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From Digitalization to Intelligentization: How Do Marine Ranches Evolve?

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Abstract

Under China's diversified food supply strategy and the accelerated modernization of its fisheries sector, marine ranches have become vital food sources and production bases. Their digital–intelligent transformation now represents a key pathway to improve resource efficiency, ensure food security, and promote sustainable marine economic development. Adopting a qualitative research design, this study examines China's marine ranches using the TOE framework and a systemic grounded theory approach to identify key elements and evolutionary logic of their digital–intelligent transformation from multi-source qualitative data. It constructs a three-stage evolutionary model comprising "Technology and Facility Capacity Building Phase–Digital Resource Integration and Application Deepening Phase–Multi-stakeholder Collaboration and Systemic Governance Phase," revealing the dynamic coupling mechanism among technological progress, organizational change, and environmental adaptation. Results indicate that the digital–intelligent transformation of marine ranches represents a systemic transition from technology-driven to collaborative governance, characterized by platform-based collaboration, factor restructuring, and institutional linkage. Based on these findings, this study proposes tiered policy and practice recommendations emphasizing institutional guidance by governments, innovation investments by enterprises, and ecological support from third-party platforms. The research not only expands the application scope of the TOE framework but also provides an applicable theoretical framework and policy reference for digital governance and sustainable development in marine fisheries.

Keywords: marine ranching; digital–intelligent transformation; evolutionary mechanism; Technology–Organization–Environment (TOE) framework

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1. Introduction

1.1. Literature Review

In recent years, in response to the growing scarcity of global fishery resources and the rising demand for ecosystem restoration, coastal nations have increasingly incorporated marine ranch construction into their fishery modernization strategies to promote the coordinated development of aquaculture enhancement, resource restoration, and ecological protection [1]. In China, coastal regions are progressively deploying marine ranches to advance high-quality aquatic product supply [2], ensure food security [3], and support marine ecosystem restoration [4]. However, China's marine ranches still face structural challenges, including low overall development levels, unstable ecological performance, weak digital infrastructure, and insufficient integration of industrial chains [5]. There is

an urgent need to introduce advanced digital–intelligent technological systems to achieve efficient, precise, and sustainable development [6].

At the same time, structural differences within China's fisheries add complexity to the modernization of marine ranching. Pelagic fisheries, which target high-value migratory species, are typically capital- and technology-intensive and rely on advanced vessels and deep-sea operational capabilities. In contrast, mesopelagic fisheries focus on midwater species with high ecological relevance but relatively low commercial exploitation, often constrained by insufficient technological development and limited market mechanisms. The coexistence of these two systems poses challenges for governance coordination, resource allocation, and ecosystem management, complicating the design of unified modernization strategies. Sustainable management of mesopelagic resources requires integrated observation networks, data-sharing mechanisms, and adaptive monitoring systems to balance ecological protection with industrial growth [7]. Addressing such disparities is essential for building digital–intelligent transformation strategies that can differentiate between deep-sea industrialized fisheries and nearshore ecological ranching, ensuring that technological innovation aligns with ecosystem conservation and regional development goals.

As digital technologies—such as big data, AI, IoT, remote sensing, and blockchain—continue to penetrate fisheries, the traditional experience-based management paradigm of marine ranches is shifting toward a data-driven, intelligence-enabled governance model [8]. Digital–intelligent approaches enable the end-to-end optimization of processes ranging from resource monitoring and aquaculture control to ecological regulation, thereby building a complete management chain covering "perception–transmission–cognition–control–decision-making." This significantly improves both production efficiency and ecological coordination in fisheries [9,10]. Against this backdrop, exploring how marine ranches can achieve an orderly evolution from digitalization to intelligentization has become an important research focus in the integration of fisheries management and emerging technologies.

In recent years, scholars both domestically and internationally have developed a relatively systemic theoretical and empirical research framework surrounding digital–intelligent transformation. Overall, related studies primarily focus on three directions: (1) the Technology–Organization–Environment (TOE) framework for digital transformation; (2) research on transformation mechanisms based on dynamic capabilities and organizational change; and (3) cross-system coordination mechanisms from the perspective of complex socio-ecological-technological systems (SETS).

