

Article

Aquaculture Industry Composition, Distribution, and Development in China

Zixuan Ma ^{1,2,3} , Hao Xu ^{1,2,3,4} , Richard Newton ⁵ , Anyango Benter ^{1,2,3} , Dingxi Safari Fang ⁶ , Chun Wang ^{1,2,3}, David Little ⁵ and Wenbo Zhang ^{1,2,3,*} 

- ¹ China-ASEAN “The Belt and Road” Joint Laboratory of Mariculture Technology, Ministry of Science and Technology of China, Shanghai Ocean University, Shanghai 201306, China
 - ² Shanghai Engineering Research Center of Aquaculture, Science and Technology Commission of Shanghai Municipality, Shanghai Ocean University, Shanghai 201306, China
 - ³ Key Laboratory of Integrated Rice-Fish Farming, Ministry of Agriculture and Rural Affairs of China, Shanghai Ocean University, Shanghai 201306, China
 - ⁴ Fisheries and Aquaculture Division, Food and Agriculture Organization of the United Nations, Viale delle Terme di Caracalla, 00153 Rome, Italy
 - ⁵ Institute of Aquaculture, University of Stirling, Stirling FK9 4LA, UK
 - ⁶ Emmett Interdisciplinary Program in Environment and Resources (E-IPER), Stanford University, Stanford, CA 94305, USA
- * Correspondence: wb-zhang@shou.edu.cn

Abstract

Aquaculture is the fastest-growing food production sector globally. As its largest producer, China plays a pivotal role in ensuring aquatic food supply and supporting the blue economy. Despite its massive scale, a systematic understanding of the geographic distribution, structural composition, and drivers of China’s aquaculture value chain remains limited. We comprehensively characterized the sector’s composition, spatiotemporal evolution, and structural dynamics. We compiled and analyzed over 2.85 million enterprise registration records from the TianYanCha database, applying rigorous industry classification, spatial mapping, correlation analysis, and bottleneck assessment with natural and socioeconomic variables. Results show that policy reforms, notably the 2013 Company Law amendment and 2016 aquaculture certification measures, drove sharp increases in enterprise registrations, particularly in retail and farming. Enterprises are highly clustered in the Yangtze River Basin, Pearl River Delta, and southeastern coast, with inland expansion along major river systems. Strong interdependencies exist among sectors, while wholesale remains numerically scarce, forming a structural bottleneck. Standardization levels are low. Foreign investment, though under 5%, concentrated in processing and distribution, contributed to advanced technologies in the 1990s–2000s. These findings highlight rapid formalization, regional clustering, and structural imbalances, suggesting that enhancing formalization and addressing intermediary bottlenecks could improve sector resilience and efficiency.

Keywords: enterprise registration; policy reforms; regional clustering; structural bottleneck; value chain



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1. Introduction

Aquatic foods are part of healthy diets, contributing to better nutrition [1]. It is an excellent source of protein and highly unsaturated fatty acids, such as EPA and DHA [2]. Aquaculture has become the fastest-growing food production sector globally, reaching

94 million tonnes in 2022 and accounting for 51% of total aquatic animal production, surpassing capture fisheries for the first time due to rapid advances in production technologies and value chains [3,4]. China is the leading producer in this field, contributing approximately 36% of the global aquatic animals produced in 2022 [4]. Over the past four decades, China's aquaculture industry has undergone profound structural and spatial transformations, reinforcing its leading position in global aquaculture production through significant policy reforms, technological innovation, and market-oriented economic shifts.

In 2024, China's total aquatic animal production reached 73.58 million tonnes, with aquaculture contributing 60.60 million tonnes and capture fisheries 12.98 million [5]. The freshwater aquaculture production (35.32 million tonnes) notably exceeds mariculture production (25.28 million tonnes), with a total value of CNY 3.42 trillion [5], due to China's extensive inland water resources that are favorable for freshwater species culture, greater ease of environmental control, and established practices in these regions compared to the coastal zones, which support mariculture [6]. The total value output of fisheries and aquaculture showed a ratio of 49:22:29 across primary industry (fish farming and capture fishing), secondary industry (processing, manufacturing, and value-added production), and tertiary industry (distribution, marketing, and service), respectively [5]. The distribution of aquaculture production in China exhibits a clear regional specialization driven by natural conditions—such as warmer temperatures that enable shorter growth cycles and abundant water resources from precipitation-fed river and lake systems—and socioeconomic factors—including proximity to high population density areas for fresh product consumption, influenced by dietary preferences emphasizing ingredient freshness and the perishable nature of aquatic products [7–10]. Current inland aquaculture in China is predominantly concentrated in the Yangtze River Basin and Pearl River Basin [11,12], while mariculture is distributed across coastal provinces [13,14]. Spatial patterns demonstrate a higher density and concentration of mudflat aquaculture in northern regions compared to southern areas [15], while raft culture zones are predominantly located in northern and central coastal areas, and cage aquaculture is primarily concentrated in the coastal regions [14].

China's aquaculture development benefited from the "reform and opening-up" policy initiated in 1978, which transitioned the sector from a centrally planned economy to a market-oriented one, fostering rapid growth, innovation, and modernization [16]. A number of policies were introduced to encourage aquaculture development, especially the policy that prioritized aquaculture over capture fisheries in 1985 [17]. China's economic reform also lifted the price control, shifting the aquaculture industry from a planned to a market economy and accelerating the development of aquaculture and related industries. Additionally, the "Fisheries Law of the People's Republic of China" enacted in 1986 provided essential legal support for aquaculture development, which established the development policy of "Prioritizing Aquaculture" and optimized the industrial structure [18]. China attracted substantial foreign investment, which brought capital and various advanced technologies such as the feed-based aquaculture systems, modern pelleted aquafeed, innovations in broodstock selection, genetic enhancement, and the introduction of new equipment [19–23]. Entering the 21st century, China's accession to the World Trade Organization (WTO) triggered a dramatic surge in aquatic product exports [24]. In recent years, aquaculture production has gradually increased at a slower pace, driving the development of the aquatic economy and related industries [25–27]. There is a fundamental shift from capture-dominated to aquaculture-dominated, with aquaculture's share increasing from 28% to 82% between 1979 and 2024.

China's aquaculture value chain includes farming, processing, wholesale, retail, cold storage, transportation, hatchery, feed, medicine, tools, machines, and technological extension. All segments are interconnected and interdependent, each playing a vital role in delivering products to consumers [28], with rapidly increasing production and transformations in feed composition, production technologies, farm management, and value chains [3]. Within the aquaculture value chain, when a particular segment contains fewer enterprises relative to the numerous players upstream and downstream, and these enterprises control critical market information, they acquire significant market power. This enables them to squeeze upstream suppliers' profits through price suppression while simultaneously imposing inflated or discriminatory prices on downstream buyers, thereby creating a bottleneck effect that restricts the smooth flow of goods and equitable profit distribution throughout the value chain [29]. Value chain bottlenecks refer to vulnerable nodes in complex supply chain networks that, due to their irreplaceability, connection weights, or positional characteristics, cause disproportionate value losses to downstream focal firms through multi-level transmission effects when their operations are disrupted [30]. In the aquaculture sector, such bottlenecks may lead to product flow disruptions, diminished farmers' bargaining power, and abnormal price fluctuations in retail markets [31,32]. However, value chain bottleneck identification remains vague, particularly concerning empirical validation of market dominance by intermediaries (e.g., wholesalers) and their effects on value distribution using large-scale enterprise data.

As the global leader of aquaculture, China's aquaculture industry structural optimization, spatial allocation, and sustainable development are pivotal to ensuring food security and advanced blue economy growth. Despite China's aquaculture industry garnering significant attention, the current understanding of the composition, distribution, enterprise investment scales, and systematic development across China's value chain remains limited and fragmented. For example, the role of foreign capital in China's aquaculture development is poorly characterized. Current studies focus predominantly on isolated segments of the aquaculture supply chain without systematically integrating upstream and downstream linkages or examining the entire value chain.

Spatiotemporal analyses of the aquaculture industry are particularly scarce. Most spatial distribution research has been confined to provincial-level administrative units, lacking comprehensive nationwide assessments. Additionally, studies have predominantly utilized GIS-based identification methods, with coastal areas receiving more extensive and granular research attention than inland regions [15,33,34]. This disparity exists because inland aquaculture systems are diverse and fragmented, requiring advanced, tailored algorithms for accurate identification of features such as scattered small ponds and integrated rice–fish farming systems [14,35–37].

Recent advances in big data analytics and industrial data transparency have elevated such registration records to a pivotal research resource for industrial studies. Enterprise registration data from TianYanCha constitutes a rich information source regarding regional and national economic and industrial structures [38]. The temporal and geospatial attributes embedded in enterprise registration information [39] enable precise quantitative analysis, visualization, and systematic comprehension of aquaculture sector development. Previous studies have used business registration data from TianYanCha to assess the development status of China's hog farming industry [40] and studied the spatial distribution of enterprises in 35 major Chinese cities [41].

To address these research gaps, this study built a comprehensive high-resolution micro-entity dataset of over 2.85 million enterprise registration records from the TianYanCha database and established a comprehensive profile of China's aquatic industry dynamics, spanning China's entire aquaculture value chain.

