.

Methodologically, this study provides a feasible framework for quantitatively analyzing the relationship between regional specialty industries and resident income.Future research could collect longer time-series data and explore incorporating multivariate grey models (GM(1,N)) to include additional factors like market prices, production costs, and policy dummy variables. This would enable more precise characterization of the complex dynamics through which the shellfish industry influences fishermen's income. Additionally, comparing Liaoning's predictive results with other major shellfish-producing provinces like Shandong and Fujian could help distill more universally applicable development patterns.

References

[1] Zhang Y Z , Xue C , Chen W G .A comparative study on the measurement of sustainable development of marine fisheries in China[J].Ocean & coastal management, 2024, 247(Jan.):106911.1-106911.9.DOI:10.1016/j.ocecoaman.2023.106911.

[2] Kong F , Cui W .Spatial-temporal evolution and drivers of ecological sustainability of coastal fisheries in China[J].Ocean & Coastal Management, 2024, 258(000).DOI:10.1016/j.ocecoaman.2024.107403.

[3] Chang Y C , Zhang X , Khan M I .The impact of the COVID-19 on China's fisheries sector and its countermeasures[J].Ocean & Coastal Management, 2022, 216:105975-.DOI:10.1016/j.ocecoaman.2021.105975.

[4] Rahman M S , Toiba H , Huang W C .The Impact of Climate Change Adaptation Strategies on Income and Food Security: Empirical Evidence from Small-Scale Fishers in Indonesia[J].Sustainability, 2021, 13(14):7905.DOI:10.3390/su13147905.

[5] Wang P , Mendes I .Assessment of Changes in Environmental Factors Affecting Aquaculture Production and Fisherfolk Incomes in China between 2010 and 2020[J].Fishes (MDPI AG), 2022, 7(4).DOI:10.3390/fishes7040192.

[6] Wang Y , Yang Y , Hu X .The evolution and effectiveness of China's marine carbon sink fishery policies[J].Ocean & coastal management, 2024(Dec.):259.DOI:10.1016/j.ocecoaman.2024.107470.

[7] Xu J , Han L , Yin W .Research on the ecologicalization efficiency of mariculture industry in China and its influencing factors[J].Marine policy, 2022(Mar.):137.DOI:10.1016/j.marpol.2021.104935.

[8] Wang B , Han L , Zhang H .Analysis on the structure effect of marine fishery total factor productivity under high-quality development in China[J].PLOS ONE, 2021, 16.DOI:10.1371/journal.pone.0259853.

[9] Su M , Cheng K , Kong H .Spatial and Temporal Differentiation of the Coordination and Interaction among the Three Fishery Industries in China from the Value Chain Perspective[J].Fishes, 2023, 8(5):21.DOI:10.3390/fishes8050232.

[10] Riantini M , Mardiharini M ,Saptana,et al.Livelihood vulnerability household fishermen household due to climate change in Lampung Province, Indonesia[J].PLOS ONE, 2024, 19(12).DOI:10.1371/journal.pone.0315051.

[11] Wang G , Feng Y .Assessment and prediction of net carbon emission from fishery in Liaoning Province based on eco-economic system simulation[J].Journal of cleaner production, 2023, 419(Sep.20):138080.1-138080.10.DOI:10.1016/j.jclepro.2023.138080.

[12] Wang P , Mendes I .Assessment of Changes in Environmental Factors Affecting Aquaculture Production and Fisherfolk Incomes in China between 2010 and 2020[J].Fishes (MDPI AG), 2022, 7(4).DOI:10.3390/fishes7040192.

[13] Li T , Nie J , Qiu G ,et al.Time Series Forecasting via an Elastic Optimal Adaptive GM(1,1) Model[J].Electronics (2079-9292), 2025, 14(10).DOI:10.3390/electronics14102071.

[14] Wang B , Li H , Sun P ,et al.The effects and paths of regional industrial structure transformation on the fluctuation and quality of the marine fisheries economy in China[J]. 2023.DOI:10.3389/fmars.2022.944630. .

[15] Wahyudi F .Analysis of the Potential of Fishermen's Communities in Increasing Income In Payangan, Sumberejo Village, Ambulu District, Jember Regency[J].PROCEEDING INTERNATIONAL CONFERENCE ON ECONOMICS, BUSINESS AND INFORMATION TECHNOLOGY (ICEBIT), 2023, 4:693-711.DOI:10.31967/prmandala.v4i0.811.

[16] Li T , Nie J , Qiu G ,et al.Time Series Forecasting via an Elastic Optimal Adaptive GM(1,1) Model[J].Electronics (2079-9292), 2025, 14(10).DOI:10.3390/electronics14102071.

[17] ningsih a r , indah p n , fitriana n h i .analisis nilai tambah dan optimasi keuntungan produksi olahan kerang kampak (studi kasus pada umkm bunda surabaya)[j].agroteksos, 2024, 34(2):249.doi:10.29303/agroteksos.v34i2.1108.

[18] Maghfira R , Maulina I , Grandiosa R ,et al.Analysis of Factors Affecting Fishermen's Income in Darmaraja District, Sumedang Regency, Indonesia[J].Asian Journal of Fisheries and Aquatic Research, 2023, 25(3):156-165.DOI:10.9734/ajfar/2023/v25i3675.

[19] Rajabhat S .Factor Effecting the Sustainable Income Generation of the Value Added Products of Local Fishery in Ranong Province, Thailand[J].International journal of health sciences, 2022.DOI:10.53730/ijhs.v6ns2.5193.

[20] Wang B , Han L , Zhang H .The Impact of Regional Industrial Structure Upgrading on the Economic Growth of Marine Fisheries in China—The Perspective of Industrial Structure Advancement and Rationalization[J].Frontiers in Marine Science, 2021, 8(8):693804.DOI:10.3389/fmars.2021.693804.

[21] Lao T , Chen X , Zhu J .The Optimized Multivariate Grey Prediction Model Based on Dynamic Background Value and Its

Application[J].Complexity, 2021, 2021.DOI:10.1155/2021/6663773.

[22] Wang B , Han L , Zhang H .The Impact of Regional Industrial Structure Upgrading on the Economic Growth of Marine Fisheries in China—The Perspective of Industrial Structure Advancement and Rationalization[J].Frontiers in Marine Science, 2021, 8(8):693804.DOI:10.3389/fmars.2021.693804.

[23] Batr E ,Aydn, Theodorou J A ,et al.Mytilus galloprovincialis's role in Integrated Multi-Trophic Aquaculture (IMTA): A comprehensive review[J].Journal of the World Aquaculture Society, 2025, 56(2).DOI:10.1111/jwas.70013.

[24] D'Orbcastel E R , Lutier M , Le Floc'H E ,et al.Marine ecological aquaculture: a successful Mediterranean integrated multi-trophic aquaculture case study of a fish, oyster and algae assemblage[J].Aquaculture International, 2022, 30(6):3143-3157.DOI:10.1007/s10499-022-00953-0.

[25] Teh L S L , Teh L C L , Sumaila U R ,et al.Poverty line income and fisheries subsidies in developing country fishing communities[J].npj Ocean Sustainability, 2023.DOI:10.21203/rs.3.rs-2731208/v1.

[26] Xu J , Han L , Yin W .Research on the ecologicalization efficiency of mariculture industry in China and its influencing factors[J].Marine policy, 2022(Mar.):137.DOI:10.1016/j.marpol.2021.104935.

[27] Wang Y , Yang Y , Hu X .The evolution and effectiveness of China's marine carbon sink fishery policies[J].Ocean & coastal management, 2024(Dec.):259.DOI:10.1016/j.ocecoaman.2024.107470.

[28] Wang P , Mendes I .Assessment of Changes in Environmental Factors Affecting Aquaculture Production and Fisherfolk Incomes in China between 2010 and 2020[J].Fishes (MDPI AG), 2022, 7(4).DOI:10.3390/fishes7040192.

[29] Li B , Liu Z .Measurement and Evolution of High-quality Development Level of Marine Fishery in China[J].Chinese Geographical Science, 2022.DOI:10.1007/s11769-022-1263-7.

[30] Zhang Y Z , Xue C , Chen W G .A comparative study on the measurement of sustainable development of marine fisheries in China[J].Ocean & coastal management, 2024, 247(Jan.):106911.1-106911.9.DOI:10.1016/j.ocecoaman.2023.106911.

Global Academic Frontiers, Vol. 4, Issue 2, 2026, pp. 47-54 Print ISSN 2995-5688 Online ISSN 2995-570X
DOI: https://doi.org/10.5281/zenodo.20605921

The Intrinsic Logic and Implementation Paths of Computing Infrastructure Driving the Integration of Digital and Real Economies

Qianlin Zhang [1*], Ling Zhou [1]

[1] School of Economics and Management, GuangXi Normal University, Guilin, 541000, China
*Corresponding author Email: 17776709884@stu.gxnu.edu.cn
Received 28 May 2026; Accepted 2 June 2026; Published 9 June 2026

Abstract: As a new type of infrastructure, computing infrastructure—comprising data centers, intelligent computing centers, and supercomputing centers—plays a pivotal role in driving the deep integration of the digital and real economies. This paper systematically investigates the intrinsic logic and mechanisms through which computing infrastructure promotes digital-real economy integration. It constructs a three-dimensional analytical framework encompassing technological empowerment, organizational response, and ecological synergy. The findings indicate that: (1) The technological empowerment mechanism lowers the threshold for real economy enterprises to adopt digital technologies and unlocks the value of data elements, enabling inclusive and intelligent access to computing power. (2) The organizational response mechanism optimizes resource allocation and improves corporate governance by easing financing constraints, curbing the tendency of enterprises to shift from real to virtual activities, and enhancing information transparency. (3) The ecological synergy mechanism, built upon an open-source innovation commons, facilitates cross-regional and cross-industry knowledge spillovers and expands innovation networks. Based on these theoretical insights, the paper proposes a collaborative governance framework of “government guidance, market drive, and social participation,” which includes optimizing the spatial layout of computing infrastructure, strengthening institutional linkages between universal computing access and open-source sharing, and implementing differentiated industrial and regional policies. This study provides theoretical support and policy references for advancing digital-real economy integration and cultivating new quality productive forces.

Keywords: computing infrastructure; digital-real economy integration; technological empowerment; ecological synergy

1. Introduction

The real economy is the foundation of a nation's economy and serves as the "ballast stone" for stable economic operation. Concurrently, the rise of the digital economy is profoundly reshaping the global economic landscape, becoming a key force in reallocating production factors and restructuring industrial structures. Deepening the integration of the real and digital economies is not only a strategic choice for seizing new opportunities presented by the latest round of technological revolution and industrial transformation but also an intrinsic requirement for developing new quality productive forces and promoting high-quality development . However, advancing this integration faces a fundamental challenge: how to effectively unleash the value of data elements and embed digital technologies into every link of the real economy. Data elements possess economic attributes such as non-rivalry, increasing returns to scale, and positive externalities, but their value realization is highly dependent on robust computing, transmission, and storage capabilities. In this context, the importance of computing infrastructure becomes increasingly evident. As a new type of infrastructure centered around data centers, intelligent computing centers, and supercomputing centers, it integrates information computing power, network carrying capacity, and data storage capacity, gradually becoming the key foundation for overcoming the "last mile" bottleneck of digital-real economy integration.

In recent years, China has continuously strengthened its strategic deployment of computing infrastructure. In 2023, the Ministry of Industry and Information Technology, along with five other departments, jointly issued the "Action Plan for High-Quality Development of Computing Infrastructure," explicitly stating the goal to "promote the high-quality development of computing infrastructure and fully leverage its driving role in the digital economy." In 2026, the "15th Five-Year Plan" further emphasized "fully implementing the 'AI+' action," "strengthening computing facility support," and "promoting deep integration of the real and digital economies." Meanwhile, the "East Data, West Computing" project has been fully launched, with eight national computing hub nodes and ten data center clusters successively established, accelerating the formation of a national integrated computing network. Behind these policy deployments lies a core theoretical question that urgently needs answering: Through what mechanisms and under what conditions can computing infrastructure effectively promote the integration of the real and digital economies?

Theoretically, the core of digital-real economy integration lies in the technical synergy and complementarity between real industries and digital industries, ultimately leading to the formation of common technologies through boundary fusion . This process requires both the proactive introduction of digital technologies by real industries to transform traditional production functions and the validation and iterative upgrading of digital industry achievements in real-world scenarios. Computing infrastructure plays a dual empowerment role in this regard: on the one hand, it provides affordable, low-cost high-performance computing resources to real enterprises, lowering the technical barriers and financial pressures of digital transformation; on the other hand, by building an open and shared computing network and an open-source innovation ecosystem, it attracts digital technology developers, research institutions, and industry chain participants to collaborate, creating a virtuous cycle of knowledge spillover and technology diffusion. Therefore, computing infrastructure is not merely a physical carrier of computing power but also an innovative public good embedded with institutional design and governance rules.

Based on this, this paper focuses on the research question of how computing infrastructure promotes the integration of the real and digital economies. It attempts to construct a three-dimensional analytical framework encompassing technological empowerment, organizational response, and ecological synergy. It systematically explains the theoretical logic and empirical evidence through which computing infrastructure promotes deep integration by unleashing the information and knowledge value of data elements, driving data element marketization and distributed innovation, and optimizing corporate governance and industrial coordination. The conclusions will provide theoretical support and policy references for optimizing China's computing infrastructure layout, building a national integrated computing network, and accelerating the cultivation of new quality productive forces.

2. Literature Review

Research on computing infrastructure construction mainly unfolds across three dimensions: micro-level enterprise effects, industrial technology integration and innovation network evolution, and green transformation and competitive advantage reshaping.

2.1.Micro-level Enterprise Effects of Computing Infrastructure: Productivity, Digital Transformation, and Technological Innovation

A substantial body of empirical research confirms that computing infrastructure construction can generate significant productivity-enhancing and technology-empowering effects at the micro-enterprise level. Studies have found that the commissioning of national supercomputing centers significantly boosts corporate total factor productivity, an effect closely related to the level of enterprise intelligence. The underlying mechanisms primarily involve promoting cooperative innovation and adjusting the skill structure of the corporate workforce (Min etal. , 2026). Regarding digital transformation, improvements in regional computing infrastructure significantly drive corporate digital transformation. This effect manifests both as substantive transformation that enhances long-term corporate value through technological upgrades and as strategic transformation that improves information disclosure quality. The former is achieved through deepening R&D and citing digital patents, while the latter is driven by signaling and legitimacy pressures (Wu etal. , 2023). Furthermore, computing infrastructure construction significantly promotes corporate AI technology development by reducing management costs, easing financing constraints, and enhancing digital technology capabilities. This effect is particularly pronounced among small and medium-sized enterprises (SMEs), manufacturing firms, and technology-intensive industries (Zhao & Dong, 2025). Additionally, computing infrastructure can curb the "shifting from real to virtual" tendency of corporate funds by lowering the threshold for intelligent transformation and guiding firms towards digital asset investment. Simultaneously, by empowering fintech development and alleviating financial resource misallocation, it curbs corporate financialization motives. This governance effect is more pronounced in non-state-owned enterprises, firms in core digital industries, and regions with better data ecological environments (Jiang, 2025).

2.2.Computing Infrastructure Driving Technology Integration between Real and Digital Industries and the Evolution of Innovation Networks

The core of digital-real economy integration lies in the deep penetration and synergistic complementarity between real industries and digital industries at the technological level. Research indicates that computing infrastructure significantly promotes technology integration between real and digital industries. The intrinsic mechanisms can be explained from two dimensions: "unleashing information value" and "extracting knowledge value." On one hand, computing infrastructure, through the marketization of data elements, expands the scope of information search, improves the quality of information matching, and accelerates the release of the information value of data elements. On the other hand, through distributed innovation, it breaks traditional linear innovation models, forming decentralized, highly interactive collaborative innovation networks that facilitate the transfer and integration of tacit and explicit knowledge among different actors (Shi etal. , 2020). These effects are more pronounced in key supported industries, regions with strong intellectual property protection, and areas with a strong willingness to invest in digitalization. At the level of industrial innovation networks, research using the construction of supercomputing centers as a quasi-natural experiment finds that computing infrastructure significantly enhances the linkage strength of a city's future industrial innovation network. The transmission mechanisms include knowledge innovation linkages, innovation factor absorption, and innovation boundary expansion (Li & Xu, 2025). Notably, computing infrastructure mainly strengthens a city's external innovation network connections, while its effect on collaboration among internal innovation actors is limited. This suggests that its innovation network restructuring function is more prominent in breaking through administrative boundaries to establish external connections. Furthermore, some studies propose the concept of an "open-source innovation commons," arguing that only when computing power is supplied as a public good and innovation results are openly shared and fed back into the community platform through open-source rules can computing infrastructure transform from a general public facility into a key hub supporting continuous innovation. The formation of this commons relies on the coupling of three elements: an "intelligent full-stack technology base," "hybrid governance rules," and the "public value of open-source innovation" (Huo etal., 2025).