The TOE framework is widely employed to explain the mechanism through which organizations are influenced by technological readiness, organizational capabilities, and external environments during technological change [11,12]. From a dynamic capability perspective, researchers argue that digitalization is not merely a linear process of technology adoption but rather a capability leap where organizations achieve resource reallocation through learning, restructuring, and knowledge renewal [13,14]. Furthermore, the recently emerged SETS analytical framework emphasizes the coupled logic between ecological constraints, technological innovation, and social governance, highlighting that digital intelligence represents a systemic structural transformation rather than a unidimensional technological upgrade [15,16].

Overall, existing literature reveals the multidimensional characteristics and complex logic of digital–intelligent transformation. However, it lacks systemic theoretical integration and evolutionary pathway analysis for typical socio-ecological-technical systems like marine ranching, providing a theoretical entry point for this study.

1.2. Previous Studies Analysis

Existing scholarly research has examined the pathways, mechanisms, and performance evaluation of digital transformation from multiple perspectives. At the theoretical level, the Technology–Organization–Environment (TOE) framework is frequently adopted to explain the multidimensional structure of influencing factors when enterprises or organizations face technological change [17,18]. Within the TOE framework, the technology dimension emphasizes infrastructure construction, platform deployment capabilities, and the maturity level of technologies [19]; the organization dimension reflects structural mechanisms, cultural characteristics, and human resource allocation [20]; and the environment dimension refers to the influence of policy context, market pressures, and ecological externalities [21]. The TOE model has been successfully applied in sectors such as agriculture, manufacturing, retail, and healthcare to analyze digital adoption behavior, evaluate the outcomes of intelligent system implementation, and explore the construction of platform ecosystems [22–25].

Research on digital transformation has also generated several subtopics, including dynamic capabilities [26], platform ecosystem governance [27], organizational path dependence and change inertia [28], and cross-sectoral collaboration and data value co-creation [29], leading to a systemic body of knowledge. However, for marine ranches—a typical social–ecological–technical system (SETS) [30]—existing studies have mostly focused on physical infrastructure construction or the embedding of individual technologies, while lacking an in-depth examination of the stage division and evolutionary mechanism of systemic digital–intelligent transformation [1]. In the context of China, research remains limited on the mechanisms of multi-actor collaborative governance, cross-system platform connectivity, and the coupling of policy and environmental factors [31].

A systemic review and comparative analysis of existing research reveal several critical gaps in the field that require further exploration: (1) Insufficient explanation of phased evolutionary mechanisms. Existing research predominantly focuses on static correlations between digital adoption or performance outcomes, while theoretical frameworks addressing phase delineation, path dependence, and dynamic coupling mechanisms within digital-to-intelligent transformation remain relatively underdeveloped. A systemic analytical framework capable of revealing evolutionary patterns has yet to emerge. (2) The dynamic interplay of environmental dimensions—such as policy, market forces, and ecosystems—remains under-explored. Existing literature often treats external environments as singular exogenous conditions, overlooking their interactive relationships with organizational decision-making, capability development, and technology deployment. The synergistic mechanisms linking policy incentives, market pressures, and ecological constraints have not been fully illuminated, and their underlying logic of influencing transformation processes through the technology-organization-environment (TOE) structure requires systemic elaboration. (3) Research on multi-stakeholder coordination and governance mechanisms lags behind. The digital–intelligent transformation of marine ranches involves a complex process engaging diverse actors, including governments, enterprises, research institutions, and fishing communities. Resource allocation, power structures, and collaborative relationships among these stakeholders profoundly shape the system's evolutionary trajectory. However, existing studies lack systemic modeling and dynamic validation of such multi-level governance structures, and the exploration of evolutionary logic for coordination mechanisms within complex socio-technical systems remains insufficient.

To address the aforementioned research gaps, this paper focuses on the digital–intelligent transformation practices of marine ranches in China's coastal regions. Based on the Technology-Organization-Environment (TOE) framework and employing a systemic grounded theory approach, it identifies a three-stage evolutionary model for digital–

intelligent transformation: the "Technology and Facility Capability Building Phase," the "Digital Resource Integration and Application Deepening Phase," and the "Multi-stakeholder Collaboration and Systemic Governance Phase." Simultaneously, it identifies the coupling relationships and dominant mechanisms among the three-dimensional elements of technology, organization, and environment. Building upon this foundation, this paper aims to address two core questions: (1) What are the primary influencing factors of the digital–intelligent transformation of marine ranches? (2) What are the phased characteristics of digital–intelligent transformation in marine ranching? By addressing these questions, this study deepens understanding of the evolutionary patterns of digital–intelligent transformation in marine ranching. It provides decision-making references for government policy support, enterprise capacity building, and regional coordination. This holds significant practical implications for advancing the high-quality development of marine ranching, promoting the digital and intelligent upgrading of marine industries, and ultimately achieving the strategic goal of building a maritime power.