This study systematically investigates China's aquaculture sector's composition, distribution, and development through TianYanCha data. Specifically, our analysis addresses five core research issues: (1) Empirical evidence on how key policies drive aquaculture industry changes over time and spatiotemporal evolution patterns, as well as the current configuration of enterprises across upstream, midstream, downstream, and support sectors in terms of quantity distribution, scale, and other characteristics. (2) Structural interdependencies among different sectors of the value chain and how enterprise distribution links with natural endowments (temperature, precipitation, marsh area, dry cropland area, cropland area, irrigated farmland area, coastline) and socioeconomic factors (population density, GDP per capita). Here, cropland area refers to all land used for growing crops, regardless of how the crops are watered; dry cropland area refers to all land without irrigation systems; irrigated farmland area refers to all land specifically equipped with irrigation systems. (3) Patterns of foreign participation regarding firm numbers, capital share, sectoral preferences, and temporal entry sequencing. The findings provide policy insights for industrial optimization and serve as a reference for other major aquaculture-producing nations. (4) Whether significant bottleneck segments exist, particularly in wholesale operations.

2. Materials and Methods

This study employs a comprehensive analytical framework to examine China's aquaculture industry structure, spatial distribution patterns, and temporal evolution through enterprise-level data analysis. Our methodology integrates multiple data sources, rigorous preprocessing procedures, and advanced analytical techniques to address research objectives. The methodological approach follows a systematic workflow encompassing data collection from diverse sources, comprehensive preprocessing and standardization procedures, multi-dimensional analysis using spatiotemporal mapping, financial analysis, and bottleneck assessment techniques, supported by robust quality control measures throughout the research process (Figure 1) and explained in sections below. This integrated framework enables a holistic understanding of China's aquaculture industry ecosystem while maintaining methodological rigor and ensuring reproducible results.

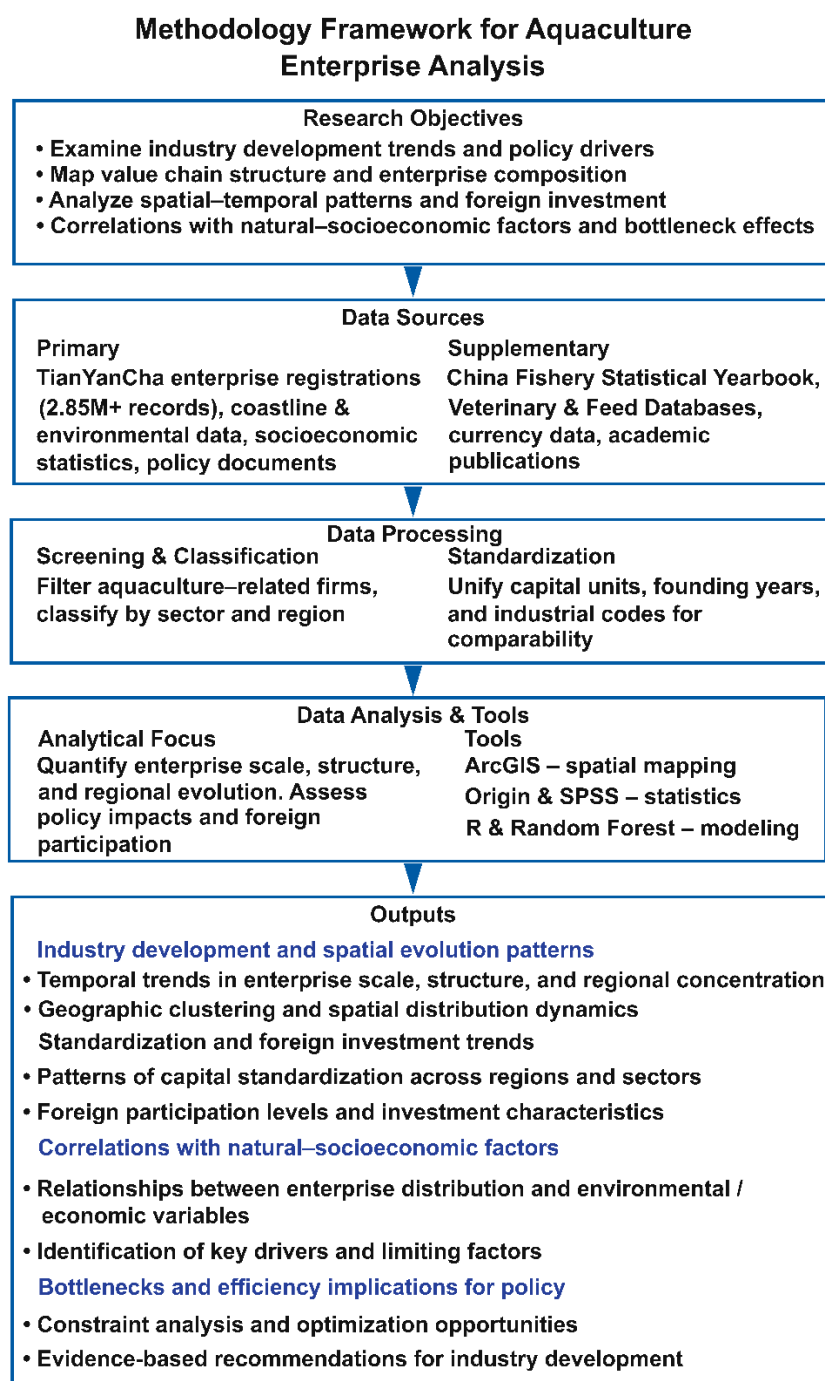


Figure 1. Methodology Framework for Aquaculture Enterprise Analysis.

2.1. Data Sources

We collected enterprise registration data from the TianYanCha business registry platform (<https://www.tianyancha.com/>) (accessed on 29 February 2024) in February 2024. We used the search keyword “水产”, which means “aquatic food” or “aquaculture” in English, obtaining over 2.85 million records.

We collected policy data from academic publications used in the timeline diagram. We annotate policies that coincide with key inflection points in the timeline of enterprise quantity changes. We collected enterprise registration data, policies, and socioeconomic (population density, GDP per capita) and natural endowment (temperature, precipitation, hydrography, coastline, land usage) data from various sources (Supplementary Information Table S1). Due to the lack of county-level coastline length data, we used ArcMap clipping

tools to extract the data boundaries on one side of the coastline and then calculated the coastline length of each county by dividing the extracted coastline boundaries according to county-level administrative units in ArcMap. The county-level coastline length data were used as a natural endowment variable in subsequent spatial and correlation analyses of enterprise distribution.

2.2. Data Preprocessing

2.2.1. Data Screening and Classification

We began by classifying industrial sections through keyword searches of business scope information, categorizing all valid data according to the classification outlined in the China Fishery Statistical Yearbook. As many enterprises have more than one aquaculture industry sector in their business scope information, one enterprise can be categorized into multiple aquaculture industry sectors. The classification of aquaculture industry sectors covers the following sectors: farming, processing, wholesale, retail (catering services not included), port, cold storage, transportation, recreation, hatchery, fine seed hatchery, feed sales, feed manufacturing, medicine sales, medicine manufacturing, tool, machine, cooperative, technology extension, research institute, and college and university (Supplementary Information Table S2). Compared with conventional hatcheries, fine seed hatcheries focus on the genetic improvement, selection, and maintenance of high-quality broodstock, often supported by the government.

To ensure analytical precision and industry-specific focus, this study concentrated exclusively on enterprises operating within aquaculture and their directly related industrial chains by implementing rigorous industry classification screening. The selected industries included farming, hatchery, cooperative, processing, feed, medicine, transportation, cold storage, technology extension, research institute, and college and university; tool, machine, recreation, and ports were included due to their direct involvement in and/or essential support for aquaculture production, processing, and distribution systems. Conversely, industries demonstrating minimal relevance to aquaculture value chains (e.g., coal mining, automobile manufacturing, real estate, utilities, and cultural/educational manufacturing) were excluded based on their low functional coupling with the aquaculture ecosystem (Supplementary Information Table S3). This targeted approach ensured all analyzed enterprises contributed meaningfully to understanding the aquaculture industrial complex while maintaining methodological rigor in sample composition.

After completing the industry classification, we refined our selection for feed production and aquaculture medicine manufacturing. For the feed industry, we referenced enterprises with annual sales exceeding 100,000 tonnes in 2024, which collectively account for approximately 89% of market share (Supplementary Information Table S1). Regarding aquaculture pharmaceutical manufacturers, we screened enterprises based on information from the National Veterinary Drug Basic Database. The enterprise registration data from the TianYanCha contained numerous aquatic veterinary drug retail companies, making it difficult to distinguish manufacturing enterprises from retailers. Since the National Veterinary Drug Basic Database includes all registered veterinary drug manufacturers in China, we used it to identify enterprises involved in aquatic veterinary drug production (see Supplementary Information Table S1).

2.2.2. Data Standardization

The raw dataset encompassed diverse information categories, from which we first extracted the data fields relevant to our study (Supplementary Information Table S4) and then conducted standardization procedures on selected original fields (Supplementary Information Table S5). The specific standardization approach was implemented as fol-

lows: company names and operational statuses remained unprocessed as they serve as qualitative identifiers or already follow a standardized format; registered capital and paid-in capital involving foreign currencies were uniformly converted to CNY based on the annual average exchange rate corresponding to the enterprise's founding year while preserving the original currency designation for subsequent analytical reference (Supplementary Information Table S6); establishment dates were simplified from the original "year-month-day" format to founding years to standardize temporal granularity for analysis; provincial/municipal/county classifications required no processing as their geographical data formats were already standardized; unified social credit codes and taxpayer identification numbers, sharing identical encoding structures, were parsed according to digit-based rules to extract registration authorities and institutional categories for categorical variable creation; while other fields including employee headcounts, company types, industry classifications, Website adoption rate, and business scopes remained unstandardized as their original formats satisfied analytical requirements.