2.3.Computing Infrastructure Reshaping Corporate Strategic Directions: Green Transformation and Digital Competitive Advantage

In the realm of green and low-carbon transformation, research focusing on listed high-energy-consuming companies finds that computing infrastructure significantly promotes corporate low-carbon transformation. The mechanisms include technological innovation and supervisory governance. Climate policy uncertainty positively moderates this relationship; that is, in environments with high climate policy uncertainty, firms face heightened environmental legitimacy pressures, making the empowering effect of computing infrastructure even more prominent (Liu etal., 2026). This finding suggests that computing infrastructure is not only an efficiency tool but also a strategic resource helping firms cope with external institutional pressures. Regarding digital competitive advantage, research shows that computing infrastructure construction significantly enhances firms' digital competitive advantage by improving operational efficiency and information transmission efficiency. This effect is more pronounced among firms with higher levels of internet adoption, those in non-core digital industries, and those in cities with higher levels of digital infrastructure (Hu etal., 2025). Moreover, in the context of strategic competition between major powers, computing infrastructure construction can promote breakthroughs in key core technologies by curbing corporate financialization tendencies, easing financing constraints, and improving R&D efficiency. This positive effect is stronger in industries affected by tariff shocks, cities designated as computing hub nodes, pilot cities for a new generation of AI development, and firms with strong technological grasp (Yong, 2013).

Existing literature has verified the positive value of computing infrastructure from multiple dimensions, including improvements in corporate productivity, promotion of digital transformation, empowerment of industrial technological innovation, and support for green development. However, regarding the core issue of "how computing infrastructure actually drives digital-real economy integration," current research still has a theoretical gap concerning the exploration of underlying mechanisms, which constitutes the starting point for this paper.

3.Theoretical Mechanisms and Paths for Computing Infrastructure to Promote Digital-Real Economy Integration3.1 Participants

3.1.Technological Empowerment Mechanism: Lowering Transformation Barriers and Unleashing Data Value

The first mechanism by which computing infrastructure promotes digital-real economy integration is technological empowerment, i.e., directly lowering the thresholds and costs for real enterprises to apply digital technologies by providing affordable, efficient, and scalable computing resources. Specifically, computing infrastructure plays a technological empowerment role in the following three aspects. First, the infrastructuralization of computing supply breaks the constraints of enterprise resource endowments. Traditionally, high-performance computing resources are expensive and complex to maintain, affordable only to a few large enterprises or tech companies. Through centralized deployment, large-scale operation, and elastic scheduling, computing infrastructure achieves the "pooling" and "servicification" of computing resources, enabling SMEs to access previously unattainable computing power on a pay-as-you-go basis (Kulshreshtha, 2018). This "universal access to computing" directly alleviates the high upfront investment risk faced by real enterprises in the early stages of digital transformation, encouraging them to experiment with cutting-edge technologies like AI, big data analytics, and digital twins.

Second, computing infrastructure accelerates the value realization process of data elements. Data itself is valueless raw records; only after cleaning, integration, analysis, and mining can it be transformed into valuable information and knowledge. Leveraging its powerful storage capacity and computing speed, computing infrastructure can efficiently process massive volumes of heterogeneous data, converting fragmented data into structured, standardized information products (Sarker etal., 2025). This process not only improves the utilization efficiency of internal corporate data assets but also facilitates the flow and sharing of data across the industrial chain, providing high-quality data fuel for technology integration between real and digital industries.

Third, the synergistic development of computing infrastructure, algorithms, and models fosters an intelligent application ecosystem. Computing power is not just "processing ability"; it is the "engine" for algorithm training and model iteration. With the proliferation of intelligent computing centers and supercomputing centers, the training time for large-scale deep learning models has shrunk from months to days or even hours. This enables real enterprises to obtain customized AI solutions at lower costs (Sharir etal., 2025). For example, manufacturing firms can use public computing platforms to train product quality inspection models, and agricultural firms can develop crop pest recognition algorithms. This synergistic empowerment of "computing + algorithms + data" allows digital technologies to truly embed into the core business operations of the real economy, rather than remaining on the periphery of management informatization.

3.2.Organizational Response Mechanism: Optimizing Resource Allocation and Improving Governance Structures

The promoting effect of computing infrastructure on digital-real economy integration is not only reflected at the technological level but also profoundly impacts the organizational behavior and governance structures of real enterprises. Computing infrastructure reshapes corporate resource allocation logic and strategic decision-making preferences by easing financing constraints, curbing financialization tendencies, and improving information transparency.

First, computing infrastructure significantly eases financing constraints for real enterprises. Information asymmetry is the fundamental reason for the difficulty and high cost of financing for SMEs. Computing infrastructure supports financial institutions in building more accurate corporate credit evaluation models, reducing information friction between banks and firms. Simultaneously, innovative models like supply chain finance and data asset pledge, supported by computing power, expand the boundaries of eligible collateral, making a company's data and technology flows new bases for financing. Easing financing constraints directly increases the long-term capital available for corporate digital transformation and R&D innovation, thereby accelerating the process of digital-real economy integration.

Second, computing infrastructure effectively curbs the "shifting from real to virtual" tendency of real enterprises. For a long time, real enterprises, facing declining profit margins in their main businesses, have allocated substantial funds to financial assets, crowding out real investment. Research finds that computing infrastructure construction, by improving the total factor productivity of main businesses, fundamentally changes the relative returns of financial assets versus industrial investment, thereby inhibiting corporate financialization motives. Specifically, computing-empowered smart manufacturing, flexible production, and precision marketing significantly enhance the profitability and market competitiveness of real enterprises, causing them to refocus on core technology R&D and production process optimization rather than chasing short-term financial gains. This "main business revitalization" effect is the micro-foundation for the sustained deepening of digital-real economy integration.

Third, computing infrastructure improves internal control quality and information transparency for enterprises. According to legitimacy theory, the negative externalities of corporate carbon emissions and digital transformation subject them to strict supervision by the government, investors, and the public. Computing infrastructure provides technical means such as real-time data collection, intelligent monitoring, and blockchain-based notarization, enhancing the traceability and auditability of corporate production and operation activities (Mahendran et al., 2025). This not only helps alleviate principal-agent problems like managerial myopia but also enables firms to more effectively communicate the genuine progress of their digital transformation in capital markets, thereby attracting more long-term investors and strategic partners.

3.3.Ecological Synergy Mechanism: Building an Open-Source Innovation Commons and Expanding Industrial Networks

The highest state of digital-real economy integration is not the digitalization of individual enterprises but the systemic restructuring of the entire industrial ecosystem. Computing infrastructure plays an irreplaceable hub role in promoting ecological synergy, with its core function being to facilitate the formation and evolution of an "open-source innovation commons." Computing infrastructure accelerates cross-regional, cross-industry technology diffusion through knowledge innovation linkages. Empirical research based on supercomputing centers shows that computing infrastructure significantly increases the level of inter-city research collaboration and the number of joint patent applications. Its mechanism lies in reducing the marginal cost of knowledge search and integration, enhancing the effectiveness of long-distance knowledge collaboration (Yang et al., 2024). These knowledge innovation linkages break the traditional constraint of geographical proximity for industrial innovation, enabling western regions or cities lacking innovation resources to access the collaborative innovation network led by computing hub nodes, thus narrowing regional gaps in digital-real economy integration.

Computing infrastructure fosters the agglomeration of talent and capital through the absorption of innovation factors. The construction and operation of computing infrastructure themselves create numerous high-skilled jobs, attracting new types of talent such as data scientists, algorithm engineers, and AI trainers to flow towards computing hub cities (Yang et al., 2024). Concurrently, the public platform nature of computing infrastructure lowers the entrepreneurial barriers for startups and individual developers, fostering a small-scale innovation ecosystem around computing platforms. This coordinated agglomeration of "talent-capital-technology" provides a continuous source of innovative energy for digital-real economy integration.

Furthermore, computing infrastructure achieves a value cycle of "use → contribute back → reuse" through open-source rules. Unlike traditional public infrastructure, computing infrastructure is not merely a one-way supplier of resources. Using open-source large models, open-source algorithm libraries, and open-source datasets as carriers, users of computing infrastructure are also contributors to innovation outcomes. When a firm uses public computing power to train an industry-specific model and open-sources it, other firms can conduct secondary development based on it, creating a multiplier effect for technological iteration. This institutional design of "universal access to computing + open-source sharing" transforms computing infrastructure from a "consumable public resource" into a "self-reinforcing innovation hub," which is a fundamental feature distinguishing it from traditional infrastructure like electricity or transportation.

4.Policy Implications: Building a Collaborative Governance System of "Government Guidance - Market Drive - Social Participation"

Based on the theoretical analysis above, this paper proposes the following policy recommendations for promoting digital-real economy integration driven by computing infrastructure.

First, optimize the spatial layout and supply model of computing infrastructure. Continue advancing the "East Data, West Computing" project, deploying large and ultra-large data center clusters in western regions to leverage their climatic and energy advantages for lower computing costs, while deploying edge computing nodes in eastern regions to meet low-latency application needs like industrial internet and autonomous driving. Simultaneously, establish a unified national computing scheduling platform and trading mechanism to enable efficient cross-regional, cross-entity allocation of computing resources.

Second, strengthen the institutional linkage between "universal access to computing" and "open-source sharing." The government can issue "computing vouchers" or establish open-source contribution reward funds to incentivize firms and developers to contribute their innovation outcomes back to the community in open-source form after using public computing power. Concurrently, establish a sound open-source licensing system, data security and privacy protection rules, and dispute resolution mechanisms for intellectual property to provide legal guarantees for the healthy development of the open-source innovation commons.

Third, implement differentiated industry and regional policies. For manufacturing, technology-intensive industries, and SMEs, priority should be given to providing computing subsidies and technical consulting services to help them overcome the "first hurdle" of digital transformation. For central and western regions and areas with high information costs, investment in computing infrastructure should be increased, and paired east-west cooperation mechanisms should be used to transfer computing application experiences and mature models from the eastern region to the west.

Competing Interests Statement

The authors declare that they have no financial or personal relationships that may have inappropriately influenced them in writing this article.

Data Availability Statement

The authors confirm that the data supporting the findings of this study are available within the article.

Funding: This study was funded by the Innovation Project of Guangxi Graduate Education in 2026 "Research on the Mechanisms, Effects, and Implementation Paths of Computing Power Deployment Empowering Enterprise Investment Efficiency Improvement" (Grant number: None).

References

[1] Min Song, Rihua Huang, Linyuan Hou & Xinyu Liu. (2026). Can computing infrastructure unlock enterprise carbon lock-in? Evidence from National Supercomputing Centers. Journal of Cleaner Production, 547, 147838-147838.

[2] Wu Wenqing, Wang Siqi, Jiang Xin & Zhou Jie. (2023). Regional digital infrastructure, enterprise digital transformation and entrepreneurial orientation: Empirical evidence based on the broadband china strategy. Information Processing and Management, 60(5).

[3] Xuanwei Zhao & Fangzhu Dong. (2025). Digital infrastructure construction and corporate innovation efficiency: evidence from Broadband China Strategy. Humanities and Social Sciences Communications, 12(1), 347-347.

[4] Hui Jiang. (2025). How does computing infrastructure deployment drive corporate digital technology innovation?. Finance Research Letters, 86(PD), 108659-108659.

[5] Shi Guofeng, Ma Zhiyun, Feng Jiao, Zhu Fujin, Bai Xu & Gui Bingxiu. (2020). The impact of knowledge transfer performance on the artificial intelligence industry innovation network: An empirical study of Chinese firms. PloS one, 15(5), e0232658.

[6] Meng Li & Yang Xu. (2025). The Impact of Computing Infrastructure Construction on Innovation in Manufacturing Enterprises: Evidence from a Quasi-Natural Experiment Based on the Establishment of China’s National Supercomputing Centers.Sustainability,17(19),8858-8858.

[7] Chunhui Huo, Shengkai Bian, Di He & Mengxiao Lv. (2025). Research on the impact of the integration of digital economy and real economy on China’s domestic value chain resilience. Digital Economy and Sustainable Development, 3(1), 13-13.

[8] Xinyu Liu, Changxin Xu, Min Song, Jiawen Li & Hanjin Li. (2026). From subsidies dependence to self-reliance: Does computing infrastructure reshape the carbon emission reduction pathway of high-energy-consuming enterprises?. Journal of Cleaner Production, 543, 147658-147658.

[9] Hu Yu, Zou Kaiti & Chen Xiaofang. (2025). The Alchemy of Digital Transformation: How Computing Power Investment Fuels New Quality Productivity. Journal of Theoretical and Applied Electronic Commerce Research, 20(4), 354-354.

[10] Jay Na Lim & Frank Peltner. (2011). Innovation performance of construction enterprises. Construction Innovation, 11(3), 282-304.

[11] K Kulshreshtha. (2018). Adoption of cloud computing by smes-a swot analysis. International journal of engineering research and technology, 3.

[12] Arup Kumar Sarker, Aymen Alsaadi, Niranda Perera, Mills Staylor, Gregor von Laszewski, Matteo Turilli, Ozgur Ozan Kilic, Mikhail Titov, Andre Merzky, Shantenu Jha, Geoffrey Fox. (2025). Radical-cylon: a heterogeneous data pipeline forscientific computing. Lecture Notes in Computer Science, 84-102.

[13] Sharir Or, Peleg Barak, Shoham Yoav. (2020). The cost of training NLP models: a concise overview. arXiv e-prints.

[14] Rakesh Kumar Mahendran, Arafat Khan, Fasee Ullah, Farman Ali & Ahmad Ali AlZubi. (2025). PRISM-IIoT: A holistic approach for privacy preservation in industrial IoT using advanced cryptography and blockchain-enabled auditability framework. Alexandria Engineering Journal, 128, 816-832.

[15] Yang Haodong, Liu Li & Wang Gaofeng. (2024). Does large-scale research infrastructure affect regional knowledge innovation, and how? A case study of the National Supercomputing Center in China. Humanities and Social Sciences Communications, 11(1).

Global Academic Frontiers, Vol. 4, Issue 2, 2026, pp. 55-66 Print ISSN 2995-5688 Online ISSN 2995-570X
DOI: https://doi.org/10.5281/zenodo.20606011

Reputation Systems, Algorithmic Management, and Gendered De-Flexibilization in Platform Work: A Conceptual Analysis

Yuan Gao [1,2*], Jiayi Luo [1,2] , Zhenghang Xu [3]

[1] College of International Economics & Trade, Ningbo University of Finance & Economics, Ningbo 315175, China
[2] Ningbo philosophy and social science key research base "Research Base on Digital Economy Innovation and Linkage with Hub Free Trade Zones", Ningbo 315175, China
[3] Hangzhou Expo Group Co., Ltd., Hangzhou 310000, China
*Corresponding author Email: gaoyuan@nbufe.edu.cn
Received 9 May 2026; Accepted 2 June 2026; Published 9 June 2026

Abstract: Reputation systems have become a central mechanism of platform labor governance. Although digital labor platforms frequently define flexibility as workers' ability to choose when and where to work, this formal discretion is increasingly conditioned by algorithmic rating, ranking, and order-allocation systems. This paper develops a conceptual framework to explain how reputation systems may transform platform flexibility into gendered de-flexibilization. Drawing on labor process theory, algorithmic management research, feminist work-family scholarship, and studies of platform governance, the paper argues that reputation systems do not merely evaluate service quality. Rather, they convert customer feedback into algorithmic signals that influence future access to work, income stability, and workers' practical control over time. The proposed framework identifies a score-order-income-time compensation chain: customer ratings affect reputation scores; reputation scores influence order allocation and platform visibility; reduced orders or penalties affect income; and workers respond by extending working time or increasing availability to restore earnings and reputation. This chain is especially consequential for women platform workers whose time is already constrained by unpaid care responsibilities and household labor. The paper contributes to platform labor studies by conceptualizing flexibility as a conditional and reversible resource, contributes to gender and work-family research by linking algorithmic control to unequal time autonomy, and provides policy implications for transparent scoring, review and appeal mechanisms, anti-discrimination safeguards, and gender-sensitive platform governance.