2. Materials and Methods

2.1. Theoretical Framework and Analytical Perspective

To delve into the evolutionary logic and impact mechanisms of digital–intelligent transformation in marine ranching, this study adopts the Technology–Organization–Environment (TOE) framework as its analytical foundation, combined with a systemic grounded theory approach. Proposed by Tornatzky and Fleischer [32], the TOE framework centers on constructing a systemic analytical logic across three dimensions—technology, organization, and environment—to reveal the multidimensional drivers of technological innovation diffusion and organizational transformation. In recent years, this framework has been widely applied in fields such as digital transformation, green innovation, and smart manufacturing to characterize the interactive processes between internal factors and external environments [33–35]. Building upon this foundation, this paper attempts to introduce the TOE framework into the study of digital–intelligent transformation in marine ranching to systemically analyze its key factors and evolutionary mechanisms.

The digital–intelligent transformation of marine ranches in China is a multi-layered and multidimensional process that requires the joint promotion and coordinated efforts of technological, organizational, and environmental elements.

1. Technological factors: Technology serves as the core driving force in digital–intelligent transformation. For marine ranches, this includes—but is not limited to—the application of advanced technologies such as the Internet of Things (IoT), big data, cloud computing, artificial intelligence, and blockchain. These technologies enable real-time monitoring of the marine environment, intelligent management of aquaculture processes, and traceability of product quality, thereby improving operational efficiency and product quality. This dimension covers the digital–intelligent application and innovation of facilities, equipment, data, and platforms, as well as the capacity for technological innovation and application, the establishment of technical standards and norms, and related elements. Together, these factors determine the technological level and innovation capacity of marine ranches in their transformation process.
2. Organizational factors: Organizational transformation is critical to the success of digital–intelligent transformation. Beyond the leading enterprises and stakeholders in marine ranching—such as government bodies, financial institutions, universities, research institutes, and fishers—this dimension also includes organizational structure, governance mechanisms, and human resources. These elements collectively influence organizational capability and collaborative efficiency. Marine ranches must develop organizational structures and management systems suited to the requirements of

digital–intelligent transformation. This includes training or recruiting personnel with relevant skills, establishing cross-departmental and cross-sectoral collaboration mechanisms, and optimizing business processes and management models. In addition, organizational culture should be adapted to encourage innovation, openness, and knowledge sharing.

3. Environmental factors: Environmental adaptability constitutes the external conditions for digital–intelligent transformation. At the macro level, national policies, laws and regulations, and the level of economic development exert significant influence. For example, governments can promote the development and application of digital–intelligent technologies through targeted policies, funding, and tax incentives. At the industry level, market competition, consumer demand, and technological trends are also critical considerations. These factors provide the necessary market conditions and policy support for the transformation of marine ranches.

Digital–intelligent transformation can be analysed from multiple theoretical perspectives, such as organizational change theory, digital innovation theory, and dynamic capability theory, each offering different analytical emphases. Organizational change theory highlights the processual and adaptive nature of transformation, focusing on how organizations adjust structures and routines in response to environmental dynamics to maintain flexibility and continuity [36]. Digital innovation theory emphasizes the co-evolution between technology and organizations, revealing how digital technologies reshape organizational boundaries and value creation models [37]. Dynamic capability theory, in turn, focuses on how firms build, integrate, and reconfigure internal and external resources to respond to rapidly changing environments [38]. These theories are valuable for explaining internal transformation mechanisms but tend to underrepresent the systemic influence of external policy environments, industrial ecosystems, and institutional settings.

In contrast, the TOE framework bridges internal and external analytical dimensions by integrating technological readiness, organizational capability, and environmental support into a unified structure [32,39,40]. This integrative logic enables a holistic examination of how digital–intelligent transformation unfolds through the interaction between internal adaptation and external drivers. Existing studies demonstrate that the TOE framework effectively captures the coupling relationships among policy guidance, infrastructure development, and managerial adaptation, providing a multidimensional understanding of transformation processes [41–45].