2.3. Data Analysis

This study employed a comprehensive analytical framework to examine the aquaculture industry's structural dynamics, spatial distribution patterns, and temporal evolution (Figure 1). The methodology integrated multiple analytical approaches, including spatiotemporal mapping, correlation analysis, and bottleneck assessment, to address four primary research objectives: (1) empirical evidence of policy-driven industry changes and enterprise configurations, (2) structural interdependencies among value chain sectors and their relationship with natural and socioeconomic factors, (3) identification of potential bottleneck segments, and (4) patterns of foreign participation across sectors and periods.

2.3.1. Temporal and Spatial Analysis

The number of enterprises across the aquaculture value chain was analyzed through timeline charts, incorporating aquatic food production volumes and relevant policy milestones as temporal reference points.

We calculated the average enterprise lifespan as the difference between the current year and the establishment year, averaged across active enterprises by industry sector. Enterprise deregistration rates were determined by dividing currently deregistered enterprises by total enterprises in each sector. Website adoption rates were determined by the proportion of enterprises with official websites, e.g., the number of enterprises with official websites divided by the total number of enterprises. Insurance coverage rates were determined by the proportion of enterprises with insured personnel in the social welfare system, e.g., the number of enterprises with insured personnel divided by the total number of enterprises.

ArcGIS ArcMap software (version 10.2) categorized active enterprises by geographic regions. A three-tier mapping approach was employed based on enterprise density: provincial-level mapping for industries with fewer than 3000 enterprises, municipal-level for 3000–49,999 enterprises, and county-level for 50,000+ enterprises to achieve the best data visualization on the map. Enterprise counts were compiled in CSV format and visualized using graduated color symbology, with areas lacking data appearing as white regions.

To identify temporal evolution patterns across different geographic scales, industrial distribution maps were generated for 2000, 2010, 2015, 2020, and 2023.

Geographic visualization was conducted using ArcGIS ArcMap software with graduated color symbology based on quantity classification. Statistical analysis and visualization were performed using OriginPro 2021 (version: 9.8.0) software for correlation matrices and timeline charts.

2.3.2. Financial and Structural Analysis

We compiled total registered capital statistics for surviving enterprises across all industry sectors, with additional box plot analysis conducted for provinces with leading aquaculture production, representing both inland and coastal regions from northern and southern China. Before creating the box plots, we applied log₁₀ transformations to all data for better visualization. County-level correlation analysis was performed using Spearman's rank correlation method ($\alpha = 0.05$) to examine relationships between registered capital, enterprise numbers across sectors (aquaculture operations, seedling farms, feed companies, chemical suppliers, retail/wholesale), and socioeconomic factors (population density, GDP per capita). Missing values were handled through pairwise deletion, and correlation matrices were generated using Origin software.

We organized the enterprise numbers of each industry at the county level, conducted correlation analysis and significance testing ($p < 0.001$) among different industries, and then created charts for visualization.

We employed Random Forest regression models to predict and analyze the key factors influencing the total number of enterprises, the number of aquaculture farm enterprises, and the registered capital of aquaculture farms. As an advanced ensemble learning algorithm, Random Forest enhances model performance by constructing multiple independent decision trees and combining their prediction results. This algorithm is based on the bootstrap aggregating (bagging) strategy, randomly selecting sample subsets and feature subsets during training to construct each decision tree, ultimately generating predictions through a mean voting mechanism for regression problems while producing importance scores for each feature. It demonstrates excellent overfitting resistance and prediction accuracy, exhibiting robustness to data noise and outliers [42].

The dataset used each county's population, GDP, temperature, and other factors as feature variables, with the total number of enterprises, and the number of aquaculture farm enterprises in each county as target variables. To ensure experimental reproducibility, a random seed of 123 was set (`set.seed(123)`), and a stratified random sampling strategy was adopted to split the dataset into training and testing sets at an 8:2 ratio, with the training set used for model learning and the testing set for evaluating model generalization performance. The regression model was constructed using R's `randomForest` function, with the number of decision trees (`ntree`) set to 500 to balance model performance and computational efficiency. Each decision tree was built during model training based on bootstrap resampled training samples and randomly selected feature subsets, effectively reducing variance and improving prediction accuracy. Feature importance scores were calculated using the `importance()` function, employing the percentage increase in mean squared error (`%IncMSE`) as the evaluation metric to quantify each feature's contribution to model prediction performance, with bar charts used for visualization to intuitively display the relative contribution of each feature to model predictions.

To understand the relationships between features and target variables, the correlation matrix was used. The `test` function was used to calculate Pearson correlation coefficients between environmental variables and target variables, obtaining correlation coefficient matrices and their significance levels (*: $p = 0.05$, **: $p = 0.01$, ***: $p = 0.001$). Correlation heatmaps were used for visualization, with color gradients representing correlation strength: purple representing positive correlation, green representing negative correlation, and color intensity reflecting the degree of correlation, revealing association patterns between features and target variables. In the model evaluation phase, a multi-metric evaluation framework was established, including mean absolute error (MAE) for measuring average deviation between predicted and actual values, root mean square error (RMSE) for assessing predic-

tion accuracy with greater sensitivity to larger errors, and coefficient of determination (R^2) for quantifying the model's ability to explain data variation.

2.3.3. Bottleneck and Foreign Investment Analysis

We analyzed enterprise numbers across the value chain (hatchery, farming, wholesalers, processing, transportation, and retail) nationally and in leading aquaculture provinces (2023) to identify potential bottleneck segments using bottleneck effect theory.

We identified foreign-funded enterprises across all industries, calculating the foreign investment proportion (paid-in capital) and the foreign enterprise proportion by number. We also analyzed temporal patterns through annual timeline charts tracking foreign investment amounts and enterprise proportions. Since no foreign investment participated in wholesale, medicine manufacturing, cooperatives, technology extension, research institutes, and colleges and universities, these industries were omitted from the timeline charts.

We assessed standardization and social welfare levels through insurance coverage rates (enterprises with social insurance records/total enterprises) and informatization rates (enterprises with official websites/total enterprises) across industry sectors.

3. Results

3.1. Policy, Number of Enterprises, Registered Capital, and Changes over Time

We collected information on 2.85 million enterprises using search keywords from the TianYanCha database. After data screening, 2.77 million enterprises were selected for further analysis. There were 0.96 million enterprises categorized into one aquaculture industry sector, and 1.33 million enterprises were categorized into multiple aquaculture industry sectors.

We found that policies and regulations have a greater effect on the number of registered enterprises than production changes (Figure 2). In the early period, enterprises could operate without registration requirements, resulting in minimal registered enterprise numbers. The subsequent refinement of administrative management systems and increased marketization since the 21st century led to progressive industry standardization, potentially explaining the "explosive growth" in registered enterprises. Key policies include the Amendments to China's Company Law in 2013, which lifted the limit on minimum registered capital and loosened control on enterprise registration. New enterprises registered every year exceeded 10,000 in 2000, averaged over 0.26 million annually after 2014, and reached 2.77 million in 2023. The Opinions of the Ministry of Agriculture on Stabilizing the Right to Use Aquaculture in Water Areas and Tidal Flats and Promoting the Certification and Registration Work for Aquaculture in Water Areas and Tidal Flats in 2016 are promulgated to fully utilize resources to develop aquaculture, thereby increasing farmers' income and stabilizing aquaculture development. Previously, the regulation did not specify the water and mudflat areas that could be used for aquaculture. This exponential growth primarily reflects the expansion of administrative registration coverage and the formalization process of business entities, rather than the proportional expansion of actual production scale.

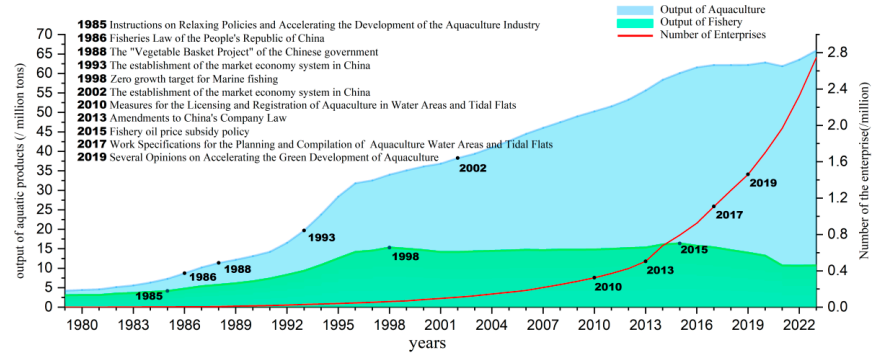


Figure 2. Aquaculture and capture fisheries production, number of active aquaculture value chain enterprises, and major policies in China in 1979–2023.

The retail sector had the highest number of enterprises in 2023, followed by farming, processing, and transportation (Figure 3). Most sectors experienced growth after 2010, with particularly steep increases after 2015, when the retail and farming industries demonstrated prominent growth. The farming sector had the highest total registered capital, followed by the retail, transportation, and processing sectors. The registered capital presented an overall steady upward trend over time across all sectors. Still, compared to the growth in registered capital, the increase in enterprise numbers has been relatively more gradual and stable.