Keywords: platform economy; algorithmic management; reputation systems; women platform workers; flexible work; de-flexibilization; work-family balance

1. Introduction

Digital labor platforms have become an important form of contemporary work organization. By using app-based interfaces to match customers, clients, and workers, platforms coordinate task allocation, payment, performance evaluation, and customer feedback within highly standardized digital systems (Donovan et al., 2016; West et al., 2018). A major attraction of this model is the promise of flexibility. Workers are commonly told that they may decide when to log on, which tasks to accept, and how much time to devote to paid work. However, this promise is increasingly mediated by algorithmic management. Scheduling, visibility, reward distribution, and sanctions are embedded in platform infrastructures rather than negotiated through visible managerial procedures (Choudary, 2018; Lee et al., 2015; Rosenblat & Stark, 2015). As a result, flexibility cannot be evaluated only in terms of formal freedom to log on and off. It must also be assessed in relation to whether workers can maintain adequate income, reputation, and future access to work when they exercise that freedom.

This issue is particularly important for women platform workers. Across many labor markets, women continue to undertake a disproportionate share of unpaid domestic work, childcare, and eldercare (Alfers, 2016; Churchill & Craig, 2019; Vyas, 2020). Working-time flexibility is therefore not merely a preference for convenience. It is often a condition for remaining attached to paid work while managing household responsibilities and income needs. Work-family research has long shown that schedule control can support labor-market participation, but it also warns that flexibility may become problematic when it is connected to insecure employment, income volatility, or employer-driven scheduling (Golden, 2001; Scandura & Lankau, 1997; Warren, 2021). In platform work, this tension becomes more visible because workers may formally choose their hours while remaining dependent on ratings, order flows, customer demand, and penalty mechanisms. For women who combine platform income with unpaid care, any disruption to ratings or allocation may be experienced not only as income insecurity but also as pressure on rest time, care routines, and work-family boundaries.

Existing research has generated important insights into platform labor, algorithmic management, and reputation systems. Studies have shown that platform work can offer limited autonomy while shifting risk to workers and governing them through ratings, rankings, penalties, and information asymmetries (Aloisi, 2015; Broughton et al., 2016; Rani & Furrer, 2019, 2020). Research on algorithmic management further indicates that digital systems can perform functions similar to human resource management, including matching, monitoring, evaluation, incentives, and sanctions (Choudary, 2018; Lee et al., 2015; Rani & Furrer, 2020; Rosenblat & Stark, 2015). Nevertheless, the gendered temporal consequences of reputation systems remain insufficiently integrated into existing theory. This gap is significant because reputation systems do more than record customer satisfaction. They translate customer feedback into platform decisions about order allocation, income penalties, visibility, and future work opportunities. When negative or biased evaluations reduce access to orders, workers may extend working hours to recover income and repair reputation. For women with care responsibilities, this process can create a distinct mechanism of gendered de-flexibilization.

To address this gap, this paper develops a conceptual framework rather than an empirical test. It asks three theoretical questions: first, how should platform flexibility be conceptualized when access to work is conditioned by reputation metrics; second, through what mechanisms do reputation systems convert customer feedback into algorithmic labor control; and third, why are these mechanisms likely to produce gendered consequences for working time? The paper makes three contributions. First, it conceptualizes platform flexibility as a conditional and reversible resource rather than a fixed attribute of platform work. Second, it places gendered care responsibility at the center of platform labor analysis, showing why time autonomy is unevenly distributed. Third, it theorizes the score-order-income-time compensation chain as a mechanism through which reputation systems reshape workers' practical control over time. The remainder of the paper is organized as follows. Section 2 reviews the relevant literature. Section 3 develops the conceptual framework. Section 4 elaborates theoretical mechanisms and propositions. Section 5 discusses policy and managerial implications. Section 6 sets out a future research agenda, and Section 7 concludes.

2. Literature Review

2.1. Platform Flexibility as a Contested Concept

Flexibility is one of the most influential claims through which digital labor platforms attract workers, but it should not be treated as a natural or stable feature of platform work. In platform discourse, flexibility usually refers to the ability to choose working time, accept or reject tasks, and combine platform work with other responsibilities.

Some studies have emphasized that platform work may lower entry barriers and provide supplementary income, especially for groups excluded from standard employment (Barnes et al., 2015; Wood et al., 2018). However, formal discretion does not necessarily produce substantive control over working time. The key issue is not whether platforms provide any flexibility, but under what conditions workers can exercise that flexibility without losing income, reputation, or future access to work.

A critical reading of platform flexibility begins with the relationship between worker discretion and platform governance. Platforms do not simply match supply and demand. They define the conditions under which workers can access tasks, maintain visibility, avoid penalties, and secure future earnings. Acceptance rules, cancellation mechanisms, customer ratings, dynamic pricing, ranking systems, and penalties all shape the value of a worker's formal choice to work at a particular time (Broughton et al., 2016; Rani & Furrer, 2019, 2020). A worker may be free to stop working, but this decision can become costly if it reduces future allocation or weakens the worker's reputation. Platform flexibility is therefore continually produced through platform rules, data infrastructures, and incentive systems.

This tension is central to debates on algorithmic management. Algorithmic systems often perform managerial functions by recommending or allocating work, monitoring performance, evaluating conduct, distributing rewards, and applying sanctions (Choudary, 2018; Lee et al., 2015; Rosenblat & Stark, 2015; Wood et al., 2018). These functions may improve coordination efficiency, but they also generate information asymmetries because workers may not know how ratings, cancellations, or acceptance histories affect future opportunities. Platform workers can therefore experience autonomy and control simultaneously. They may select their working hours while remaining dependent on algorithmic systems that determine whether sufficient work will be available during those hours.

The concept of contested flexibility helps move the discussion beyond a simple opposition between autonomy and exploitation. Platforms may define flexibility as the ability to log on and off. Workers may define it as the ability to earn sufficient income within available time without unpredictable penalties. Customers may indirectly define it through demand patterns and service expectations. Algorithms then mediate these definitions by determining which workers receive orders, how quickly they must respond, and what consequences follow from negative evaluations. Flexibility is therefore an outcome of interaction among platform rules, customer demand, algorithmic allocation, and workers' economic constraints.

2.2. Gendered Care Responsibility and Time Autonomy

The meaning of flexibility is strongly gendered because workers do not enter platform labor with equal household responsibilities or equivalent control over time. Feminist work-family research has repeatedly shown that women perform a disproportionate share of unpaid domestic labor, childcare, and eldercare (Alfers, 2016; Churchill & Craig, 2019; Vyas, 2020). These responsibilities shape labor-market participation, employment preferences, and exposure to precarious work. For many women, working-time flexibility is not a lifestyle preference. It is a practical requirement for coordinating paid work with care obligations, household labor, and family income needs.

Classic research on flexible work shows that schedule control can support job satisfaction, organizational commitment, and labor-market attachment, especially where workers face family responsibilities (Golden, 2001; Scandura & Lankau, 1997). At the same time, flexibility may involve trade-offs when it is tied to insecure work, unpredictable schedules, or income volatility (Warren, 2021). Childcare costs and insufficient care support can reduce women's labor-market participation, while unstable working time can intensify rather than reduce work-family conflict (Vyas, 2020; Warren, 2021). The central issue is therefore not flexibility in the abstract, but whether workers have reliable time autonomy: the capacity to plan, interrupt, and resume paid work without disproportionate penalties.

Platform work appears to address this need because it promises income without a conventional fixed schedule. Yet recent scholarship warns that platform labor may relocate rather than resolve work-family conflict. Women may work at night, accept tasks around school or care routines, fragment paid work into short intervals, or intensify labor during limited windows of availability (James, 2024; Warren, 2021). These practices show agency, but they also reveal constraint. The burden of making platform work compatible with family life is often individualized. Women must reorganize rest, care, and household time around platform demand rather than receiving institutional support for care responsibilities.

This gendered context changes how algorithmic systems are experienced. Metrics such as response speed, acceptance rate, cancellation rate, and customer satisfaction may appear neutral, yet they privilege workers who can remain continuously available to the market. A worker without care responsibilities may treat platform flexibility as discretionary scheduling. A worker responsible for childcare or eldercare may experience the same platform rules as fragile because a family interruption can affect response time, task acceptance, customer evaluation, and income. If a rating loss requires additional hours to restore income or reputation, women with care duties may need to take that time from rest or domestic routines.

2.3. Reputation Systems as Algorithmic Control

Reputation systems are a key mechanism through which platform flexibility can turn into practical constraint. At first glance, reputation systems appear to solve a market problem by allowing customers to assess service quality, create trust among strangers, and reward reliable workers. However, in platform labor they also perform managerial functions. Customer ratings and feedback are translated into scores, rankings, or reputational indicators that may influence order allocation, platform visibility, penalties, income stability, and the capacity to refuse work (Broughton et al., 2016; Lee et al., 2015; Rani & Furrer, 2019, 2020). Reputation is therefore not only a signal of past performance. It becomes platform-mediated capital that workers must protect to maintain future access to work.

The disciplinary power of reputation systems lies in the chain that connects customer evaluation to working time. A negative rating may lower a reputation score; a lower score may reduce order allocation or trigger financial penalties; reduced orders and earnings may require workers to work additional hours; and additional hours may be needed not only to recover lost income but also to accumulate positive reviews and restore the score. This score-order-income-time compensation chain is central to understanding de-flexibilization. Workers are rarely ordered directly to work longer hours. Instead, the platform architecture makes additional labor a rational response to rating loss, income insecurity, and fear of future exclusion.

Opacity intensifies this control. Workers often do not know how many negative reviews will trigger penalties, how scores are weighted, how long penalties last, or how reputation interacts with allocation algorithms. This uncertainty encourages self-discipline because workers may overcompensate to avoid unknown risks (Rani & Furrer, 2019, 2020). Research on algorithmic management shows that workers' interpretations of automated assessment and allocation systems can affect work experience and behavior (Choudary, 2018; Lee et al., 2015; Rani & Furrer, 2020; Rosenblat & Stark, 2015). Similarly, studies of platform ratings and feedback systems suggest that customer evaluation can extend beyond the immediate task by shaping income security, future access to work, and workers' willingness to increase availability (Broughton et al., 2016; Rani & Furrer, 2019, 2020). Reputation-based control is therefore temporal as well as evaluative.

Reputation systems also delegate part of managerial authority to customers. Customers are not formal supervisors, yet their ratings can trigger managerial consequences. This delegation matters because customer feedback is not always neutral or accurate. Ratings may reflect misunderstanding, strategic complaints, mood, prejudice, or gendered expectations rather than service quality alone (Broughton et al., 2016; Chen, 2024). When platforms treat customer feedback as objective data, biased evaluations can be transformed into apparently neutral algorithmic decisions. Evidence from online labor markets indicates that reputation systems do not automatically eliminate inequality, and recent research shows that platform ranking algorithms can amplify gender gaps when past customer behavior enters future allocation or visibility mechanisms (Chen, 2024). For women workers, customer-side bias may therefore be converted into lower scores, fewer orders, income loss, and additional time spent repairing reputation.

This literature review identifies the theoretical tension that guides the paper. Platform flexibility is not naturally present; it is shaped by platform rules, customer demand, order allocation, and algorithmic control. Women's need for flexible time is not merely personal preference; it is embedded in gendered care responsibility, household labor division, and economic pressure. Reputation systems are not neutral feedback tools; they translate customer evaluation into allocation, penalty, and score-recovery mechanisms that may invisibly extend working time. The unresolved theoretical question is how these three dynamics interact to produce gendered de-flexibilization.

3. Conceptual Framework

3.1. Conceptual Approach and Scope

By synthesizing labor process theory, algorithmic management research, feminist work–family scholarship, and platform governance literature, this paper explains how reputation systems may generate gendered de-flexibilization. It clarifies a mechanism that is evident in existing research but remains insufficiently integrated: when future access to work depends on reputation metrics, platform flexibility becomes conditional; when workers' time is structured by unpaid care responsibilities, this conditionality produces gendered consequences.

The conceptual approach is appropriate because the problem lies at the intersection of several fields. Labor process and HRM research explain how platforms exercise control through algorithms. Platform studies explain how digital infrastructures organize market exchange. Work-family scholarship explains why time autonomy is socially unequal. Discrimination research explains how customer evaluation may reproduce bias. A conceptual framework can connect these fields by specifying how reputation systems translate customer judgment into algorithmic control, how algorithmic control reshapes working time, and why the temporal burden is likely to fall unevenly on women workers.

3.2. Core Concepts

The framework is built around four concepts. First, formal flexibility refers to the platform-level ability to choose when to log on, accept tasks, or stop working. It is the form of flexibility most frequently emphasized in platform narratives. Second, substantive time autonomy refers to the practical capacity to earn adequate income during available working windows without disproportionate penalties for interruption, refusal, or delay. Substantive time autonomy depends on income stability, order availability, predictable consequences, and meaningful worker voice. Third, reputation capital refers to the accumulated score, review history, or platform-visible credibility that affects future access to work. It is often non-portable and platform-specific. Workers may lose it quickly, cannot easily transfer it across platforms, and may spend unpaid or underpaid time protecting or repairing it. Fourth, de-flexibilization refers to the process through which nominally flexible work becomes practically inflexible through indirect pressures such as rating anxiety, score recovery, income loss, and fear of future exclusion.

These concepts distinguish flexibility as a formal platform promise from flexibility as a lived temporal condition. A platform may provide formal flexibility while undermining substantive time autonomy. Similarly, reputation may appear to measure service quality while functioning as a labor-control mechanism. De-flexibilization does not require direct instruction. It can occur when workers voluntarily extend working hours because the alternative is lower income, reputational decline, or reduced future access to orders. The conceptual contribution is to show that flexibility, reputation, and control are linked through a temporal mechanism rather than operating as separate features of platform work.

3.3. The Score-Order-Income-Time Compensation Chain

The central mechanism in the framework is the score-order-income-time compensation chain. The chain begins with customer evaluation. A negative rating, complaint, or low score is processed by the platform as a signal of worker reliability or service quality. The second link is order allocation. When reputation metrics are tied to ranking or matching systems, lower scores may reduce the worker's visibility, priority, or access to desirable tasks. The third link is income. Reduced orders, direct penalties, or lower-quality tasks can reduce current earnings and create uncertainty about future earnings. The fourth link is time compensation. Workers respond by extending working hours, accepting less desirable tasks, working during rest time, or increasing availability to recover income and rebuild reputation. The outcome is conditional flexibility: workers retain formal choice over working time but lose meaningful control over when and how long they need to work.

This chain is important because it explains how control operates without explicit command. Platform workers are not necessarily instructed to work longer hours after a rating loss. Nevertheless, the platform architecture makes additional labor the most rational strategy for restoring income and reputation. In this sense, the chain produces anticipatory discipline. Workers adjust present behavior in anticipation of future allocation decisions that they cannot fully observe. The chain also explains why reputation systems have temporal effects. They do not only evaluate completed tasks; they reorganize the worker's future time by making access to work conditional on maintaining or repairing reputation.

Figure 1. Conceptual framework of reputation-system-induced gendered de-flexibilization

Customer rating, review, or complaint
Reputation score and platform visibility
Order allocation, income penalty, and future access
Compensatory labor: longer hours, score recovery, and anticipatory compliance
Gendered de-flexibilization under care responsibility, income dependence, algorithmic opacity, and customer bias

Note. The model conceptualizes de-flexibilization as a process rather than as an outcome imposed directly by a manager. Platform rules, customer evaluation, and gendered care constraints jointly shape whether formal flexibility becomes substantive time autonomy.