In the context of marine ranching—a complex system integrating ecological, industrial, and social functions—the TOE framework offers strong theoretical advantages. It supports the systemic analysis of how diverse actors and elements interact to promote technological upgrading, organizational adaptation, and environmental coordination. Therefore, the TOE framework serves as the theoretical foundation of this study, providing a structured basis for identifying key drivers, interactive mechanisms, and evolutionary patterns of marine ranch digital–intelligent transformation, as summarized in Table 1.

During the digital–intelligent transformation of marine ranches, it is essential to strengthen R&D investment in digital–intelligent services and technologies, introduce or develop technologies suited to specific operational needs, facilitate efficient communication between leading enterprises and other stakeholders, promote organizational change and management innovation, and develop structures and systems suited to digital–intelligent transformation. Building a marine ranch ecosystem that supports data sharing and industry linkage, advancing value chain integration, adapting proactively to external environmental changes, and fully leveraging policy and market resources can accelerate transformation. Ultimately, upgrading to an intelligent governance community can har-

monize economic, social, and ecological values, driving the high-quality development of China's marine economy.

Table 1. TOE framework: connotation and extension in the context of marine ranch digital–intelligent transformation.

TOE Dimension	Connotation	Extension
Technological Factors	Technological Advancement and Applicability: The maturity and practical effectiveness of digital and intelligent technologies in marine ranch applications. Technological Innovation Capability: The research, development, introduction, and innovation capabilities of marine ranches and related enterprises in digital and intelligent technologies.	Technical Infrastructure: The sophistication of equipment and systems including network communications, data processing, and sensors. Technical Standards and Specifications: The level of standardization and normalization of digital and intelligent technologies in marine ranch applications, as well as their alignment with international standards. Technical Training and Promotion: The extent of training, dissemination, and promotion of digital and intelligent technologies for marine ranch practitioners.
Organizational Factors	Organizational Structure and Culture: Whether the organizational structure of marine ranches and related enterprises aligns with the demands of digital–intelligent transformation, as well as the openness and innovation-driven nature of their organizational culture. Organizational Resources and Capabilities: The allocation and utilization efficiency of resources—including capital, talent, and management—in the digital–intelligent transformation process.	Inter-organizational Collaboration: Cooperation mechanisms and outcomes between marine ranches and research institutions, universities, other enterprises, etc. Organizational Learning and Innovation: Learning capacity, innovation capability, and adaptability of marine ranches during digital–intelligent transformation. Organizational Policies and Systems: Internal corporate policies supporting digital–intelligent transformation, incentive mechanisms, and institutional frameworks.
Environmental Factors	Macro Environment: The impact of national policies, laws and regulations, and economic development levels on the digital–intelligent transformation of marine ranches. Industry Environment: The competitive landscape, market demand, and technological trends within the marine ranch industry.	Socio-cultural Environment: The impact of public acceptance of digital and intelligent technologies, consumption habits, and cultural traditions on the digital–intelligent transformation of marine ranches. International Environment: The influence of global trends in marine ranch digitalization, international cooperation, and competitive dynamics on China's development. Natural Environment: Potential impacts of natural factors such as marine ecosystems and climate change on the digital–intelligent transformation of marine ranches.

Note: Source: Author's own.

2.2. Research Method and Analytical Approach

To construct a theoretical model grounded in empirical evidence, this study employs systemic Grounded Theory as its primary research methodology. Originally developed

by Strauss and Corbin, this approach emphasizes the systemic coding and ongoing comparison of raw data to abstract concepts, categories, and their interrelationships, thereby enabling theoretical induction and construction. Compared to traditional hypothesis-driven approaches, grounded theory places greater emphasis on the researcher's ability to identify problems, recognize patterns, and refine relationships within real-world contexts. It is particularly suited for fields where theoretical frameworks are still developing, research subjects are complex, and evolutionary characteristics are pronounced [46–48].

The digital–intelligent transformation of marine ranches represents an emerging and representative practice domain. Existing research predominantly focuses on singular perspectives such as policy orientation, technological application, or management models, with limited systemic exploration of multidimensional factor interactions and evolutionary patterns. To address this gap, this study employs systemic grounded theory analysis based on multi-source qualitative data to distill the key influencing factors, stage characteristics, and underlying logic of marine ranch digital–intelligent transformation. The research process comprised three stages: open coding, axial coding, and selective coding. Through successive abstraction, continuous comparison, and theoretical integration, a systemic understanding of the digital–intelligent transformation's evolutionary process was developed.