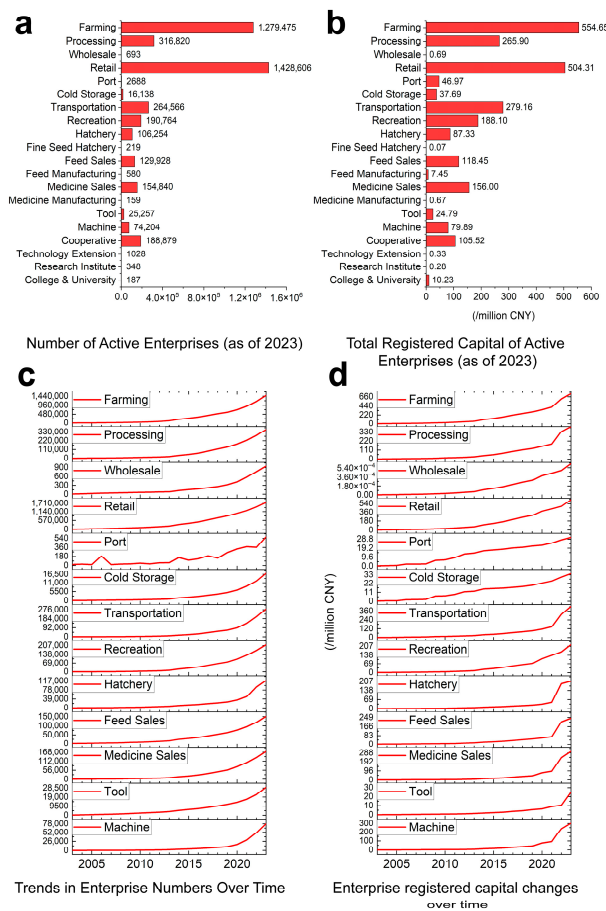


Figure 3. Active aquaculture value chain enterprises' number, registered capital, and changes over time. (a) Number of active aquaculture value chain enterprises in 2023. (b) Registered capital of active aquaculture value chain enterprises in 2023. (c) Number of active aquaculture value chain enterprises between 2003 and 2023. (d) Registered capital of active aquaculture value chain enterprises between 2003 and 2023.

We found substantial variation in capital requirements and investment scales across different aquaculture-related sectors (Figure 4). College and university operations exhibited the highest median capital levels, followed by feed manufacturing, medicine manufacturing, and port sectors, while technology extension, research institutes, and fine seed hatcheries maintained the lowest typical investment requirements. Retail showed the most extensive range, indicating substantial variation from minimal to huge capital investments. In contrast, specialized sectors such as cooperative and fine seed hatcheries showed more concentrated capital distributions with narrower ranges and fewer extreme values. Additionally, institutional sectors displayed distinctly different patterns, with technology extension showing the lowest capital requirements.

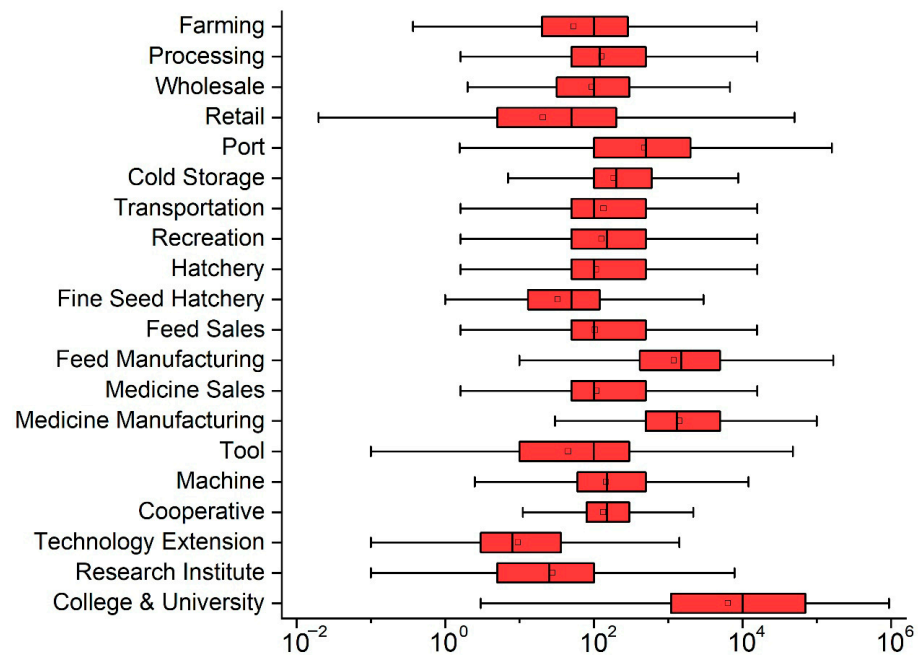


Figure 4. Log₁₀ transformed registered capital (CNY) of active aquaculture value chain enterprises in 2023.

3.2. Geographic Distribution and the Temporal and Spatial Changes

China's aquaculture and related industries currently exhibit pronounced spatial clustering characteristics in their distribution (Figure 5), with patterns jointly influenced by natural water systems, economic development levels, and population distribution. The whole industrial distribution map reveals that aquaculture-related industries are highly concentrated in the Yangtze River Basin, Pearl River Delta, and southeastern coastal regions, forming typical industrial clusters in Jiangsu, Guangdong, Zhejiang, Fujian, Anhui, and Hubei provinces. This pattern highly corresponds with the distribution of China's major rivers and lakes, as water systems such as the Yangtze River, Pearl River, Poyang Lake, Dongting Lake, and Taihu Lake provide abundant water resources and ecological environments for aquaculture. The regions with the highest distribution density of aquaculture include the Jiangsu coast, Guangdong's Pearl River Delta, the Fujian coast, Hunan's Dongting Lake region, and Hubei's Jiangnan Plain, representing China's core aquaculture areas. Processing industries are highly concentrated in coastal provinces such as Guangdong and Shandong and river-adjacent cities like Wuhan.

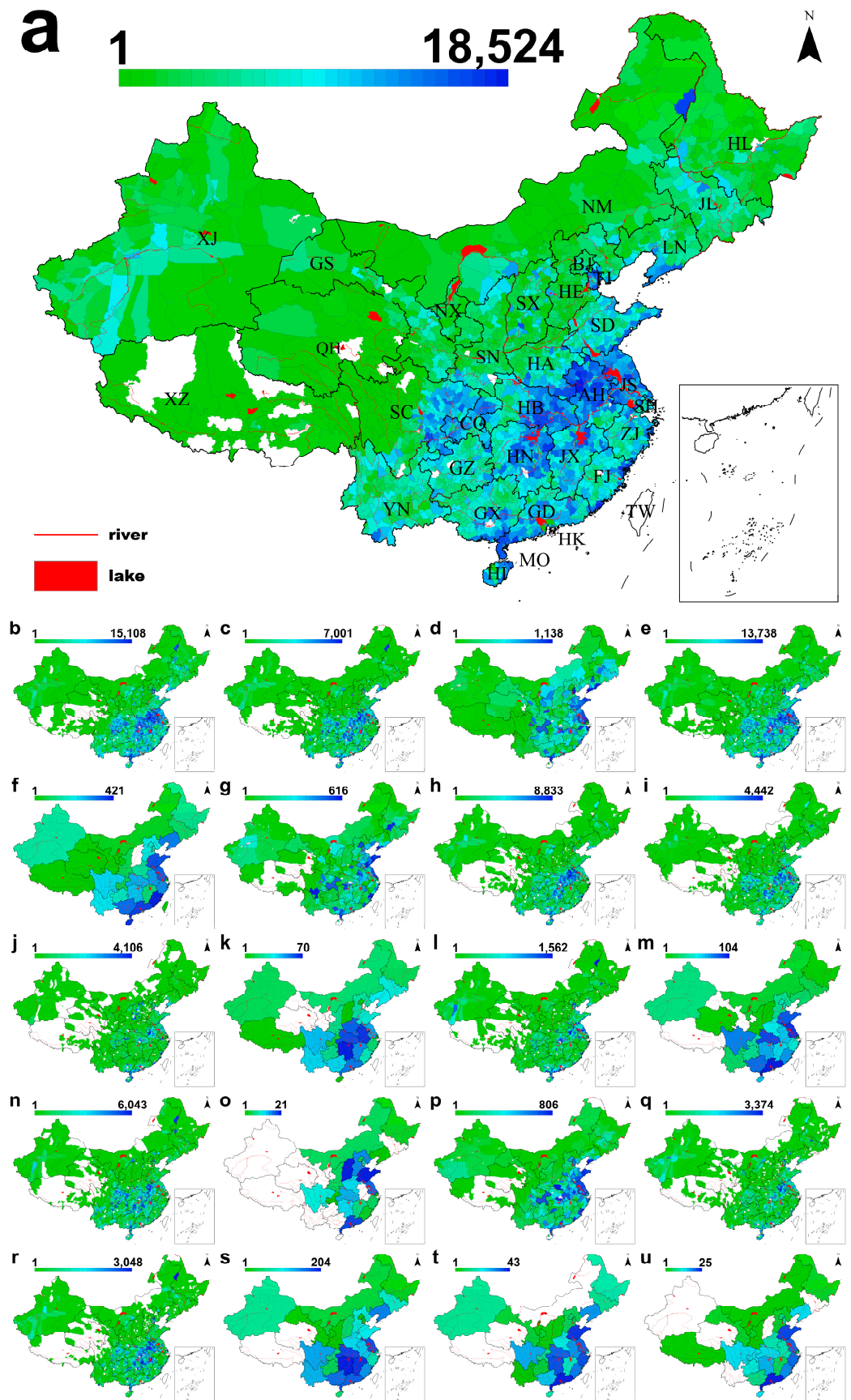


Figure 5. Distribution of active aquaculture value chain enterprises in China in 2023. (a) Overall sector; (b) farming; (c) processing; (d) wholesale; (e) retail; (f) port; (g) cold storage; (h) transportation; (i) recreation; (j) hatchery; (k) fine seed hatchery; (l) feed sales; (m) feed production; (n) medicine