3.4. Boundary Conditions

The framework identifies five boundary conditions that shape the strength of gendered de-flexibilization. The first is care intensity. Workers with frequent childcare, eldercare, or household responsibilities are more vulnerable to the temporal consequences of rating loss because they have fewer discretionary hours for score recovery. The second is income dependence. Workers who rely heavily on platform earnings are more likely to compensate for reduced income by extending hours. The third is algorithmic opacity. When workers cannot understand how ratings affect allocation, they may overcompensate by increasing availability and accepting unfavorable tasks. The fourth is customer-side bias. Where customer evaluations reflect gendered or other discriminatory assumptions, reputation systems can convert bias into algorithmic disadvantage. The fifth is institutional protection. Appeal procedures, social protection, childcare support, anti-discrimination rules, and algorithmic accountability can reduce the extent to which workers must repair reputational harm through unpaid or underpaid additional labor.

These conditions clarify why the framework does not claim that all platform work produces de-flexibilization in the same way. Platform sectors differ in task type, customer contact, visibility of worker identity, rating design, income dependence, and regulatory context. This contingency-based view is consistent with digital transformation research showing that digital intelligence technologies create value when information-processing capacity, coordination mechanisms, and social norms fit the specific organizational context (Pang et al., 2024; Pang et al., 2025). A remote crowdworker, a food-delivery courier, a domestic-service worker, and a professional freelancer may all be subject to reputation systems, but the temporal and gendered consequences may vary. The framework is therefore intended as a mechanism-based model that can guide comparative research rather than as a universal description of all platform labor.

4. Theoretical Mechanisms and Propositions

4.1. Reputation-Contingent Flexibility

The first mechanism is reputation-contingent flexibility. Platforms may present flexibility as a worker-controlled resource, but reputation systems make flexibility dependent on maintaining favorable metrics. A worker with a high score may enjoy greater access to orders and therefore greater practical choice over working time. A worker whose score declines may retain formal freedom to log on, but the value of that freedom falls if the platform allocates fewer tasks or lower-quality work. Flexibility thus becomes a status that must be earned, defended, and restored.

Proposition 1: Platform flexibility is more likely to become de-flexibilization when workers' access to future work is strongly contingent on reputation metrics rather than transparent and stable scheduling rights.

4.2. Anticipatory Compliance and Hidden Working Time

The second mechanism is anticipatory compliance. Reputation systems discipline workers not only through actual penalties but also through the fear of future penalties. When workers do not know how many poor reviews trigger sanctions, how long low scores affect allocation, or how quickly reputation can be restored, they may increase availability to protect themselves against uncertain risk. This can create hidden working time: time spent waiting for orders, handling feedback, contesting reviews, accepting low-value tasks, or working during rest periods to rebuild reputation.

Proposition 2: The more opaque the relationship between ratings, penalties, and order allocation, the more likely workers are to engage in anticipatory compliance that extends working time beyond the formally chosen schedule.

4.3. Customer Delegation and Biased Evaluation

The third mechanism is customer delegation. Reputation systems place customers in a quasi-managerial position because customer ratings can trigger algorithmic consequences. This delegation may improve service accountability, but it also exposes workers to subjective, inconsistent, and potentially biased evaluations. When customer feedback is treated as neutral data, prejudice or misunderstanding can be converted into platform-visible reputation loss. For women workers, customer-side gender assumptions may affect how performance is judged, especially in customer-facing sectors where gender is visible and service encounters are direct.

Proposition 3: Reputation systems are more likely to generate gendered de-flexibilization when customer evaluations are directly incorporated into allocation, penalty, or ranking systems without robust procedures for detecting bias and contesting unfair feedback.

4.4. Gendered Care Constraints and Temporal Penalties

The fourth mechanism links reputation systems to gendered care constraints. Platform metrics often reward uninterrupted availability, fast response, low cancellation, and high customer satisfaction. These metrics may appear neutral, but they are easier to maintain for workers whose time is not frequently interrupted by care. Women with childcare, eldercare, or household responsibilities may have less capacity to respond quickly, accept tasks at inconvenient times, or extend hours after reputation loss. When a low score reduces income, the additional time required for recovery may be taken from rest or care routines.

Proposition 4: The temporal costs of reputation loss are likely to be greater for women workers with unpaid care responsibilities because score recovery requires discretionary time that is already constrained by household labor.

4.5. Institutional Mitigation and Platform Accountability

The fifth mechanism concerns mitigation. De-flexibilization is not inevitable. The relationship between reputation systems and working time depends on platform design and institutional context. Transparent rating rules, meaningful appeal mechanisms, human review, rating portability, client accountability, and anti-discrimination monitoring can reduce the disciplinary power of unfair or opaque ratings. Broader social policies also matter. Childcare provision, social insurance, income protection, and training opportunities can reduce workers' dependence on unstable platform earnings and make it easier to resist unfair demands.

Proposition 5: The negative effects of reputation systems on substantive time autonomy are weaker where platforms and regulators provide transparent scoring rules, effective appeal mechanisms, anti-discrimination safeguards, and social protections that reduce workers' dependence on continuous platform availability.

Table 1. Summary of theoretical propositions

Proposition	Theoretical claim
P1	Platform flexibility becomes de-flexibilization when future access to work is strongly contingent on reputation metrics.
P2	Algorithmic opacity encourages anticipatory compliance and hidden working time.
P3	Customer evaluations produce gendered de-flexibilization when they directly shape allocation and penalties without robust bias review.
P4	The temporal costs of reputation loss are greater for women workers with unpaid care responsibilities.
P5	Transparent rules, appeal mechanisms, anti-discrimination safeguards, and social protection weaken the de-flexibilizing effects of reputation systems.

5. Policy and Managerial Implications

The framework has implications for platform design. First, platforms should distinguish between formal flexibility and substantive time autonomy. It is not sufficient to state that workers can choose when to work if the rating architecture penalizes interruptions, refusals, or limited availability. Platforms should disclose how ratings affect order allocation, income penalties, and score recovery. Workers need actionable information, including which behaviors affect ratings, how quickly scores recover, whether a poor review is weighted by customer history, how penalties are calculated, and how long allocation effects last. Without such information, workers cannot plan their schedules or protect themselves from arbitrary income loss.

Second, platforms should establish meaningful review and appeal mechanisms. Customer feedback should not automatically trigger allocation or income consequences without procedural safeguards. Platforms could require customers to provide reasons for very low ratings, audit patterns of repeated customer complaints, suspend the effect of contested ratings while review is pending, and allow workers to flag discriminatory or malicious feedback. Worker voice should be built into the reputation infrastructure itself. This is particularly important because customer feedback becomes disciplinary when platforms make it consequential without reciprocal accountability.

Third, reputation systems should be assessed for indirect discrimination. Metrics such as acceptance rate, cancellation rate, and response speed may appear neutral but can disadvantage workers with care responsibilities, safety concerns, or limited availability. Platforms should conduct algorithmic audits to examine whether rating and allocation systems disproportionately reduce work access for particular groups. Possible design alternatives include separating customer-service feedback from allocation eligibility, weighting ratings by customer reliability, providing grace periods for care interruptions, and creating non-punitive mechanisms for temporary unavailability.

Fourth, policy makers should recognize that platform flexibility does not automatically provide decent work. Social protection, anti-discrimination rules, and platform accountability are necessary to prevent flexibility from becoming a justification for insecurity (Vyas, 2020; Warren, 2021). Where reputation scores affect access to work, workers should have rights to explanation, correction, and human review. Regulators could require platforms to disclose the main parameters through which ratings influence work allocation, provide accessible complaint procedures, and monitor whether evaluation systems generate indirect discrimination.

Finally, the framework has implications for human resource management. Algorithmic reputation systems perform recognizable HR functions, including performance appraisal, reward allocation, discipline, and retention. Yet these functions are often enacted outside conventional employment protections. Treating reputation systems as algorithmic HRM tools shows why platform work belongs within mainstream debates on fairness, worker voice, performance management, and employee well-being. Recent research on Logistics 4.0 further suggests that employee voice contributes to performance when it is matched by supervisor listening and perceived respect, reinforcing the need for voice-sensitive governance in digitally mediated work systems (Pang et al., 2026). Platform companies should therefore be evaluated not only as digital intermediaries but also as organizations that design and operate consequential labor-management systems.

6. Future Research Directions

As a conceptual paper, this article does not provide empirical estimates of the causal effects of reputation systems on working time. Future research should test and refine the proposed framework through multiple designs. Qualitative studies can examine how workers interpret rating systems, how they manage score recovery, and how care responsibilities shape platform strategies. Semi-structured interviews are particularly useful for exploring sensitive issues such as discrimination, income insecurity, and work-family conflict. Thematic analysis can then identify mechanisms and compare patterns across platform sectors.

Quantitative and mixed-methods research could examine whether the score-order-income-time compensation chain is observable in platform records. Access to rating histories, allocation data, cancellation metrics, earnings records, and working-time logs would allow researchers to test whether rating decline is followed by fewer orders, income loss, and increased working hours. Experimental or quasi-experimental designs could examine whether changes in rating systems, appeal procedures, or customer-feedback rules alter workers' time allocation. Longitudinal designs could also examine whether reputation accumulation creates sticky labor by making workers reluctant to leave platforms because their reputation capital is non-portable (Sun et al., 2021).

Comparative research should investigate how the framework varies across sectors and institutional contexts. Food delivery, ride-hailing, domestic services, online freelancing, healthcare platforms, and professional service platforms all use reputation systems, but they differ in customer contact, worker visibility, task duration, safety risk, pricing rules, and income dependence. Cross-national research could examine how childcare provision, labor regulation, and social protection shape the gendered effects of platform reputation systems. Large-scale surveys and public datasets may help situate platform experiences within broader labor-market trends.

Future studies should also examine intersectionality. The effects of reputation systems may vary not only by gender but also by race, age, migration status, disability, class position, and household structure. A worker's vulnerability to rating loss may depend on multiple identities and resources. Research that treats women platform workers as a homogeneous category may miss important differences in exposure to customer bias, dependence on platform income, and capacity to contest unfair evaluations.

7. Conclusion

This paper has developed a conceptual framework for explaining how platform-based reputation systems can transform the promise of flexible work into gendered de-flexibilization. Its central argument is that flexibility should not be evaluated only by formal schedule choice. It must be assessed by the real conditions under which workers can preserve income, reputation, and future access to work while also meeting care responsibilities. Reputation systems matter because they connect customer evaluation to order allocation, income penalties, and score recovery. Through the score-order-income-time compensation chain, customer feedback becomes a mechanism of algorithmic labor control.

The paper has advanced three contributions. First, it conceptualizes platform flexibility as contested, conditional, and reversible rather than as a stable attribute of platform work. Second, it places gendered care responsibility at the center of platform labor analysis, showing why working-time flexibility is often a structural requirement rather than a personal preference for women workers. Third, it theorizes reputation systems as algorithmic control mechanisms that can restructure workers' practical time autonomy without direct managerial instruction. The proposed propositions provide a basis for future empirical research on how ratings, allocation systems, customer bias, and care responsibilities interact across different platform sectors.

The broader implication is that platform flexibility is neither inherently empowering nor inherently exploitative. Its effects depend on the design of reputation systems, the transparency of algorithmic allocation, the fairness of customer evaluation, the availability of worker voice, and the social conditions under which workers organize paid and unpaid labor. A fairer platform economy therefore requires not only flexible access to work but also substantive time autonomy, procedural justice, and gender-sensitive labor protection.

Funding: This manuscript has been prepared for journal-style submission. Funding information should be added before submission if applicable.

Funding: This study was partially supported by the Research Fund Project of Ningbo University of Finance and Economics(No.1320252012). This article represents one of the research outputs of the project.

References

[1] Alfers L. Our children do not get the attention they deserve: A synthesis of research findings on women informal workers and child care from six membership-based organizations [R]. Women in Informal Employment: Globalizing and Organizing, 2016.

[2] Aloisi A. Commoditized workers: The rising of on-demand work, a case study research on a set of online platforms and apps [J]. SSRN Electronic Journal, 2015, 37(3).

[3] Barnes S A, Green A, de Hoyos M. Crowdsourcing and work: Individual factors and circumstances influencing employability [J]. New Technology, Work and Employment, 2015, 30(1): 16-31.

[4] Broughton A, Green M, Rickard C, et al. Precarious employment in Europe: Patterns, trends and policy strategies [R]. European Parliament, 2016.

[5] Chen Y. Does the gig economy discriminate against women? Evidence from physicians in China [J]. Journal of Development Economics, 2024, 169: 103275.

[6] Choudary S P. The architecture of digital labour platforms: Policy recommendations on platform design for worker well-being [R]. International Labour Office, 2018.

[7] Churchill B, Craig L. Gender in the gig economy: Men and women using digital platforms to secure work in Australia [J]. Journal of Sociology, 2019, 55(4): 741-761.

[8] Donovan S A, Bradley D H, Shimabukuro J O. What does the gig economy mean for workers? [R]. Congressional Research Service, 2016.

[9] Golden L. Flexible work schedules: What are we trading off to get them? [J]. American Behavioral Scientist, 2001, 44(7): 1157-1178.

[10] James A. Platform work-lives in the gig economy: Recentering work-family research [J]. Gender, Work & Organization, 2024, 31(2): 513-534.

[11] Lee M K, Kusbit D, Metsky E, et al. Working with machines: The impact of algorithmic and data-driven management on human workers [C]. Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, 2015.

[12] Pang, Q., Cai, L., Wang, X., & Fang, M. (2024). Digital transformation as the fuel for sailing toward sustainable success: The roles of coordination mechanisms and social norms. Journal of Enterprise Information Management, 37(3), 1069-1096.

[13] Pang, Q., Liu, X., & Su, M. (2025). Leveraging digital intelligence technologies for green shipping: Organization information processing and contingency perspective. Business Strategy and the Environment, 34(7), 9023-9039.

[14] Pang, Q., Wang, M., Yao, J., & Fang, M. (2026). Employees' perceived respect and performance in Logistics 4.0: A dyadic perspective of the congruence between employee voice and supervisor listening. International Journal of Physical Distribution & Logistics Management, 56(2), 224-248

[15] Rani U, Furrer M. On-demand digital economy: Can experience ensure work and income security for microtask workers? [J]. Jahrbuecher fuer Nationaloekonomie und Statistik, 2019, 239(3): 565-597.

[16] Rani U, Furrer M. Digital labour platforms and new forms of flexible work in developing countries: Algorithmic management of work and workers. Competition & Change, 2020, 25(2): 212-236.

[17] Rosenblat A, Stark L. Uber's drivers: Information asymmetries and control in dynamic work [J]. SSRN Electronic Journal, 2015.

[18] Scandura T A, Lankau M J. Relationships of gender, family responsibility and flexible work hours to organizational commitment and job satisfaction [J]. Journal of Organizational Behavior, 1997, 18(4): 377-391.

[19] Sun P, Chen J Y, Rani U. From flexible labour to sticky labour: A tracking study of workers in the food-delivery platform economy of China [J]. Work, Employment and Society, 2021, 36(3): 412-431.

[20] Vyas N. Gender inequality - now available on digital platform: An interplay between gender equality and the gig economy in the European Union [J]. European Labour Law Journal, 2020, 12(1): 37-51.
[21] Warren T. Work-life balance and gig work: Where are we now and where to next with the work-life balance agenda? [J]. Journal of Industrial Relations, 2021, 63(4): 522-545.
[22] West J, Carblanc A, Ferguson S. Online platforms: A practical approach to their economic and social impacts [M]. OECD Publishing, 2018.
[23] Wood A J, Graham M, Lehdonvirta V, et al. Good gig, bad gig: Autonomy and algorithmic control in the global gig economy [J]. Work, Employment and Society, 2018, 33(1): 56-75.