During open coding, sentence-by-sentence analysis of field survey data, policy documents, and interview records from Shandong's Blue Economic Zone yielded initial concepts related to marine ranch digital–intelligent transformation. These include "application of intelligent monitoring devices," "remote control system construction," "data analysis and decision support," "IoT platform development," "digitalization of organizational management," and "platform interconnectivity." This process ensured data openness and diversity, grounding research concepts in practical contexts.

During the axial coding phase, researchers clustered and integrated concepts from open coding to identify underlying logical relationships, forming three core categories: intelligent management platform construction, digital ecosystem network development, and organizational system digital transformation. This step reveals the coupling mechanisms between technology, organization, and platform construction, providing mid-level support for model abstraction.

During the selective coding phase, analysis centered on the core theme of "digital–intelligent transformation of Marine Ranches," further integrating the three axial categories into a systemic framework. Ultimately, a three-stage evolutionary model for marine ranch digital–intelligent transformation was abstracted: the "Technology and Facility Capability Building Phase," the "Digital Resource Integration and Application Deepening Phase," and the "Multi-stakeholder Collaboration and Systemic Governance Phase." This model presents an evolutionary path from digital infrastructure construction to platform interconnection and ultimately to cross-regional industrial collaboration, offering an operational theoretical framework for understanding the systemic logic of digital–intelligent transformation.

In the research design, the TOE framework served as an analytical lens, providing theoretical grounding and dimensionality for grounded theory coding. Specifically, the TOE framework guided the identification and classification of initial concepts, enabling systemic organization and interpretation of abstract concepts within the "technology–organization–environment" triadic structure. Subsequently, through continuous comparison and theoretical abstraction, this paper constructs an empirical model reflecting the evolutionary patterns of digital–intelligent transformation in marine ranching. This model retains the empirical inductive characteristics of grounded theory while embodying the structured analytical advantages of the TOE framework, thereby achieving an organic integration of theoretical and empirical logic.

To ensure research reliability and validity, this study adheres to the triple verification principle of grounded research: First, cross-validation of information through multiple data sources including field interviews, policy documents, and media materials. Second, ensuring coding stability and completeness via continuous comparison and theoretical saturation testing. Third, enhancing the scientific rigor and consistency of data interpretation through expert review and research team discussions. These steps collectively guarantee the systemic nature and credibility of the research conclusions, providing a solid foundation for subsequent empirical findings and model construction.

2.3. Data Sources and Case Selection

When quantitatively identifying the influencing factors in the digital–intelligent transformation of marine ranches, the integration of multi-source heterogeneous data is essential. The data used in this study include traditional statistical data, field investigation data, and environmental monitoring data. These sources provide a comprehensive understanding of the typical characteristics and contextual basis of transformation.

On one hand, traditional statistical data help analyze the historical development trends, industrial structure changes, and economic benefits of marine ranches. They assist in identifying major issues in the transformation process, such as outdated technology, low management efficiency, and insufficient resource utilization. On the other hand, field investigation data supplement the analysis at the micro level. In-depth, on-site surveys were conducted to examine the condition of facilities and equipment, current technology applications, personnel structures, and interactions among stakeholders. This allowed the identification of practical challenges such as technical bottlenecks, talent shortages, and incomplete resource allocation mechanisms.

In the context of China's coastal regions, marine ranches serve as important food sources and production bases. Their digital–intelligent transformation is a vital pathway for enhancing marine resource utilization efficiency, ensuring food security, and promoting the high-quality development of the marine economy. To strengthen the representativeness and practical significance of the empirical analysis, this study selects the National Marine Ranch Demonstration Zone in the Shandong Blue Economic Zone as a typical case for in-depth research.

The Shandong Blue Economic Zone, designated as a national-level marine economic development demonstration area, has played a pioneering role in the digital–intelligent transformation of marine ranches. Case selection was based on three main considerations: (1) The region possesses abundant marine resources, providing a solid foundation for ranch construction. (2) The region has actively explored and implemented digital–intelligent transformation practices, accumulating systemic management and technological experience. (3) The region's experience is typical and representative, offering valuable reference for other coastal areas.