sales; (o) medicine manufacturing; (p) tool; (q) machine; (r) cooperative; (s) technology extension; (t) research institute; (u) college and university. (a–c, e, h–j, l, n, q, r) are data maps disaggregated at the county level, (d, g, p) district level, and (f, k, m, o, s, t, u) province level. The two-letter abbreviations for Chinese provincial-level administrative divisions follow the ISO 3166-2: CN Standard. Complete list: AH: Anhui; FJ: Fujian; GS: Gansu; GD: Guangdong; GZ: Guizhou; HI: Hainan; HE: Hebei; HA: Henan; HL: Heilongjiang; HB: Hubei; HN: Hunan; JS: Jiangsu; JX: Jiangxi; JL: Jilin; LN: Liaoning; QH: Qinghai; SD: Shandong; SX: Shanxi; SN: Shaanxi; SC: Sichuan; YN: Yunnan; ZJ: Zhejiang; GX: Guangxi; NM: Inner Mongolia; NX: Ningxia; XZ: Xizang (Tibet); XJ: Xinjiang; BJ: Beijing; CQ: Chongqing; SH: Shanghai; TJ: Tianjin; HK: Hong Kong; MO: Macau; TW: Taiwan. Data source from reference [43].

From the year 2000 to 2023, the spatial and temporal distribution of enterprises in both the “overall sector” and “farming” sector in China expanded in scale and density, with pronounced regional clustering and movement from coastal to inland areas, especially along the Yangtze River (Figure 6). In 2000, the number of enterprises was sparse, primarily concentrated in a few coastal and central provinces such as Jiangsu, Zhejiang, and Guangdong. By 2010, there was a marked increase in enterprise density, particularly around the Yangtze River Delta and Pearl River Delta regions, indicating the initial stages of industrial clustering. In 2015, more inland regions such as Hunan, Hubei, and Anhui showed increasing enterprise presence, reflecting a spatial diffusion from coastal to inland provinces. In 2020, the maps revealed a widespread proliferation of overall sector and aquaculture farm enterprises, with eastern and southeastern regions becoming hotspots. By 2023, the distribution pattern exhibited peak concentration in the Yangtze River Basin and southeastern provinces, with extensive clustering also emerging in southwestern and northern China. The expansion closely aligns with major river and lake systems, indicating a strong correlation between hydrographic features and aquaculture enterprise development.

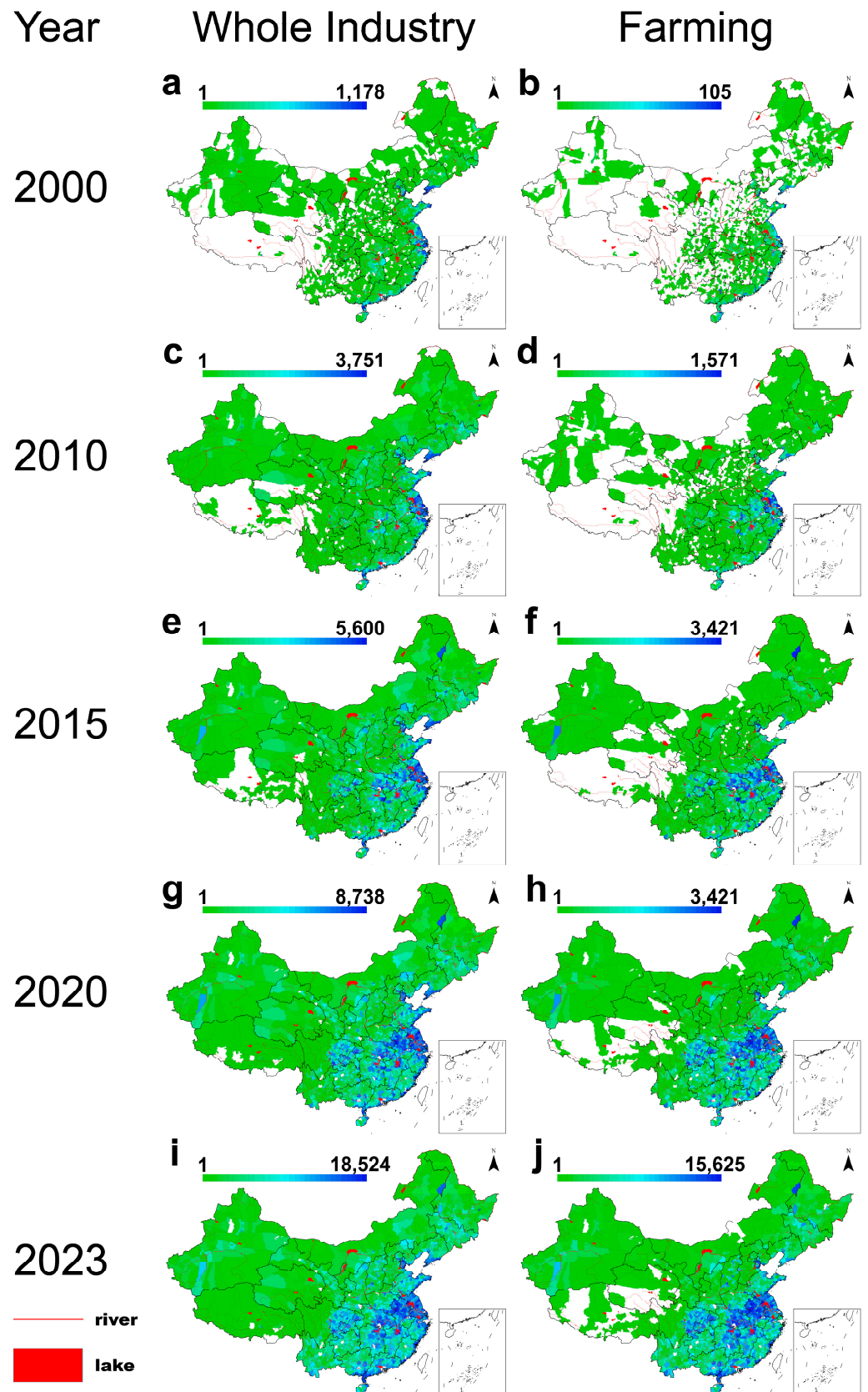


Figure 6. The temporal and spatial changes in active aquaculture value chain enterprises in China. (a) Number of active aquaculture value chain enterprises of the overall sector in 2000. (b) Number of active aquaculture value chain enterprises of farming in 2000. (c) Number of active aquaculture

value chain enterprises of the overall sector in 2010. (d) Number of active aquaculture value chain enterprises of farming in 2010. (e) Number of active aquaculture value chain enterprises of the overall sector in 2015. (f) Number of active aquaculture value chain enterprises of farming in 2015. (g) Number of active aquaculture value chain enterprises of the overall sector in 2020. (h) Number of active aquaculture value chain enterprises of farming in 2020. (i) Number of active aquaculture value chain enterprises of the overall sector in 2023. (j) Number of active aquaculture value chain enterprises of farming in 2023.

3.3. Sectoral Variations in Operational Performance and Formalization Levels

We found sectoral variations in operational indicators across different aquaculture-related sectors, including average enterprise lifespan, deregistration rates, insurance coverage rates, and website adoption rates (Figure 7). Currently, approximately 0.87 million enterprises have been deregistered (Supplementary Information Figure S1), 0.28 million enterprises have social insurance records, and 34,700 enterprises have official websites. Medicine manufacturing demonstrates the longest average enterprise lifespan, followed by research institutes, while most other sectors show lifespans between 3 and 6 years. Research institutes and technology extension show notably high deregistration rates, while most commercial sectors maintain lower deregistration rates below 30%. Website adoption rates are generally low across all sectors, with most industries showing rates below 10%, though medicine manufacturing, colleges, and universities achieve higher adoption rates of approximately 50–60%. Insurance coverage rates display more variation, with colleges and universities reaching nearly 100%, while most commercial sectors range between 10 and 40%. Sectors with longer enterprise lifespans tend to have different operational characteristics. At the same time, website adoption and social insurance coverage rates appear to correlate with the level of formalization and regulatory compliance within each sector.



Figure 7. Deregistration rate, average enterprise age, website adoption rate, and social insurance coverage rate of active aquaculture value chain enterprises in 2023.

Feed manufacturing and medicine manufacturing demonstrate the highest numbers of insured employees, indicating the presence of large-scale enterprises with significant employment levels (Figure 8). Most sectors exhibit much lower numbers of insured employees, indicating a lower level of scale. Colleges and universities exhibit the lowest median insured employee numbers, which is caused by most of them not disclosing their insured employee numbers in the registration system.