Global Academic Frontiers, Vol. 4, Issue 2, 2026, pp. 67-78 Print ISSN 2995-5688 Online ISSN 2995-570X
DOI: https://doi.org/10.5281/zenodo.20606133

Current Status, Challenges, and Recommendations for the Shellfish Industry in Qingdao

Shenghu Zhu [1*], Tian Chen [1], Jiawen Liu [1], Mali Gong [1]

[1] School of Economics and Management, Dalian Ocean University, Dalian, Liaoning 116000, China
*Corresponding author Email: 1299261652@qq.com
Received 4 December 2025; Accepted 3 April 2026; Published 9 June 2026

Abstract: The shellfish industry constitutes a vital component of Qingdao's marine economy, renowned for its long history and diverse species including clams, oysters, and scallops. This study systematically analyzes the current development status and prominent challenges facing Qingdao's shellfish industry based on data from the city's aquaculture germplasm resource census, regional aquaculture statistics, and representative case studies. It proposes targeted development strategies. Findings indicate that Qingdao's shellfish industry has achieved steady growth in total output, establishing an industrial structure dominated by clams, oysters, and scallops. This sector has also produced a number of superior varieties and renowned brands, including "Haida 1-4" and "Hongdao Clam." However, the industry's sustainable development faces severe challenges, including intensified ecological pressures in aquaculture zones (such as overcapacity farming and starfish blooms), frequent marine disasters, an incomplete industrial chain, and low product value-added. Therefore, this paper proposes that aquaculture activities should be scientifically assessed and planned around the core principle of "determining scale by capacity"; strengthening seed industry system construction and protecting local germplasm resources; promoting the industry's transition towards green, efficient, and facility-based operations; and enhancing market competitiveness through deepening processing and brand building. This study aims to provide theoretical foundations and practical references for the high-quality development of the shellfish industry in Qingdao and similar coastal regions across China.

Keywords: Shellfish farming; Qingdao; Sustainable development; Aquaculture capacity; Industry upgrading; Germplasm resources

1 Introduction

Qingdao City, blessed with natural harbors such as Jiaozhou Bay and Dingzi Bay, possesses outstanding marine resources and serves as a major shellfish farming and export base in China. [1]As a vital component of the coastal economy, the shellfish industry not only provides stable support for the local fishery economy but also acts as a key industrial vehicle for boosting fishermen's incomes and advancing the rural revitalization strategy. In recent years, driven by both sustained growth in market demand and continuous innovation in aquaculture techniques, Qingdao's shellfish farming has steadily expanded in scale and progressively optimized its industrial structure. This has fostered a regionally distinctive industry system centered on key species like clams, oysters, and scallops, with local brands such as "Hongdao Clams" gaining increasing recognition. [2]However, alongside rapid industrial expansion, a series of deep-seated structural issues and challenges in the new development phase have become increasingly prominent. Environmental pressures on aquaculture waters continue to intensify, with overcapacity farming emerging in localized areas. Certain shellfish germplasm resources face degradation risks, threatening local genetic diversity. Furthermore, constraints such as short industrial chains, low product value-added, and intensifying domestic and international market competition collectively hinder the high-quality and sustainable development of Qingdao's shellfish industry. Although significant progress has been made in the overall research of China's shellfish industry, systematic studies on typical regions like Qingdao remain relatively weak. In particular, comprehensive analyses integrating the latest germplasm resource survey data, ecological environment assessments, and industrial upgrading pathways are notably lacking.[3]

Therefore, based on the 2021–2024 survey of aquaculture germplasm resources and aquaculture statistics in Qingdao City, combined with field research and case studies, this study aims to systematically analyze the current status and characteristics of the shellfish industry in Qingdao.[4] It seeks to precisely identify the core constraints and transformation challenges faced by the industry, thereby proposing a sustainable development strategy centered on "ecological priority, technology-driven innovation, and value chain extension." This study not only fills a gap in systematic research on regional shellfish industries but also provides theoretical references and practical models for fisheries transformation and upgrading, as well as policy formulation in similar coastal areas.[5]

2 Current Status of the Shellfish Industry in Qingdao

2.1 The shellfish industry in Qingdao holds a significant position within the fisheries economy.

The shellfish industry in Qingdao holds a pivotal strategic position within its marine fishery economic system. As a major shellfish cultivation and supply base in northern China, this industry not only serves as a stable contributor to local fishery economic output but also stands as a key pillar for ensuring regional food safety, promoting employment and income growth among coastal fishermen, and achieving rural industrial revitalization. Recent aquaculture statistics indicate that Qingdao's total shellfish production has shown steady growth, maintaining an average annual growth rate of approximately 2.7%. [6]This has established an industrial structure dominated by three major categories: clams (primarily Philippine clams), oysters (represented by Pacific oysters), and scallops. Clams and oysters together account for over 70% of total production, forming the industry's foundation. Oysters, with their approximately 30% share of output, serve as the core engine driving overall production growth.[7]

Shellfish farming activities in Qingdao exhibit high spatial concentration and functional differentiation, primarily concentrated in natural harbors such as Jiaozhou Bay, Dingzi Bay, Aoshan Bay, and Lingshan Bay. Huangdao District, leveraging the expansive waters of Lingshan Bay and Gongkou Bay, serves as the largest cultivation zone, producing oysters, scallops, clams, abalone, and cockles. [8]The waters of Aoshan Bay and Dingzi Bay in Jimo District form another core production area spanning 10,603 hectares, where clam cultivation holds an absolute dominance. Chengyang District and Jiaozhou City, encircling Jiaozhou Bay, have formed an intensive aquaculture zone focused on clams and oysters. Areas like Laoshan District emphasize premium and specialty aquaculture. Regarding aquaculture area dynamics, a slight contraction occurred in 2023 but rebounded in 2024, reflecting the industry's resilience in sustaining development amid adjustments.[9]

Total production has grown steadily over the past three years, with an average annual increase of approximately 2.7%. Clams and oysters together account for over 70% of the total output, while scallops consistently rank third. Among these, oysters contribute about 30% of the total production, emerging as the primary driver of overall output growth. [10]

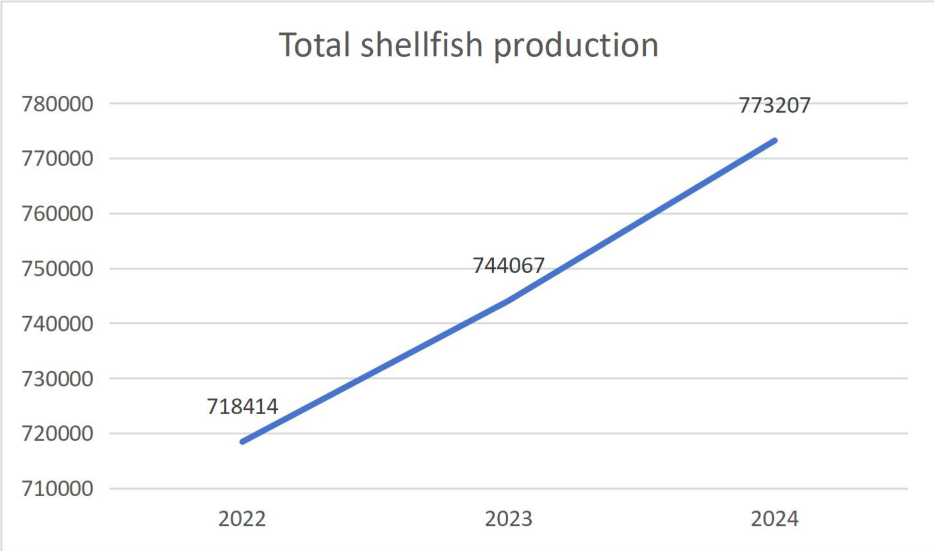
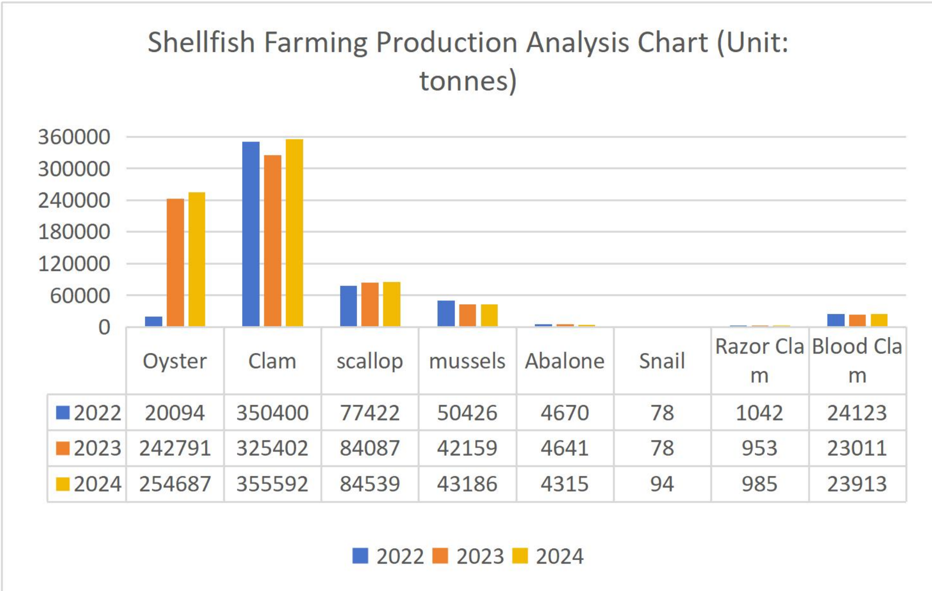


Figure 1: Total Shellfish Farming Production



	Oyster	Clam	scallop	mussels	Abalone	Snail	Razor Clam	Blood Clam
2022	20094	350400	77422	50426	4670	78	1042	24123
2023	242791	325402	84087	42159	4641	78	953	23011
2024	254687	355592	84539	43186	4315	94	985	23913

Figure 2: Analysis of Shellfish Farming Production in Qingdao

The total area experienced a slight contraction in 2023 before rebounding in 2024, with clam farming occupying the largest area followed by oyster farming. The area dedicated to oyster cultivation increased from 6,975 hectares in 2022 to 8,039 hectares in 2023.

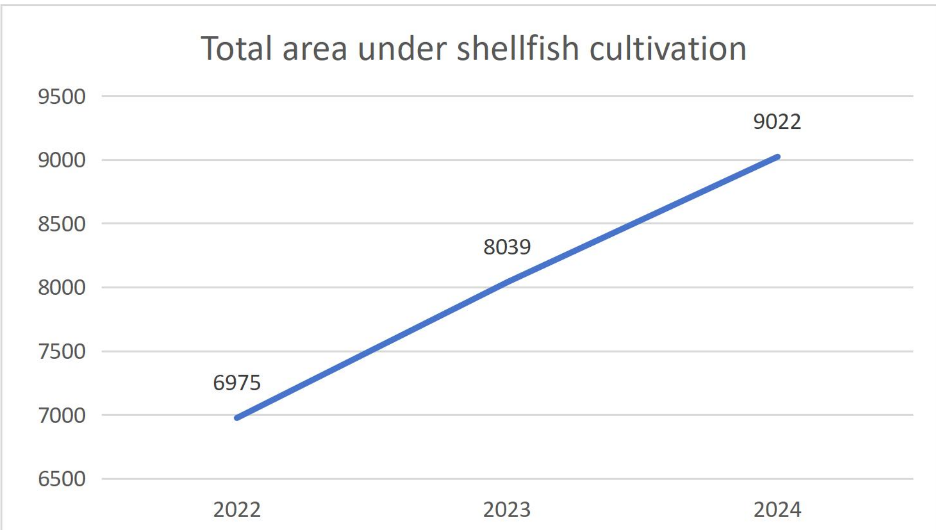


Figure 3: Analysis of Total Shellfish Farming Area

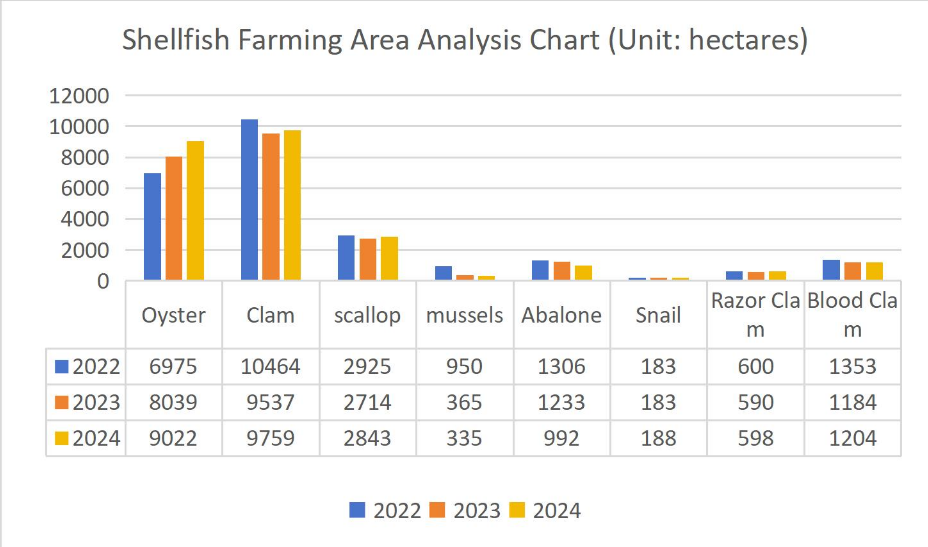


Figure 4: Analysis of Shellfish Farming Areas in Qingdao

As shown in Figures 1 and 2, both the aquaculture area and total production of shellfish in Qingdao exhibited a significant synergistic growth trend from 2022 to 2024. This synchronized upward trajectory clearly indicates that the overall scale of Qingdao's shellfish industry expanded steadily during this period, with increasingly active farming activities. The increase in production is not solely attributable to expanded farming areas but likely also benefits from improved farming techniques, the promotion of superior varieties, and enhanced management practices. This reflects the industry's initial transition from extensive to intensive growth. Qingdao boasts a long history of shellfish farming with a diverse range of species, including clams, oysters, scallops, and abalone. In recent years, driven by growing market demand and advancements in aquaculture techniques, Qingdao's shellfish industry has continuously developed and expanded. It now not only meets local market needs but also exports nationwide, becoming a shining emblem of Qingdao's marine economy.

2.2 Basic Information Census

To systematically understand the status of aquaculture germplasm resources, Qingdao City completed its first comprehensive census of basic aquaculture conditions in 2021. Building upon this foundation, the 2022 systematic germplasm resource survey further narrowed its focus, designating Pacific oysters (Crassostrea gigas) and Philippine clams (Ruditapes philippinarum) as priority species (☆). [11]It also conducted in-depth investigations on five major economic bivalve species: Scapharca broughtonii, and Scapharca subcrenata. This marks a new phase of precision and systematization in Qingdao's mollusk germplasm resource management.[12]

The statistical data in Table 1 clearly reveals the industrial structure and development trends of shellfish farming in Qingdao City. Pacific oysters dominate the industry, with both their farming area (115,139.3 mu) and production volume (152,911 tons) far surpassing others, serving as the core pillar of the industry. Clams (primarily Philippine clams) consistently rank second in both farming area and production volume, forming an important foundation of the industry. Notably, despite relatively low production volume (1,454.5 tons), the abalone's exceptionally high market price per unit (230 yuan/kg) propels its output value (335.42 million yuan) to second place, highlighting the immense potential of high-value-added species in enhancing the industry's economic efficiency. Concurrently, species like the scallop and the razor clam demonstrate stable, large-scale cultivation trends. However, the data also reveals imbalances in the seed supply system. For instance, seed production data is missing for several species like clams and razor clams(—), indicating strong reliance on external seed sources. This highlights the need to strengthen localized, large-scale seed breeding systems, providing clear direction for future seed industry development.

Table 1: Statistical Summary of Marine Shellfish Seed Production and Cultivation

species	Seedling yield (ten thousand seeds)	Cultivation area (mu)	Seedling quantity (ten thousand units)	Production (tonnes)	Farmgate price (RMB/kg)	Output value (ten thousand yuan)
Green-shelled abalone	—	950	10	47.5	200	950
Long-tailed skink	2863812	115139.3	177029092.7	152911	4.8	74293
Clam	—	38514	3818174	61246	6	37599
Gulf scallop	12000	328	680	772.4	8	633.6
Mussel	8000	450		22.5	6	13.5
Penglai Red No. 2	—	100	3000	600	7	420
Four-cornered clam	—	500	390	73.4	8	59.9
Venus clam	—	310	743.6	41.7	24	100
Clam	—	1266	35030	1364	7	938.6
Comb-toothed scallop	—	15605.87	311003.25	12220	10	12208
Chinese horse clam	500	569.2	49	16.6	81.4	
Wrinkled-disk abalone	6210	16757.41	623.26	1454.5	230	33542
Purple mussel	—	25.3	248	85	3	25.4

The shellfish industry in Qingdao holds a crucial strategic position within its marine fishery economic system. As a major shellfish cultivation and supply base in northern China, this industry not only serves as a stable contributor to the local fishery economy's output value but also acts as a key pillar in ensuring regional food safety, promoting employment and income growth for coastal fishermen, and achieving rural industrial revitalization. According to the latest aquaculture statistics, the 2024 shellfish farming landscape in Qingdao is dominated by three primary species: clams (Crassostrea gigas), oysters (Crassostrea ostrea), and scallops. Clam farming occupies over 40% of the total area, while oyster farming accounts for approximately 35%, together forming the foundation of Qingdao's shellfish industry. Jimo District, the largest farming area, leverages its expansive waters including Aoshan Bay and Dingzi Bay to cultivate 10,603 hectares of shellfish. This includes a balanced structure of 5,132 hectares for clams, 2,985 hectares for oysters, and 1,012 hectares for scallops. It also maintains a 30-hectare abalone farming zone, demonstrating the industry's diverse development characteristics.

Huangdao District, with Lingshan Bay and Gongkou Bay as its primary bases, boasts an aquaculture area of 9,465 hectares. It features a dominant oyster cultivation of 3,521 hectares, complemented by coordinated development of scallops (1,800 hectares), clams (1,414 hectares), and abalone (942 hectares), making it a key production area for high-quality shellfish products in Qingdao. Chengyang District, leveraging the northern waters of Jiaozhou Bay, cultivates across 4,543 hectares. It has established a dual-dominant model with clams (2,243 hectares) and oysters (2,223 hectares) equally prominent, demonstrating stable production capacity for traditional flagship species. As a key production area in the southwest of Jiaozhou Bay, Jiaozhou City has a farming area of 1,310 hectares, featuring 970 hectares of clams as its primary specialty, supplemented by oysters (200 hectares) and 140 hectares of razor clams. Laoshan District leverages Laoshan Bay for premium aquaculture, covering 144 hectares dedicated to high-quality shellfish production: 93 hectares for oysters, 31 hectares for scallops, and 20 hectares for abalone. This represents the industry's direction toward enhanced quality and efficiency. In terms of species structure, Qingdao's shellfish industry has developed a distinctively layered and specialized variety system. Clams (primarily Philippine clams) serve as the foundational species, widely distributed across all production zones with a total area exceeding 9,700 hectares, forming the industry's solid foundation. Oysters (mainly Pacific oysters) act as the pillar species, covering approximately 9,000 hectares and leading the industry in technological innovation and brand development. Scallops serve as an important supplement, covering approximately 2,800 hectares and achieving large-scale production in Jimo District and Huangdao District. Abalone, as a high-value-added species, though occupying a small proportion of the total area, is concentrated in Huangdao District and Laoshan District, representing the direction of industrial upgrading and profit enhancement.

Table 2: Current Status of the Shellfish Industry in Qingdao

Region or Unit	Subtotal	Oyster	Bao	Snail	Blood Clam	mussels	Jiang Yao	scallop	Clam	Razor clam
Shandong Province	4817133	1657092	39290	10019	7342	277478	0	1017839	1351057	142965
Qingdao City	773207	254,687	4315	94	985	43,186	0	84,539	355592	23,913
Huangdao District	232,872	71,693	4,299	94	0	36,966	0	51,527	52,803	10,594
Laoshan District	1,925	835	1	0	0	0	0	1,089	0	0
Chengyang District	204,594	87,633	0	0	0	0	0	0	116,836	125
Jiaozhou City	75,785	8,458	0	0	0	0	0	0	65,032	2,295
Jimo City	258,03	86,068	15	0	985	6,220	0	31,923	120,921	10,899

Aquaculture practices exhibit diverse characteristics, encompassing tidal flat cultivation, raft-based suspended farming, bottom seeding enhancement, and intensive factory farming, reflecting an organic integration of traditional and modern techniques. Notably, traditional production zones for geographical indication products such as the ‘Hongdao Clam’ are progressively adopting modern production management standards while preserving their distinctive qualities. Qingdao hosts leading marine research institutions including Ocean University of China and the Institute of Oceanology, Chinese Academy of Sciences, providing robust technological support for shellfish innovation. This support manifests in breakthroughs in seedling propagation techniques, optimised farming models, and enhanced quality control. Each production area has developed differentiated pathways based on its resource endowments: Jimo District and Huangdao District focus on large-scale production and diversified development; Chengyang District and Jiaozhou City concentrate on consolidating and enhancing traditional superior varieties;

while Laoshan District specialises in premium, high-value-added development. This regionally tailored differentiation strategy has effectively boosted the overall competitiveness of Qingdao's shellfish industry.

This scientific regional layout and species configuration not only fully leverages the ecological advantages of each sea area but also establishes a solid foundation for Qingdao's shellfish industry to withstand market and natural risks, providing robust safeguards for the industry's sustainable development.

3 Analysis of Development Status and Characteristics of Major Aquaculture Species

3.1 Long Oyster Current Cultivation Scale and Production Volume in Qingdao City

The Pacific oyster (Crassostrea gigas) serves as the cornerstone species of Qingdao's shellfish industry, characterized by high industrialization and dominant market presence. According to the latest germplasm resource census data, the city currently hosts 366 Pacific oyster farming entities, with initial signs of industry concentration emerging. [13]Among these, seven entities operate farms exceeding 400 mu (approximately 26.7 hectares), while 15 entities manage farms larger than 300 mu (approximately 20 hectares). Driven by scale, key industry metrics are outstanding: annual seedling usage reaches 536.5 billion units, with local seedling production averaging 28.6 billion units annually. Total farming area spans 7,365 hectares, yielding 143,200 metric tons annually and generating an output value of 691 million yuan, securing a central position in northern China's oyster industry. [14]This robust growth stems from formidable seed industry innovation capabilities. Led by research institutions like Ocean University of China, a series of proprietary new varieties—including "Hai Da 1-4," "Hai Yi 1-2," and "Qian Yan 1"—have been successfully developed and promoted. These varieties generally exhibit economic traits such as rapid growth, large individual size, high glycogen content, and excellent meat quality, earning high market recognition. [15]They currently account for approximately 70% of the market share in northern oyster farming areas, serving as a key driver for industrial upgrading.

The cultivation model exhibits characteristics of both diversification and specialization. Cultivated species originate from naturally attached diploid oysters in marine areas, artificially bred diploid oysters, and triploid oysters.[16] Cultivation methods adapt to local conditions, encompassing bottom seeding enhancement, raft-based rope suspension, and net cage cultivation, forming a production system tailored to different marine environments.

Leading enterprises such as Qingdao Xiadelu Aquaculture Co., Ltd. have achieved large-scale, efficient production by leveraging the natural seedling-rearing area of Aoshan Bay. In 2024, the company's oyster farming area in the region reached approximately 2,985 hectares, yielding over 86,000 metric tons. By 2025, its planned cultivation area will expand to 26,000 mu (approximately 1,733 hectares), with an estimated 100-120 million ropes supporting 250 million oyster spat.[17] This demonstrates the company's formidable production organization capabilities and exemplary leadership effect.。

3.2 Philippine clam

The Philippine clam (Ruditapes philippinarum), particularly its GI-certified product "Hongdao Clam," stands as Qingdao's most renowned traditional shellfish specialty. Industry surveys indicate the city currently has 32 clam farming entities, utilizing 30.314 billion seed clams annually. Cultivation spans 27,600 mu (approximately 1,847 hectares), yielding 34,300 metric tons with an annual output value of approximately 210 million yuan. Both cultivation area and production volume rank first among all shellfish species. Production is highly concentrated in the tidal flat areas of Jiaozhou Bay and Dingzi Bay, employing traditional tidal flat farming methods. The "Hongdao Clam" brand enjoys significant recognition, with stable farming areas exceeding 2,200 hectares and annual output surpassing 110,000 tons. Market supply and demand remain robust, with peak-season daily shipments reaching up to 300,000 jin (150,000 kg) in 2024.[18]

However, this industry's prosperity conceals a severe germplasm crisis. Over 90% of the seed stock in current farming areas relies on southern supplies. After migrating northward, southern populations gained competitive advantages in growth rate and survival rate, gradually encroaching on the ecological niche of local indigenous populations. Combined with historically unregulated harvesting, this has caused the local indigenous population to decline sharply, bringing it to the brink of extinction. This situation has significantly impacted the genetic structure of local populations, resulting in severe loss of genetic diversity and rendering the germplasm foundation for sustainable industry development extremely fragile. Implementing systematic conservation and restoration plans for indigenous germplasm resources is now urgent.

Production efficiency analysis demonstrates its microeconomic viability. Taking Qingdao Xidayang Aquatic Products Co., Ltd.'s demonstration base as an example, its 300-mu aquaculture area achieved an average selling price of approximately ¥3.8 per jin during one production cycle. After deducting costs such as seedling fees, beach access fees, and marine area usage fees, the base achieved sales revenue of approximately 2.8 million yuan and a net profit of 1.315 million yuan, with an average profit per mu reaching 4,833 yuan. [19]This demonstrates sound economic benefits, providing economic incentives for achieving stable industrial development under conservation principles.

3.3 Scallops

Scallop farming constitutes a vital segment of Qingdao's shellfish industry, centered on the cultivation of comb scallops (Chlamys farreri) and bay scallops (Argopecten irradians). The city hosts 74 farming entities, utilizing 3.147 billion scallop seeds annually across 10,000 mu (approximately 1,000 acres) of aquaculture area. Annual production reaches 13,600 metric tons, generating an output value of approximately 130 million yuan. The primary cultivation method employed is modern cage farming.

Production exhibits regional clustering characteristics. Areas such as Fengjiahe Village along the coast of Aoshan Bay in Jimo District serve as core cultivation zones, boasting tens of thousands of mu of offshore farming areas. During peak periods, daily harvests can reach 100,000 jin. In 2024, Ao Shan Bay produced 31,900 tons of scallops across 1,012 hectares of aquaculture area.[20] Ling Shan Bay recorded higher output at 51,500 tons over 1,800 hectares, while Lao Shan Bay served as a premium cultivation zone yielding 1,089 tons. Regarding market dynamics, by 2025, some high-yield zones could achieve yields of 8,000-10,000 jin per mu. However, wholesale prices are projected to be approximately 5-6 yuan per jin, slightly lower than previous years, indicating the need to focus on market supply-demand balance and value enhancement.[21]

The industry's sustained growth stems from steady progress in superior strain breeding. Breeding bases like Qingdao Baxiandun Marine Delicacies Cultivation Co., Ltd. play a pivotal role. In 2023, the company produced 4.5 million scallop seedlings and preserved 1,000 kilograms of seed stock. In 2024, it further conducted cultivation tests on new strains such as “ZY,” “ZB,” and “PRR,” while systematically preserving superior varieties like the “Penglai Red” series.[22] Preservation quantities exceeded 10,000 units for each strain, providing crucial seedstock assurance and technological outreach for germplasm renewal and disease prevention in the scallop industry.

3.4 Other Specialty Shellfish

Beyond the three dominant species, Qingdao is actively developing other high-value or ecologically functional specialty shellfish to diversify its product portfolio and explore new aquaculture models.

Cephalopods such as golden squid: As species for stock enhancement and potential aquaculture, Qingdao Jinshatan Aquatic Development Co., Ltd. has successfully achieved large-scale artificial breeding of golden squid and Manchurian squid in collaboration with experts from the Yellow Sea Fisheries Research Institute of the Chinese Academy of Fisheries Sciences. Between 2024 and 2025, thousands of broodstock were cultivated, yielding over 2.5 million fertilized eggs and more than 1 million hatched juveniles, with an average hatching rate of 87.5%. Successful stock enhancement trials integrated with seagrass bed ecological restoration were conducted, achieving significant ecological and resource recovery outcomes.

Scapharca broughtonii (Chinese cockle): As a highly valuable intertidal shellfish, successful cultivation trials were conducted in Jiaozhou Bay. Following promotion from 2022 to 2024, the cultivation area has exceeded 10,000 mu (approximately 667 hectares).[23] Its cultivation cycle is approximately 7-8 months, with seedling stocking density at 40-50 seeds per jin (500g), market size at 16-30 seeds per jin, and selling price ranging from 3.8-4.5 yuan per jin. The statistical survival rate is 60%-80%, with daily harvests of 3,000-5,000 jin. with cultivation profitability reaching 50%-100%. This demonstrates strong economic viability and ecological adaptability, offering a new option for optimizing tidal flat utilization.

4 Challenges Facing the Shellfish Industry in Qingdao

While achieving remarkable accomplishments, Qingdao's shellfish industry now faces a series of severe and complex challenges to its sustainable development. These challenges span multiple dimensions — including ecological environment, market structure, and the industry's own capabilities — intertwining to form critical bottlenecks constraining the industry's advancement to higher levels.

4.1 Ecological and Environmental Pressures

The ecological and environmental pressures stemming from industrial expansion are becoming increasingly prominent, primarily manifested in aquaculture activities exceeding environmental carrying capacity and frequent natural and biological disasters.

Overcapacity in aquaculture has become a core environmental issue. Research indicates that the optimal farming density for Philippine clams in Jiaozhou Bay should be maintained below 1,000 clams per square meter, with the ideal range being 550-750 clams per square meter. However, current actual seeding densities far exceed this scientific threshold. This has led to water eutrophication, sediment organic matter overload, and deteriorating bottom environments, imposing sustained pressure on the bay's ecosystem material cycles and biodiversity. A striking example is the annual release of 6,000–8,000 truckloads of oyster spat attached to scallop shells in recent years (each 9.6-meter truck carrying 23,000–25,000 jin). In 2021 alone, the combined weight of scallop shells and oyster spat released reached 80,000 tons. This extensive production model, lacking ecological capacity assessments, underscores the urgency for scientific planning and refined management.

Second, the threat of marine disasters has become normalized. Qingdao's coastal waters frequently endure extreme weather events like typhoons and storm surges, which directly destroy aquaculture facilities, leading to mass escapes or deaths of shellfish. Additionally, harmful algal blooms like red tides occur frequently. The toxins they produce can accumulate in shellfish, triggering product safety crises and causing significant economic losses for farmers. The outbreak of biological disasters has amplified industry risks. For instance, Jiaozhou Bay has experienced multiple large-scale outbreaks of the starfish Asterias amurensis in recent years. As voracious predators of shellfish, the proliferation of starfish has dealt devastating blows to bottom-cultured species like clams and oysters, exposing the weakness of biological control capabilities under ecosystem imbalance.

4.2 Intensifying Market Competition

At the market level, Qingdao's shellfish industry faces increasingly fierce competitive pressure. Domestically, as shellfish farming techniques advance and scale expands in regions like the Bohai Rim and Southeast Coast, product homogenization intensifies competition. Areas such as Fujian and Liaoning have developed strong competitive advantages in oysters and scallops, while some regions hold comparative advantages in cost control or logistics efficiency. This continuously erodes Qingdao's traditional market share, driving price competition to fever pitch. The international market presents even more complex challenges. On one hand, Qingdao faces competition from high-quality shellfish products from neighboring countries like South Korea and Japan. On the other hand, export markets demand increasingly stringent requirements for seafood quality and safety, traceability, certification standards (such as ASC and BAP), and sustainability metrics. Green trade barriers and technical trade measures have emerged as new challenges, requiring the industry to comprehensively enhance its quality, safety, and environmental standards to maintain and strengthen its international competitiveness.