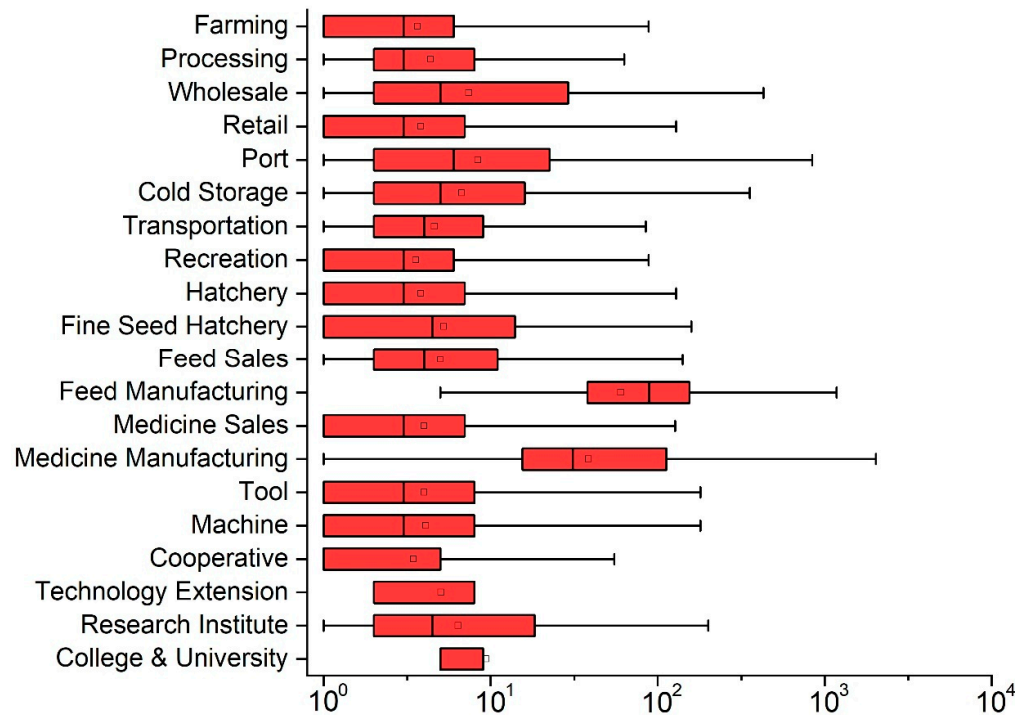


Figure 8. Log₁₀ transformed number of insured employees of active aquaculture value chain enterprises in 2023.

3.4. Foreign Investment

From 1979 to 2023, 0.16 million foreign-invested enterprises were registered in China, with total registered capital reaching CNY 377.91 million. From the reform and opening-up period to the early 20th century, the annual number of registered foreign-invested enterprises remained at a relatively high level, with the annual number of newly registered enterprises staying at high levels from 1990 to 2000 (Figure 9). By number, foreign-invested enterprises comprise a small proportion of aquaculture-related industries. The highest concentrations appear in processing, recreation, and feed manufacturing. At the same time, Cooperative and Wholesale have no foreign enterprises. Foreign investment shows different concentration patterns by capital, with recreation, feed manufacturing, farming, and processing attracting the most foreign capital.

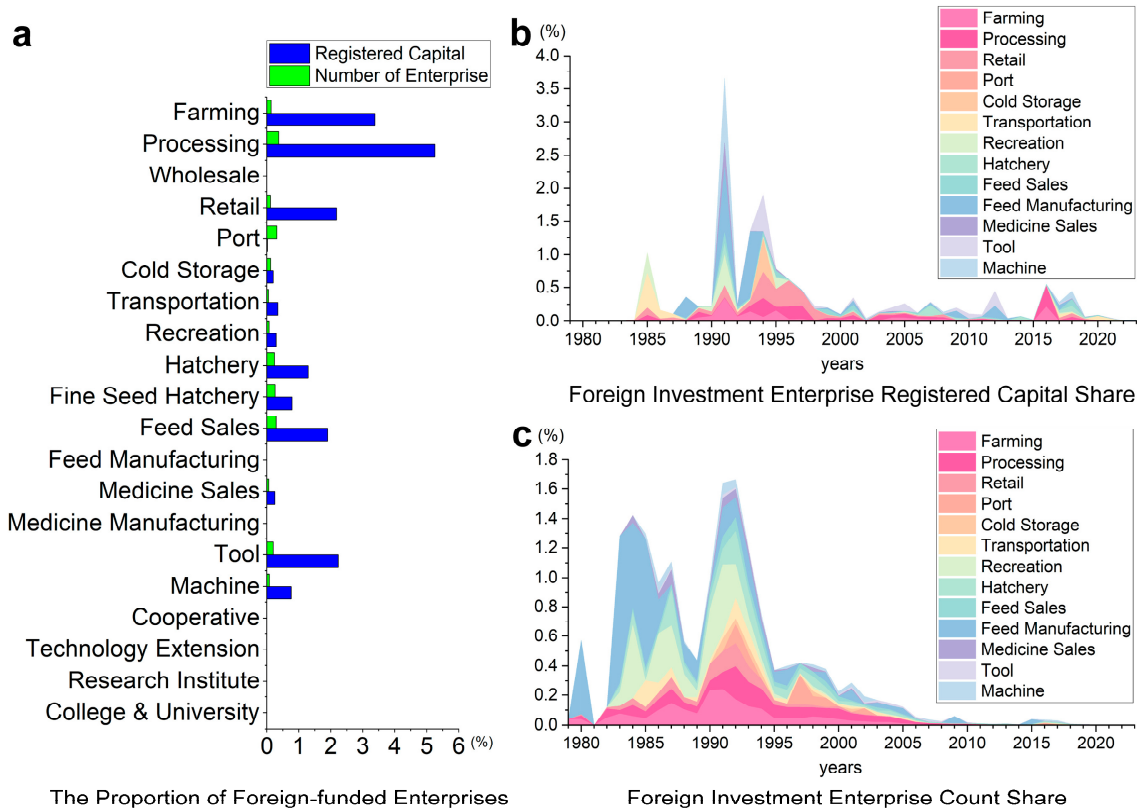


Figure 9. The share of foreign investment by number and registered capital of all aquaculture value chain enterprises by sector in 2023 and changes over time. (a) The share of foreign investment by the number of all aquaculture value chain enterprises by sector in 2023. (b) The share of foreign investment by number and registered capital of all aquaculture value chain enterprises by sector in 1979–2023. (c) The share of foreign investment in the number of all aquaculture value chain enterprises by sector from 1979 to 2023.

3.5. Structural Interdependencies and Correlation with Natural Endowments and Socioeconomic Factors

Spearman rank correlation analysis reveals clear structural interdependencies and high internal correlation within aquaculture-related industries, reflecting that regional industrial development typically exhibits symbiotic and synergistic effects (Figure 10). Farming is the most important sector in the value chain, exhibiting strong positive correlations with processing (0.77), retail (0.82), transportation (0.73), cooperative (0.70), and recreation (0.65). Processing was also strongly associated with transportation (0.79), emphasizing the importance of logistics and consumption-driven services in the post-harvest phase. In contrast, sectors such as wholesale and port showed weaker correlations with others, implying a degree of specialization or operational separation. Hatchery and fine seed hatchery maintained moderate relationships with core sectors like aquaculture and feed sales but were less connected to technical or institutional domains.

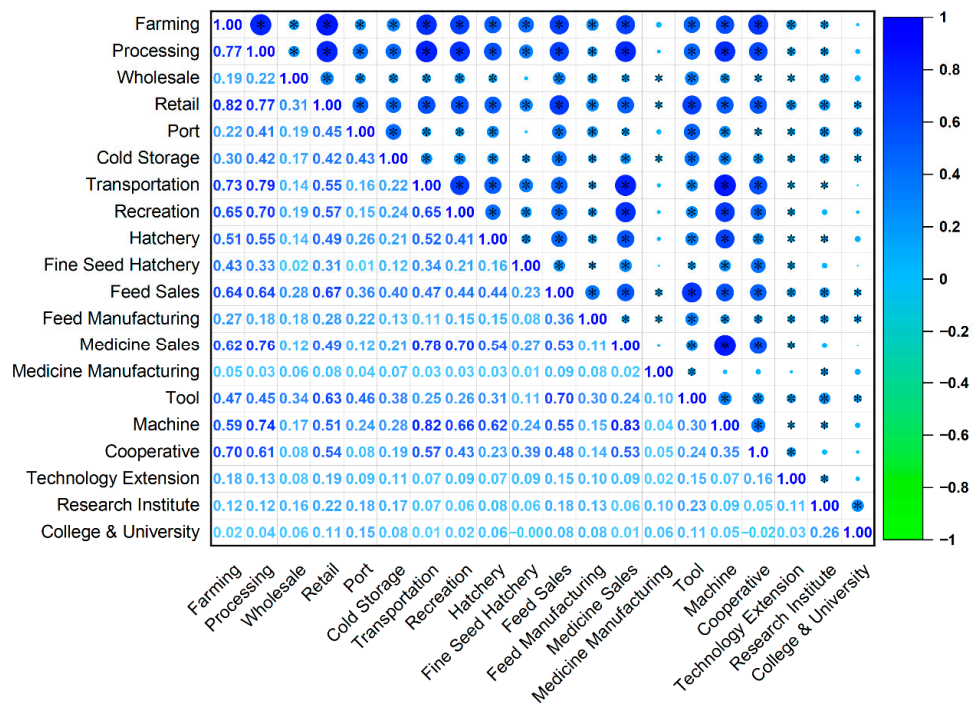


Figure 10. Correlation of numbers of active aquaculture value chain enterprises among different sectors at the county level in China in 2023 (* indicating $p = 0.001$).