4.3 Industry Development Bottlenecks

Structural issues within the industry also constrain its high-quality development. The primary bottleneck is an incomplete industrial chain with weak coordination. Current industry strengths are concentrated in aquaculture production, while critical upstream and downstream segments lag behind. The upstream seed industry system remains underdeveloped, with certain species (e.g., clams) overly reliant on externally sourced seedlings. Downstream, deep processing capabilities are weak, resulting in most products being sold in primary fresh forms. Low processing rates mean technological added value is underutilized. Concurrently, supporting service systems—including cold chain logistics, brand marketing, and modern supply chain management — are insufficiently developed, limiting the industry's overall risk resilience and value capture capacity.

Low product value-added serves as a concrete manifestation of these industrial chain shortcomings. Most shellfish products enter the market in raw or minimally processed forms, exhibiting weak brand premium potential and facing severe profit compression in distribution channels. Despite possessing regional brands like "Hongdao Clams," their brand value has yet to be translated into significant market premiums through systematic quality grading, standardized packaging, and narrative-driven marketing. Implementing a quality-based branding strategy to transition products from being sold by weight to being valued for quality and brand recognition has become an urgent priority for enhancing the industry's economic efficiency.

4.4 Recommendations for the Shellfish Industry Development in Qingdao

To effectively address the aforementioned challenges and propel Qingdao's shellfish industry from scale expansion toward a high-quality development phase that prioritizes both quality and efficiency alongside ecological harmony, this study proposes a systematic and actionable strategic framework encompassing three core dimensions: ecological conservation, industrial upgrading, and market expansion.

4.5 Implement Precision Management Based on Ecological Carrying Capacity

Ensuring ecological sustainability is fundamental to industrial development. The principle of "determining scale by capacity" must be established and strictly enforced to achieve dynamic equilibrium between aquaculture activities and marine ecosystems. Immediately conduct comprehensive precision assessments of aquaculture capacity in major bays such as Jiaozhou Bay and Aoshan Bay, comprehensively considering hydrodynamics, sedimentation, nutrient cycling, and biological carrying capacity. Based on assessment results, scientifically delineate no-farming zones, restricted-farming zones, and permitted-farming zones. Establish differentiated aquaculture capacity indicators by species and region to eliminate overcapacity farming at its source. Construct a real-time online environmental monitoring network covering key aquaculture areas, enabling routine monitoring of water quality (dissolved oxygen, pH, nutrients, harmful algal blooms, etc.), sediments, and aquaculture organism health indicators. Leverage big data and IoT technologies to enable early environmental risk warnings and trend analysis. Establish a robust multi-departmental marine disaster early warning and emergency response mechanism to enhance prediction accuracy and warning dissemination efficiency for typhoons, storm surges, and red tides. Concurrently, intensify research into the ecological mechanisms of harmful species outbreaks (e.g., starfish) and develop biological control technologies, forming an integrated "monitoring-warning-control" solution to systematically reduce losses from natural and biological disasters.

4.6 Promoting Modernization Across the Entire Industry Chain and Value Chain Enhancement

The future competitiveness of the industry hinges on its modernization level and value creation capabilities. Comprehensive upgrades toward greener, facility-based, and standardized operations must be pursued. Place germplasm resource conservation and innovation at the strategic core. Establish living gene banks and protected areas for superior native germplasm (e.g., indigenous clam populations, distinctive oyster strains). Intensify breeding efforts for stress-tolerant, high-yielding, and premium new varieties (e.g., triploid oysters, highly disease-resistant scallops), promoting modern biotechnologies like molecular marker-assisted breeding to achieve industrial and commercial scale in elite strain development. Encourage environmentally friendly facility farming models such as deep-water wave-resistant cages, ecological raft-based suspended culture, and multi-trophic level integrated aquaculture. Develop and promote standardized production protocols covering the entire process from "seedling-feed-environmental control-disease prevention-harvest," enhancing farming efficiency and product consistency. Develop and deploy rapid on-site detection technologies for pollutants (heavy metals, microorganisms, algal toxins) in shellfish. Establish a disease surveillance and early warning network covering major production areas and species. Utilize blockchain and other technologies to build a comprehensive quality and safety traceability system from farm to table, earning market trust through exceptional quality and safety standards.

4.7 Optimize Product Structure and Strengthen Brand Marketing

Breaking free from the constraints of primary product competition hinges on enhancing product value-added and brand influence to achieve value-driven growth. Deepen processing and optimize product structure: Vigorously support R&D and industrialization of advanced shellfish processing technologies, prioritizing high-value-added directions such as ready-to-eat products, condiments, and extraction of functional bioactive compounds (e.g., glycogen, peptides, taurine). Guide farmers to moderately reduce the scale of highly homogenized species based on market demand, increasing the cultivation proportion of high-value and functional species like abalone, giant clams, and specialty squid to achieve diversified and premium product structures. Implement brand-building and market diversification strategies: Systematically elevate core regional public brands like “Hongdao Clam,” establishing rigorous brand usage standards and quality grading systems. Continuously host high-caliber seafood festivals, participate in premier domestic and international food expos, and leverage new media marketing to effectively communicate Qingdao shellfish's “ecological story” and “quality narrative.” Actively expand into domestic premium fresh markets, restaurant supply chains, and international high-standard export markets to reduce over-reliance on traditional wholesale channels. This will enhance brand premium pricing power and market resilience.

References

[1] L. Cui., "From human-driven eutrophication to effective management: Controlling brown tides in the coastal waters of Qinhuangdao, China," Harmful Algae, 2025.

[2] M. Troell., "Perspectives on aquaculture' s contribution to the Sustainable Development Goals for improved human and planetary health," J. World Aquac. Soc., vol. 54, pp. 447–479, 2023.

[3] F. J. Oficialdegui., " Non-Native Species in Aquaculture: Burgeoning Production and Environmental Sustainability Risks," Rev. Aquac., 2025.

[4] W. Liu, X. H. Wang, and W. Wu, "Assessment of coastal eco-environmental sustainable development under multiple pressures: A case study of Jiaozhou Bay, China," J. Environ. Manage., 2024.

[5] Y. Gao and G. Ji, "Sustainable Development and Ecosystem Health at Oyster Farming," Oceanography & Fisheries Open Access J., 2024.

[6] S.-E. Yu and Y. Mu, "Evaluation of green development in mariculture: The case of Chinese oyster aquaculture," Aquaculture, 2023.

[7] Y. Zhang., "Ecological carrying capacity and carbon sequestration potential of *Ruditapes philippinarum*: a case study in Dashentang National Marine Ranch in Tianjin Bohai Bay, China," *Front. Mar. Sci.*, 2025.

[8] P. Yu., " Current status and application of largemouth bass (*Micropterus salmoides*) germplasm resources," *Reprod. Breeding*, vol. 4, pp. 1–16, 2024.

[9] Z. Liu, C. Wang, and B. Guo, "Biodiversity—The cornerstone of sustainable aquaculture development: Insights from the breeding of approved fish varieties for aquaculture from 1996 to 2024 in China," *Rev. Aquac.*, 2025.

[10] D. Wei., "Genetic and haplotype diversity of Manila clam *Ruditapes philippinarum* in different regions of China based on three molecular markers," *Animals*, vol. 13, 2023.

[11] S. Zheng., "Population genetics of Manila clam (*Ruditapes philippinarum*) in China inferred from microsatellite markers," *Biology*, vol. 12, 2023.

[12] Y. Zhang., "Ecological carrying capacity and carbon sequestration potential of *Ruditapes philippinarum*: A case study in Dashentang National Marine Ranch in Tianjin Bohai Bay, China," *Front. Mar. Sci.*, 2025.

[13] J. Wang., "Production traits and fertility of reciprocal hybrids between *Argopecten irradians irradians* and *A. i. concentricus*," *J. Oceanol. Limnol.*, 2023.

[14] Z. Liu, C. Wang, and B. Guo, "Biodiversity—The cornerstone of sustainable aquaculture development: Insights from the breeding of approved fish varieties for aquaculture from 1996 to 2024 in China," *Rev. Aquac.*, 2025.

[15] K. Jiang., "Genetic improvement of oysters: Current status, challenges, and prospects," *Rev. Aquac.*, 2023.

[16] C. Lodeiros., "Kelp breeding in China: Challenges and opportunities for solutions," *Rev. Aquac.*, 2023.

[17] J. Lan, P. Liu, X. Hu, and S. Zhu, "Harmful algal blooms in eutrophic marine environments: Causes, monitoring, and treatment," *Water*, vol. 16, 2024.

[18] H. Liang., " Unveiling the eutrophication crisis: 20 years of nutrient development in Zhanjiang Bay, China," *Front. Mar. Sci.*, vol. 11, 2024.

[19] S.-L. Dong., "Advancements and hurdles of deeper-offshore aquaculture in China," *Rev. Aquac.*, vol. 16, 2024.

[20] M. Zahir., "A review on monitoring, forecasting, and early warning of harmful algal bloom," *Aquaculture*, vol. 581, 2024.

[21] J. Lan., "Harmful algal blooms in eutrophic marine environments: causes, monitoring, and treatment," *Water*, vol. 16, 2024.

[22] H. Liang., " Unveiling the eutrophication crisis: 20 years of nutrient development in Zhanjiang Bay, China," *Front. Mar. Sci.*, vol. 11, 2024.

[23] L. Yao., "Typical marine ecological disasters in China attributed to marine organisms and their significant insights," *Biology*, vol. 13, 2024.

Global Academic Frontiers, Vol. 4, Issue 2, 2026, pp. 79-86 Print ISSN 2995-5688 Online ISSN 2995-570X
DOI: https://doi.org/10.5281/zenodo.20606277

From Form to Meaning: Contemporary Expression and Aesthetic Implication of Traditional Dance Elements

Zhou Tiantian [1*]

[1] Guangzhou University, Guangzhou, 510006, China
*Corresponding author Email: ttianztt@163.com
Received 9 May 2026; Accepted 13 May 2026; Published 9 June 2026

Abstract: "From form to meaning" is both the spiritual pulse of Chinese art and the aesthetic path for traditional dance elements toward contemporary expression. This paper takes "form" and "meaning" in traditional dance as core categories to explore their way of regeneration in contemporary dance creation. The "form" of traditional dance contains stylized bodily logic and the rhythmic beauty of national culture; meanwhile, "meaning" is the spiritual imagery and emotional charm revealed through bodily perception. With the introduction of modern dance trends, "form" in dance is no longer a static symbol but becomes a medium for the generation of "meaning". This paper analyzes the contemporary expression strategies of traditional dance elements from three levels: the abstraction of movement structure, the symbolization of imagery expression, and the aesthetic reconstruction of bodily perception. It points out the dynamic relationship of being mutual surfaces and interiors, symbiosis, and resonance formed by "form" and "meaning" in contemporary creation. The study believes that the modern transformation of traditional dance elements should not stop at formal renewal, but should achieve the reappearance of cultural spirit and the contemporary rebirth of imagery through bodily perception and aesthetic generation.

Keywords: Form and Meaning, Traditional Dance Elements, Contemporary Expression

Introduction

The relationship between "form" and "meaning" almost runs through the entire intellectual lineage of Chinese art. From the Classic of Music saying emotion is stirred within and takes form in words, to Zong Baihua proposing "depicting spirit through form" and "depicting meaning through form," this aesthetic logic always reveals the spiritual orientation of Chinese art moving from technique to Dao and manifesting meaning through form. Dance, as the most direct art form using the body as a medium, becomes the most vivid existence of the interweaving of form and meaning with its dynamic rhythm and flow of qiyun. It conveys emotion through the form of movement and manifests spirit through the motion of qiyun, making the body a field for the generation of imagery. However, the author finds that in the actual process of contemporary creation, choreographers often face a dilemma when facing tradition: on the one hand, the reuse of traditional dance elements is the ultimate creative resource in the process of modern choreographers' creation; on the other hand, this "reuse" often briefly stays at the reproduction of forms and the collage of symbols, failing to truly touch the generation of "meaning" behind it. If the citation of traditional elements in contemporary dance creation is limited to the replication of formula and costuming, it is easy to fall into the superficial polyphony of "form" while ignoring the deep logic of "depicting spirit through form and conveying meaning through motion" in traditional dance. How to make "form" a medium for "meaning" rather than its shackle has become a subject that current dance creators must face.

Behind this problem, in fact, lies the root proposition of the Chinese artistic spirit. Zong Baihua once said that "dance" is the model of all artistic realms in China, embodying "generative rhythm" and the cosmic consciousness of "governing space with time". It can be seen that the "form" of dance is never isolated from the pursuit of formal beauty, but is the manifestation of "the flow of vital energy" and the concretization of the rhythm of life. Every rotation and pause of a dancer is the echo of the rhythm of "qi" in space. If the beauty of "form" lacks the inner content of "meaning," dance only stops at the stacking of skills; conversely, if "meaning" is not born relying on "form," it is also difficult to concretely manifest its spiritual pulse. Therefore, the relationship between "form" and "meaning" is not two opposite poles, but a life process of being mutual substance and function, and being interdependent and intergenerating. Under the innovative context of contemporary dance, the reconstruction of the "form-meaning" relationship is not only an aesthetic return to traditional culture but also a rethinking of the way of bodily cognition. Modern dance trends introduce the concept of "de-formalization," making the dancer's body no longer subject to formula but becoming the subject of perception and expression. The contemporary expression of traditional dance elements should obtain rebirth in this open bodily consciousness—both continuing the rhythmic logic of the "form" of tradition and giving it new life tension with contemporary "meaning". In this way, the "form" of dance can be transformed into a dynamic spiritual language, and "meaning" can also be reconstructed in the flowing body.

What this paper explores is precisely this artistic self-awareness of "attaining meaning through form". By tracing the ideological basis of "form" and "meaning," revealing its archetypal structure in Chinese artistic thinking, and taking this concept as a reference, it examines the aesthetic generation of traditional dance elements in contemporary expression. Such exploration does not stay at the level of form and technique, but intends to explain: the value of traditional dance lies not in the reproduction of its external appearance, but in its continuous generation as cultural spirit. Thus, "from form to meaning" is not only a path of dance creation but also a conceptual dimension for reconstructing Eastern bodily aesthetics—letting traditional form become the breath of meaning; letting contemporary dance return to the origin of spirit.

1."From Form to Meaning": The Intellectual Gene of Chinese Aesthetics

"From form to meaning" is not only a path of artistic creation but also a spiritual pulse running through the history of Chinese aesthetic thought. It reveals the internal mechanism of Chinese art moving from technique to Dao and from image into meaning, and also constitutes the philosophical prototype of traditional dance aesthetics. Viewed from the depth of philosophy, the source of this thought can be traced back to classical cultural traditions such as the I Ching, Classic of Music, Zhuangzi, and Zen; viewed from the horizontal perspective of aesthetics, it obtained systematic expression in the discussions of modern scholars and became an important category of the Chinese artistic spirit.

As early as the Pre-Qin period, the Classic of Music took "emotion is stirred within and takes form in words" as the starting point of its discussion, pointing out the interaction between "form" and "emotion". Here, "form" is not a simple external form, but the natural flow of emotion in the body and movements, and the sensory manifestation of "meaning". Later, "Dashing Life" in Zhuangzi proposed "joining the natural with the natural," advocating the fit between the movement of the body and the movement of the mind, making "dance" a rhythmic expression of life self-awareness. It can be said that "form" in ancient Chinese artistic concepts was never a physical body on the material level, but a carrier of spirit and qiyun; while "meaning" is generated in this process of "the flow of vital energy," moving from the rhythm of the body to the imagery of the mind.

Entering the modern aesthetic context, Zong Baihua deepened this thought with his unique "dance" theory. He pointed out that the worldview of the I Ching is "one Yin and one Yang is called Dao," and all things are born from the qi of heaven and earth, and the flow of qi is the rhythm of life. The perceptible manifestation of this rhythm is "dance"—it is the visualization of the "generative way". Zong Baihua therefore believed: "Dance, this highest degree of rhythm and order, is simultaneously the highest degree of life and passion". In his view, "form" is the appearance of rhythm, and "meaning" is the generation of rhythm—the two are not separated from each other, but have a "substance and function" relationship of "containing stillness in motion" and "revealing spirit through form". This viewpoint provided a theoretical basis for understanding the internal logic of Chinese dance aesthetics: that is, the morphological movement of the body does not serve formal beauty, but conveys the meaning of the mind through the flow of qiyun.