We found that, by the number of enterprises of the overall sector, coastline length, irrigated farmland area, precipitation, population, and temperature are the dominant determinants for their distribution at the county level. In contrast, wetland area and GDP per capita exert comparatively minor influence (Figure 11). The number of enterprises of the overall sector exhibits positive correlations with coastline length, irrigated farmland area, precipitation, population, and temperature, and negative correlations with cropland area. Turning to the right panel, we find that coastline length, irrigated farmland area, temperature, and precipitation exert the most decisive influence on the spatial distribution of aquaculture farms. In contrast, GDP per capita has only weak effects. The number of aquaculture farms displays positive correlations with irrigated farmland area, temperature, and population, whereas they show negative correlations with cropland area.

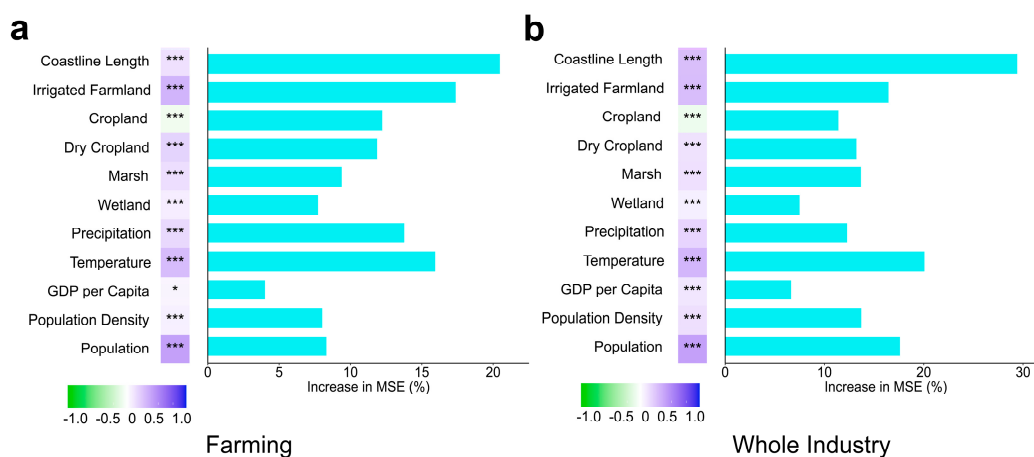


Figure 11. Dominant determinants and correlation between number of active aquaculture value chain enterprises and natural and socioeconomic factors (*: $p = 0.05$, ***: $p = 0.001$). The color scale from purple to green indicates correlation strength ranging from weak to strong.

3.6. Structural Bottleneck

We found numerical disparities between different value chain segments, and an apparent bottleneck effect emerges at the wholesale sector (Figure 12). Wholesale enterprises constitute only 0.8% of the total enterprises, representing the most constrained segment of the value chain. By contrast, farming (38.4%) and retail (41.3%) are the most abundant enterprises at the value chain's upstream and downstream ends. Processing (9.2%), transportation (7.6%), and hatchery (3.1%) show more balanced distributions. Minor differences exist among different provinces' aquaculture value chains. Still, the wholesale sector consistently constitutes the lowest number of sectors across all provincial contexts. This demonstrates that this bottleneck effect represents a systematic structural characteristic rather than a region-specific phenomenon.

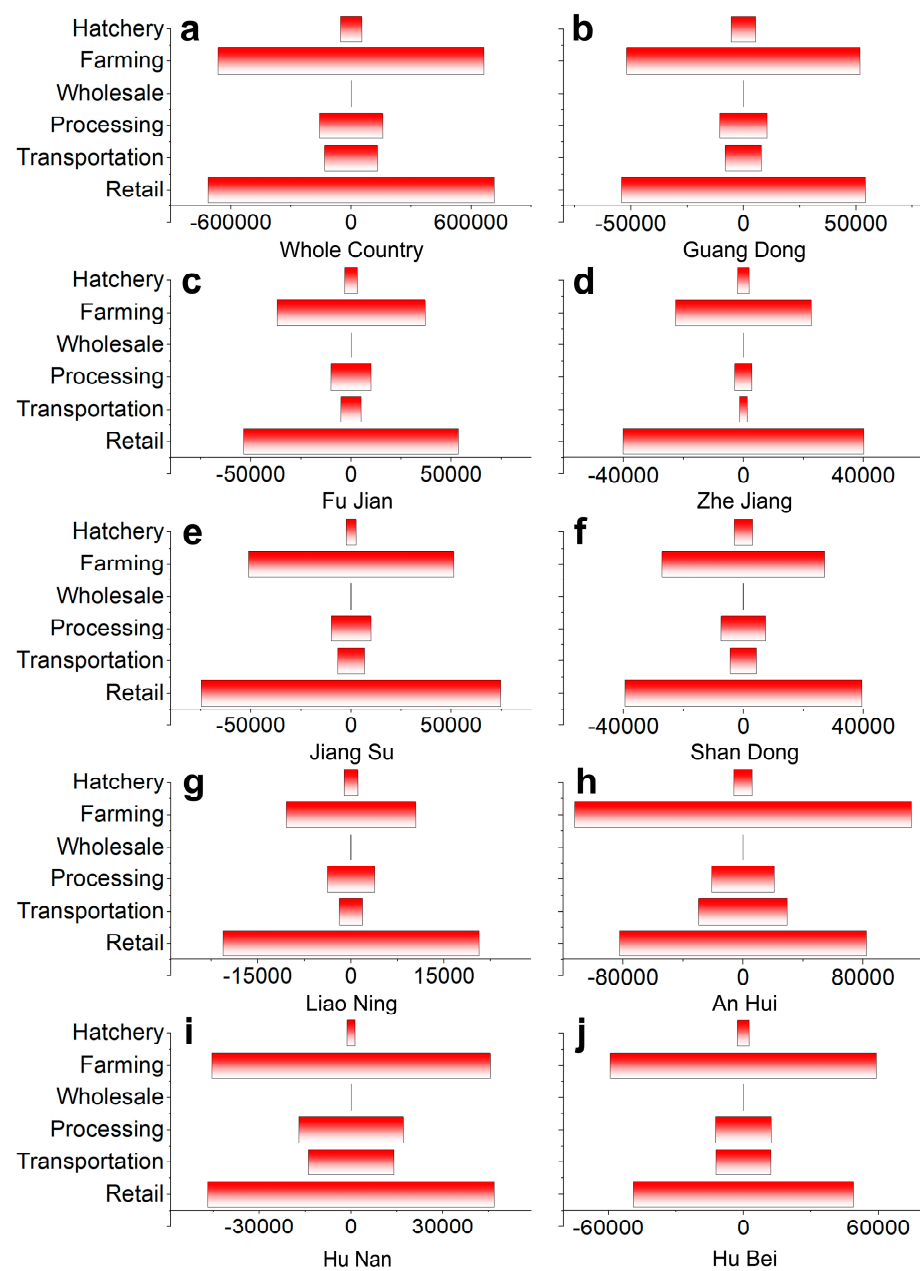


Figure 12. The number of active aquaculture value chain enterprises by sector in 2023, indicating the bottleneck effect of the aquaculture value chain. (a) Overall Sector; (b) Guangdong Province; (c) Fujian Province; (d) Zhejiang Province; (e) Jiangsu Province; (f) Shandong Province; (g) Liaoning Province; (h) Anhui Province; (i) Hunan Province; (j) Hubei Province.

The wholesale segment's limited number relative to other value chain components supports the theoretical framework of bottleneck effects, where numerically scarce intermediaries can exert disproportionate control over market information and pricing mechanisms, indicating a severe structural imbalance that could enable wholesale intermediaries to compress upstream profits from farmers while transmitting asymmetric pricing pressures to the extensive retail network.

4. Discussion

4.1. Policy

Policy support from a country is crucial for industrial development [44,45]. China has a long history of aquaculture, but it has only experienced rapid development since the reform and opening-up in the late 1970s. China implemented the household contract responsibility system reform, and the aquaculture industry entered a new era [46]. During this period, many laws and regulations were promulgated to promote aquaculture development. For example, in 1983, the Ministry of Agriculture of the People's Republic of China issued the "Regulations on Agricultural Technology Extension (trial)" [18]. The "Guiding Opinions on Relaxing Policies to Promote Aquaculture Industry Development", released in 1985, stimulated the enthusiasm of farmers [16]. In 1986, the Fisheries Law of the People's Republic of China was issued, which promoted some new breeding technologies [18]. In 1988, to address the shortage of non-staple food products, the government established the "Vegetable Basket Project" to solve the problem [47]. In 2001, China joined the World Trade Organization, and the aquatic product import and export industry experienced rapid development [24]. All these policies contributed to the rapid aquaculture development in China [6].

However, we found that the number of aquaculture enterprises did not increase simultaneously with the increase in production, due to changes in laws and regulations over time. We observed a sudden surge in newly registered enterprises between 2013 and 2014, which may be related to the revision of the "Company Law of the People's Republic of China" approved by the Standing Committee of the National People's Congress, which eliminated the minimum registered capital threshold [48]. In 2010, the "Measures for Registration and Certification of Aquaculture in Water Areas and Beaches" were implemented and enforced. Through certification, property rights were clarified, facilitating resource circulation and better protecting the rights and interests of fishermen [49].

We also observed sudden surges in registered capital since 2021, which may have resulted from restrictions on real estate investment policies. For example, the "three red lines" policy in China, which started in 2021, restricted the financing capacity of real estate developers, causing a large amount of funds that were initially flowing into the real estate sector to shift to other areas [50].

4.2. Number of Enterprises

Retail enterprises constitute the largest number among currently existing enterprises, due to the diverse consumption scenarios of aquatic products [51], leading to the segmentation and diversification of retail formats. For example, in traditional channels, supermarkets and wet markets are the most common places where residents consume aquatic products [6,52], as well as community aquatic product stores (with low entry barriers and large registration volumes) [53]. In emerging channels, fresh food e-commerce and live-streaming sales have driven the favorable development of retail enterprises. In addition, Chinese dietary habits are predominantly characterized by the consumption of fresh and live aquatic products [54]. The retail sector requires a dense network distribution to ensure supply timeliness [6].

4.3. Structural Interdependencies

We found clear structural interdependencies among different sectors of the value chain. In the aquaculture value chain, any minor price fluctuation in any segment has an impact on all segments [31]. The aquaculture value chain represents a tangible network of activities through which commodities and services flow from raw material and production to distribution and end-users [55]. The country has established strong seed production and breeding systems [56], improved feed quality through industry–research collaboration [57,58]. Cold-chain logistics have evolved into an integrated, efficient network [59,60]. China’s aquatic retail sector is undergoing pivotal structural transformations driven by policy reforms and consumption upgrading from “meeting basic needs” to “pursuing quality”, accelerated by urbanization and mounting environmental pressures [45,54].

4.4. Geographic Distribution and Correlation with Natural Endowments and Socioeconomic Factors

The combined forces of natural resources and economic development drive the distribution pattern of aquaculture enterprises. Water resource endowment is one of the most important factors, as areas densely populated with rivers and lakes support various farming models, including pond, lake, and paddy field aquaculture [11,12,35,37]. Favorable climate conditions are important, such as high temperature and high humidity in the southern regions, which are suitable for diverse aquatic product cultivation, with provinces like Guangdong, Guangxi, and Fujian having longer year-round cultivation cycles and higher yields [15,61]. Liaoning, Shandong, Zhejiang and Fujian provinces possess a port, a resource, and space for developing marine aquaculture (cage and raft farming), facilitating the development of processing and export-oriented industries [14,62,63]. Total population shows a high positive correlation with enterprise quantity, as dense population brings stable consumer demand and labor supply, serving as the core factor driving the development of retail and distribution sectors [52,53]. For example, populous provinces like Sichuan and Jiangsu have higher numbers of retail enterprises than the average. Economic development does not seem important, as county-level per capita GDP shows weak correlation with enterprise quantity, probably because 95% of counties have per capita GDP higher than CNY 89,000 (daily, 2024), making it less of a restriction on aquaculture development. However, high-GDP regions tend to attract capital-intensive industry layouts, such as cold-chain logistics and deep processing sectors, which are primarily concentrated in high-economic zones like the Yangtze River Delta, Pearl River Delta, and Bohai Rim. In contrast, central and western inland regions primarily undertake basic production functions, with Hunan and Hubei mainly engaged in aquaculture production. Coastal regions possess superior natural endowments and advantages in trade, export, and marine resource utilization [64,65]. Relatively, some non-coastal provinces may have abundant aquaculture resources but lag behind in logistics, transportation, and cold-chain infrastructure, affecting the integrity of the industrial chain.

4.5. Contribution of Foreign Investment

We found some foreign investments in the aquaculture value chain, especially in the 1990s. Although the proportion of foreign investment by number of enterprises and registered capital is less than 5%, the contribution of foreign investment to aquaculture development in China is worth further investigation. Foreign investment promotes factor-mobility-oriented opening-up, driving cross-border flows of technology, products, and services through supply chains, enabling China to participate deeply in the global industrial division of labor and cooperatives [66]. Foreign investment in China’s aquaculture sector evolved through distinct phases, with the 1990s representing the critical expansion

period. After a tentative entry in the 1980s, foreign investment accelerated and peaked in 1991–2000, driven by market-oriented reforms and structural adjustments that attracted substantial foreign capital to the processing and retail sectors. However, foreign investment patterns shifted notably after 2016, initially due to policy regulations and later influenced by developed countries' "decoupling" and "derisking" policies beginning around 2018–2019, which intensified during the US–China trade tensions. These policies, aimed at reducing strategic dependencies on China, have contributed to more cautious foreign investment approaches since 2021 [67]. In recent years, foreign investment in China has been increasingly concentrated in the secondary and tertiary industries, particularly in manufacturing, scientific and technical services, and information technology. In contrast, investment in the primary industry, including agriculture, forestry, animal husbandry, and fisheries, has remained minimal, accounting for less than 1% of total utilized FDI. This shift indicates that foreign capital is aligning with China's industrial upgrading and service-oriented economic transformation [68].

4.6. Standardization Level

Our research found that, except for college and university and related manufacturing industries, other sectors show low website adoption rates and social insurance coverage rates, indirectly indicating that the standardization level of China's aquaculture and related industries is not high. We also observe that the aquaculture industry has relatively low average registered capital and few insured employees, indicating that small-scale operations still dominate. In the future, with the decline in the working population, the aquaculture industry needs to further enhance its formalization and intensification levels [27].

4.7. Bottleneck Effect

We found that numerical disparities between different value chain segments indicate a bottleneck effect in the aquaculture value chain. The wholesale segment in China's aquaculture value chain has a much smaller number of enterprises, creating a bottleneck effect, echoing some supply chain studies. Some studies [69,70] have found that dealers (wholesalers) influence the upstream and downstream of the grass carp aquaculture value chain, and farmers only get one-third of the value generated. Farmers and retailers are positioned at the upstream and downstream ends of the value chain, respectively, characterized by small individual scale, high dispersion, and relatively weak market power. In contrast, wholesalers occupy the intermediate position and, leveraging their advantages in quantity, information, and economies of scale, have developed strong market dominance [71]. Consequently, wholesalers in the aquaculture industrial chain are often able to capture excess profits, exhibiting certain monopolistic characteristics. This highly concentrated distribution system further amplifies the market power of wholesalers. The emergence of large retailers may improve this situation, as they can procure directly from source suppliers, bypassing intermediaries, reducing costs, and benefiting consumers [72].

4.8. Limitations

This study has several limitations. First, it focuses on formally registered enterprises and excludes informal or unregistered participants, which are prevalent in specific segments of the aquaculture industry. Second, the registration data derives from administrative records rather than reflecting actual operational activities. Therefore, even though we have excluded information on deregistered and suspended enterprises, we cannot confirm that all registered enterprises in the data are actively operating. Third, the analysis is observational and does not establish causality. While the observed patterns correspond with policy reforms and structural changes, we cannot draw causal inferences from the data. Furthermore, the lack of detailed firm-level information restricts our ability to as-

assess industry dynamics comprehensively. Fourth, the registered capital of enterprises in TianYanCha does not represent the actual investment situation and may deviate from the real circumstances. Additionally, some unregistered informal actors are excluded from the TianYanCha database. Future work could link registry data with sustainability metrics, trade outcomes, and informal supply chains to enhance understanding of these complex relationships. Linking firm-level records with sustainability metrics, such as water use or habitat impacts, would enable spatial assessments of environmental risk. Trade and export data could clarify the role of formalization in international market participation. Informal and unregistered firms, currently excluded, could be studied through surveys or local administrative data; including them would offer a fuller picture of aquaculture's social inclusiveness.

5. Conclusions

This study provides a comprehensive assessment of the composition, spatial distribution, and structural evolution of China's aquaculture industry based on more than 2.85 million enterprise registration records. The results demonstrate that policy reforms—particularly the 2013 Company Law amendment and the 2016 aquaculture certification measures—have been pivotal in accelerating industry formalization. The rapid growth in enterprise registrations primarily reflects regulatory and institutional transformations rather than proportional increases in production, underscoring the policy-driven nature of China's aquaculture expansion. Spatially, aquaculture enterprises are concentrated in regions with abundant water resources, favorable climatic conditions, and high population density, notably in the Yangtze River Basin, Pearl River Delta, and coastal provinces. Strong interdependencies among farming, processing, and retail sectors highlight the interconnectedness of the aquaculture value chain, while the limited presence of wholesale enterprises forms a structural bottleneck that constrains market efficiency and upstream profitability. Although foreign investment remains limited in both enterprise numbers and capital share, it has contributed to technological advancement and modernization, particularly in processing and production. However, persistent challenges—including low standardization, weak social insurance coverage, and the predominance of small-scale operations—continue to hinder sustainable development. Looking ahead, promoting industry-wide standardization, enhancing transparency across all value chain segments, and improving coordination between production, processing, logistics, and retail will be crucial to achieving a more resilient, efficient, and sustainable aquaculture sector in China.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/su172411331/s1>, Figure S1: Distribution of deregistered enterprise of the whole aquaculture value chain in China in 2023; Table S1: Data sources of the present study; Table S2: Keywords for categorizing the main business in the value chain; Table S3: Industry category for Screening; Table S4: Raw data fields and analytical applications; Table S5: Data standardization methods; Table S6: Annual exchange rate (1 unit of foreign currency to CNY); Table S7: Coastline length (coastal county boundaries). Refs. [73–80] are included in Supplementary Materials.

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Data Availability Statement: The data supporting the findings of this study are available from the TianYanCha enterprise registration database (<https://www.tianyancha.com>), which is a publicly accessible commercial database. Aggregated and processed data generated during this study are available from the corresponding author upon reasonable request.

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