The view of the body in the contemporary philosophical context gives a new explanatory path to this ancient proposition. Merleau-Ponty pointed out in Phenomenology of Perception that the body is not an object perceiving the world, but a field where meaning is generated. The form of the body generates meaning because of perception; the movements of dance obtain symbolic power because of the flow of bodily intentionality. This coincides with the ancient Chinese thoughts of "depicting spirit through form" and "both spirit and form being complete": the body is not a carrier, but a way of generating thought. Thus, the "form" of dance is not a simple external performance, but the concretization of spiritual activities; the "meaning" of dance is not an emotional vent of the heart, but the result of the joint action of bodily perception and cultural memory. The reason why traditional dance can transcend the times and be unceasing is precisely because it contains meaning in "form" and manifests form in "meaning".

The ideological basis of "from form to meaning" was thus established. It contains triple logic: first, "vital energy thinking" at the worldview level—replacing entities with flow and replacing static states with generation; second, "conveying meaning through form" at the art theory level—revealing the existence of spirit through the rhythm and structure of the body; third, "mutual reflection of spirit and form" at the aesthetic level—letting viewers realize the flow of meaning in perceiving form. This thought runs through various fields of Chinese art and is particularly vivid in dance. The form of dance never stops at modeling but is composed of the movement of "qi" and the circulation of "meaning"; the beauty of dance is not in the precision of external form, but in the internal breathing and charm. Just as Zong Baihua said: "The life of art lies in its rhythm". Form is the body of rhythm, and meaning is the soul of rhythm; the two are born together and manifest each other.

Therefore, "from form to meaning" is not only an artistic logic but also an aesthetic attitude. It allows us to no longer be limited to the imitation of form when facing tradition, but to use the body as a medium to re-experience the "movement of qiyun" within it. When the boundary of form is opened by the meaning of perception, the meaning of dance transcends the technical level and becomes a contemporary expression of cultural spirit. Thus, traditional dance elements are no longer restored historical symbols, but cultural energy that can be regenerated. In this sense, "from form to meaning" is a continuous movement of thought—both looking back at classical roots and pointing to modern creation; it is both an aesthetic proposition and the way of breathing between the body and culture.

2."Form" and "Meaning": Artistic Archetypes in Somatic Language

In the art of dance, the body serves not merely as a representational tool but as a primary site for the generation of meaning. The pursuit of "Form" (Xing) and "Meaning" (Yi) in traditional dance facilitates a spiritual sublimation from technique to essence via the somatic medium. Within classical Chinese aesthetics, the discourse on the "Form-Meaning" relationship is essentially a philosophical inquiry into the "Body-Spirit" duality. Revealing meaning through form and generating form through meaning constitute the internal circulation of Chinese art and the conceptual archetype upon which the aesthetic system of traditional dance is constructed. Consequently, the distinctiveness of Chinese art lies not in formal divergence but in its pervasive cognitive methodology: "depicting spirit through form and constructing realms through meaning."

Firstly, "Form" in traditional dance represents a codified somatic logic. It is not a collection of isolated poses but a "body method" (Shenfa) imbued with cultural cadences. From the "fluid elegance" of Han and Tang music-dance to the "subtle restraint" of the Song and Yuan dynasties, and the "strength within softness" of the Ming and Qing court dances, these morphologies embody the cultural ethos of "carrying the Dao through form." These "formulaic codes" (Chengshi) function as both kinetic paradigms and symbols of cultural memory; they encode ethnic somatic experiences into a system of rhythm and posture, externalizing the cultural spirit. Zong Baihua’s concept of "generative rhythm" identifies the vital foundation of this somatic logic—wherein the rhythmic flow of the body during every breath, contraction, extension, and transition constitutes the morphological representation of life.

Secondly, "Meaning" in dance is not an abstract concept but a synthesis of perception and affect generated through somatic kinesis. Traditional aesthetics emphasize "depicting spirit through form" and the "unity of form and spirit," which essentially signifies the externalization of "Meaning" through sensory bodily action. The dancer’s respiration, center of gravity, and rhythmic modulations serve as media for imagery. As Zhu Guangqian observed, "meaning resides beyond words, while spirit dwells within form"; thus, "Meaning" in dance flows incessantly within the dynamic generation of "Form." Somatic movement, therefore, transcends the mimesis of external objects to become a self-manifestation of internal Qiyun and spiritual rhythm. In other words, "Meaning" is not an appendage to "Form" but is experienced and created during the unfolding of "Form" itself.

Furthermore, from an artistic-genealogical perspective, the establishment of the "Form-Meaning" relationship defines a unique aesthetic paradigm for Chinese dance. Unlike Western ballet, which prioritizes spatial modeling and structural force, Chinese dance aesthetics focus on the "flow of momentum" (Shi) and the "connectivity of Qi." The sequence of initiation, development, transition, and resolution is not a mechanical shift but a continuous extension of internal vigor. Traditional theory posits that "form may break, but meaning remains connected" and "meaning leads the form," suggesting that the continuity of "Form" relies on the coherence of "Meaning," while "Meaning" requires the vessel of "Form" for its concrete realization. This relationship, described by Zong Baihua as "mutual rooting of motion and stillness, and reciprocal generation of void and solid," constitutes the most characteristically Eastern logic of expression.

Finally, the somatic language of dance is inherently an "imagistic" expression. Through symbolic postures, rhythms, and spatial trajectories, it reconstructs the relationship between the body and the cosmos. As Zong Baihua noted in his treatise on dance, the dancer’s movements align with the laws of Yin and Yang; their rotations and inclinations mirror the rhythms of the universe. In this conceptual framework, every rise and fall of the body is more than an individual movement—it is a manifestation of the "flow of vital energy" and a resonance between life and cosmic rhythm. Thus, "Form" and "Meaning" in traditional dance are not static entities but vital cadences within a spatio-temporal flow, representing a state of communion between the individual body and the rhythm of nature.

In conclusion, "Form" and "Meaning" constitute the two poles of Chinese somatic language: the formal pole of cultural codification and the spiritual pole of fluid imagery. When the body attains perceptive awakening through rhythm, "Form" ceases to be a constraint and becomes the generative source of "Meaning." Within this interdependent and dynamic relationship, Chinese dance establishes its unique aesthetic archetype—traversing into the meaning of life through somatic form and manifesting spiritual imagery through rhythmic motion.

3.The Symbiosis of "Form" and "Meaning": Paths for the Contemporary Expression of Traditional Dance Elements

The core challenge of contemporary choreography lies not merely in "inheriting" tradition, but in "activating" it. Between external form and internal spirit exists an aesthetic passage leading from Xing (Form) to Yi (Meaning). Traditional dance elements endure across time because their "Form" is never a static symbol, but a dynamic structure open to perception and reinvention; similarly, their "Meaning" transcends classical semiotics to be regenerated within contemporary somatic awareness. By adopting a "Form-Meaning" symbiosis, we can redefine contemporary expression—not as an accumulation of forms, but as a resurgence of meaning; not as a mimesis of antiquity, but as a re-perception of life’ s rhythm.

3.1 Abstraction of Movement Structures: From Formula to Imagery

Codified formulae (Chengshi) in traditional dance are the crystallization of historical somatic experiences—the sedimentation of "Form." However, the direct application of these formulae in contemporary contexts often results in a loss of vitality, reducing them to fossilized symbols. Consequently, abstraction emerges as a vital strategy—a process of "de-reification" rather than mere distortion. By distilling structural elements such as rhythm, center of gravity, and respiration, choreographers transform concrete movement vocabularies into spiritually oriented morphologies. For instance, the "Azure-Green Body Method" in A Panorama of Rivers and Mountains does not merely replicate Tang dynasty dance; rather, it adheres to the principle of "infusing dance with calligraphic intent." Through the circularity of the arms and the subtle inclination of the torso, it transforms "Form" into "Momentum" (Shi), which in turn generates "Meaning," recreating the aesthetic grandeur of landscape painting through abstract somatic contours. Thus, abstraction facilitates the regeneration of "Form"—revealing the deep rhythmic pulse of cultural spirit once the literal narrative is stripped away.

3.2 Symbolization of Imagery: From Narrative to Spirit

The transition from "Form" to "Meaning" is predicated on the potential for symbolic generation. The aesthetic core of traditional Chinese art, including dance, resides in "Imagery" (Yixiang). Symbolic expression allows movement to transcend singular narrative functions, becoming a vessel for concepts and affects. In assimilating traditional elements, contemporary dance establishes symbolic visual semantics through spatial composition, prop utilization, and ensemble configurations. For example, the dance drama Confucius employs ritualistic gestures such as "folded hands," "bowing," and "prostrating" as motifs. Through rhythmic variations, the physical form of "Ritual" (Li) is sublimated into the spirit of "Benevolence" (Ren). Similarly, in Great Dream of Dunhuang, the "caressing of sleeves" and "rotation of wrists" symbolize the awakening and flow of Buddhist nature, transforming the individual body into a metaphorical space for cultural belief. This symbolic path ensures that "Meaning" is no longer an appendage to external narration but an internal spiritual catalyst for the dance itself.

3.3 Aesthetic Reconstruction: Contemporary Manifestations of "Form-Meaning" Symbiosis

The ultimate goal of the "Form-Meaning" transition is to establish a novel aesthetic structure. In contemporary contexts, the revitalization of traditional elements signifies an aesthetic reconstruction of how beauty is perceived and how meaning is generated. This marks a shift from "somatic representation" to the "reconstruction of aesthetic experience," and from "formal imitation" to "meaningful resonance." The crux of contemporary expression lies in a dynamic equilibrium: without Form, Meaning lacks a vessel; without Meaning, Form loses its soul.

Firstly, this reconstruction is evident in the **redefinition of the spectator-performer relationship**. Traditional aesthetics often centered on a "gaze-based" model, maintaining a distance between the stage and the observer. Contemporary expression, however, emphasizes "synesthesia" and "presence"—the spectator becomes a participant in imagery-generation. In the work Soul of Qin Terracotta Warriors, the choreographer utilizes rhythmic shifts in lighting and ensemble breath to allow the audience to "perceive the motion of Form and realize the birth of Meaning" within a shared spatio-temporal field. This "resonant" aesthetics transforms "Form" and "Meaning" from a unidirectional transmission into a collaborative experiential process.

Secondly, it involves the **translation of cultural contexts and spiritual renewal**. While traditional "Meaning" is rooted in Confucian, Daoist, or Zen philosophies, contemporary dance re-activates these spirits within a globalized context, transforming classical imagery into modern emotional structures. For instance, A Panorama of Rivers and Mountains translates the "rhythmic vitality" of classical aesthetics into a contemporary visual perceptual structure; The Rite of Spring: Classic of Mountains and Seas converts the "Daoist" worldview of "Nature's Way" into a contemporary philosophical inquiry on life’s resonance through primal physical power.

Finally, the core of this reconstruction is **symbiotic generation**. Within this new system, "Form" is a dynamic carrier of "Meaning," while "Meaning" attains sensory manifestation through movement. Zong Baihua’s "generative rhythm" serves as the internal logic here—where Xing and Yi are mutually constitutive (Ti-Yong). In my own creative practice, Cloud Sleeves (Yun Xiu), this relationship is central to the work’s architecture. Using "clouds" as the image and "sleeves" as the form, the piece seeks a path to spiritual imagery between traditional vocabulary and modern somatic perception. The sleeve's line is the externalization of "Form," while the cloud's flow is a metaphor for "Meaning"; their spatial interplay facilitates a transition from the visible to the intangible. By guiding the spectator through somatic logic rather than narrative, the work achieves what Chinese aesthetics calls "the image beyond the image, the meaning within the meaning."

In summary, the contemporary expression of traditional dance elements is an integrated systemic renewal. Through the reconstruction of spectator relations, the translation of cultural contexts, and the symbiotic generation of Form and Meaning, contemporary dance achieves a creative "attainment of meaning through form." This reconstruction ensures the continuity of traditional spiritual imagery while imbuing the "Form-Meaning" logic of Eastern aesthetics with renewed vital tension.

Conclusion

The transition "from form to meaning" represents not only an aesthetic methodology for artistic creation but also a spiritual recursion of Chinese dance culture. The contemporary value of traditional dance elements lies not in the restoration of external forms but in the revitalization of their spirit; it resides not in the mere continuation of archaic techniques but in the reactivation of the body and perception, enabling classical aesthetics to radiate a renewed vitality within a contemporary spatio-temporal framework.

As demonstrated in the preceding analysis, the **abstraction of "Form"** liberates traditional formulae from fixed syntaxes, integrating them into a fluid spatial logic. The **symbolization of "Meaning"** transforms classical imagery into perceptual symbols of contemporary consciousness. Furthermore, the **aesthetic reconstruction of the "Form-Meaning" symbiosis** completes the translation of traditional dance aesthetics into contemporary experiential structures through the reconfiguration of spectator relations and cultural contexts. This process is essentially a cultural resurgence defined by "attaining meaning through form and revealing the Dao through meaning"—a transition that transforms dance from a historical legacy into a vibrant, contemporary presence. Consequently, the trajectory from "Form" to "Meaning" signifies a modern return to the essence of Chinese aesthetics. As Zong Baihua posited, the pinnacle of art lies in "generative rhythm"—the harmonious resonance between life and the cosmos, body and spirit. If contemporary choreography can perceive the genesis of "Meaning" within the rhythm of "Form," it can transcend formal innovation to reconnect with the metaphysical roots of Chinese art. In this context, "Form" is not merely the appearance of movement but a cultural cadence; "Meaning" is not merely an abstract emotion but a manifestation of somatic perception. Their symbiosis constitutes the ultimate aesthetic aim of Chinese art: "depicting spirit through form and actualizing form through meaning."

In summary, I contend that the contemporary expression of traditional dance elements should be understood as a dual generative process of aesthetic and cultural renewal: it reshapes classical imagery through somatic rhythm and achieves the re-manifestation of cultural spirit through formal modernization. Future research in Chinese dance aesthetics should continue to explore the dynamic interaction of the "Form-Meaning" relationship, investigating how body, space, time, and perception co-constitute meaning in contemporary contexts. This will allow traditional dance to serve as an authentic artistic bridge connecting antiquity and modernity, form and spirit. "From form to meaning" is more than an artistic path; it is a cultural stance—enabling Chinese dance to articulate the Eastern aesthetic narrative of life, time, and spirit on the global stage through its unique Qiyun and rhythm.

References

[1] Zhu, F. Q. (2018). Zong Baihua "wu" de chanshi yu Zhongguo wudao meixue tezheng [Zong Baihua's interpretation of "dance" and the aesthetic characteristics of Chinese dance]. Journal of Beijing Dance Academy, (02), 41–46.

[2] Liu, J. L. (2015). Cong Zong Baihua meixue sixiang kan Wei Jin wudao yishu fengge [On the artistic style of Wei and Jin Dynasties' dance from the perspective of Zong Baihua's aesthetic thought]. Journal of Beijing Dance Academy, (04), 22–27.

[3] Su, X. (2021). Wudao de chuantong yu dangdai, duihua yu gongxiang——2020 nian Beijing Wudao Xueyuan Minzu Wudao Wenhua Yanjiu Jidi nianhui ji chuantong wudao wenhua de dangdai shijianxing yanjiu yantaohui ceji [Tradition and contemporary, dialogue and sharing: A report on the 2020 annual meeting of the Ethnic Dance Culture Research Base of Beijing Dance Academy]. Journal of Beijing Dance Academy, (02), 140–144.

[4] Wang, X. K., & He, J. Q. (2018). Xiandai yu chuantong de jiaorong: Zhongguo xiandaiwu zhong de chuantong wenhua yuansu [The integration of modernity and tradition: Traditional cultural elements in Chinese modern dance]. Journal of Henan Normal University (Philosophy and Social Sciences Edition), 45(01), 152–156.

[5] Xia, J. (2022). Dangdai wudao de minzuxing biaoda yu jiazhi zhuiqiu [National expression and value pursuit of contemporary dance]. Journal of Beijing Dance Academy, (02), 15–21.

Global Academic Frontiers

Volume 4 • Issue 2 • June 2026

ISSN 2995-5688

9 772995 568261 06

Free Copy