Data collection was conducted through three main channels: (1) Field investigations of the National Marine Ranch Demonstration Zone in the Shandong Blue Economic Zone to document specific practices and achievements in digital–intelligent transformation. (2) systemic collection of relevant policy documents, project plans, and evaluation reports to build a comprehensive secondary text database. (3) Semi-structured interviews with key stakeholders, including enterprise managers, technical staff, and government officials, to obtain first-hand information and feedback.

Detailed background information on the interviewees and a summary of the collected data are provided in Appendix A, while the interview outline and guiding questions used during the fieldwork are presented in Appendix B to ensure transparency and reproducibility of the research process.

2.4. Overall Research Framework

Marine ranching is an emerging industry integrating environmental protection, resource conservation, and sustainable fishery output. It provides high-quality protein and ensures nearshore ecological security. Digital–intelligent transformation represents an advanced stage built upon digitalization, emphasizing the intelligent application of artificial intelligence technologies to data as a production factor. This transformation can improve production efficiency, reduce costs and risks, promote sustainable development, extend the industrial chain, increase value-added, and enhance market competitiveness.

This study takes China's marine ranches as the research object. Following the logic of "theoretical interpretation → mechanism analysis → policy recommendations," it focuses on the development stages and evolutionary mechanisms of marine ranch digital–intelligent transformation under the background of a diversified food supply strategy. Figure 1 presents the conceptual framework of this study.

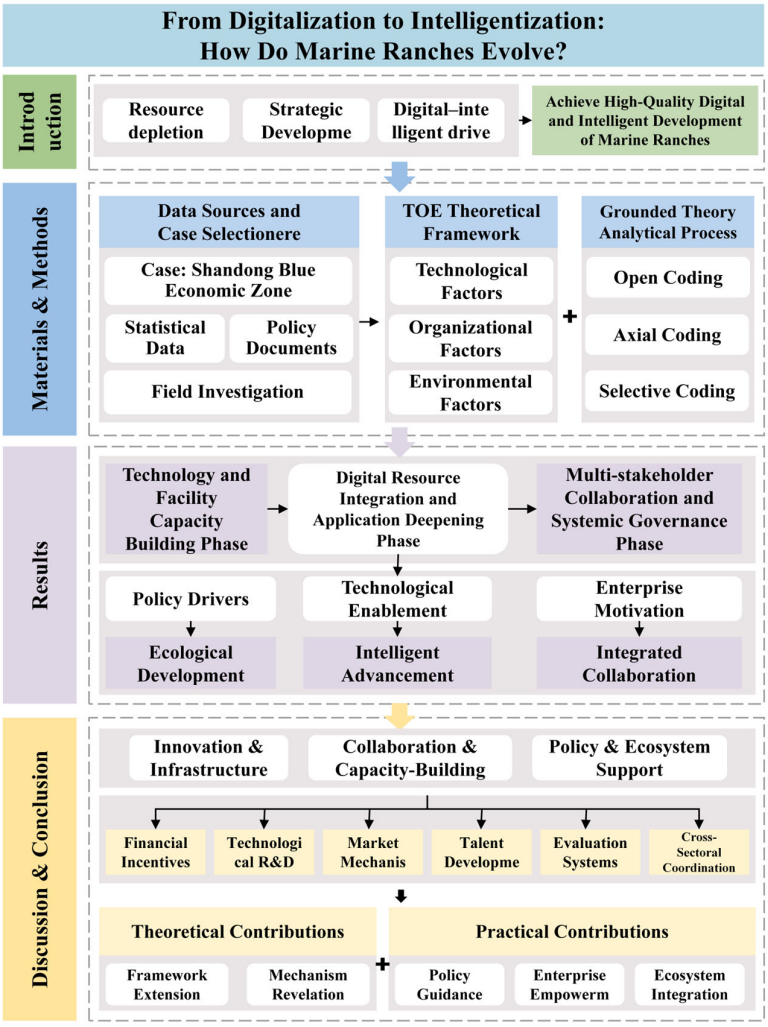


Figure 1. Conceptual framework of this study. Source: Author's own.

3. Results

3.1. Coding Process and Extraction of Core Concepts

To systemically reveal the key processes and evolutionary mechanisms of the digital–intelligent transformation of marine ranching, this study adopts the systemic grounded theory paradigm in combination with the three-dimensional structure of the TOE framework. Original data were obtained from the typical practices of the National Marine Ranch

Demonstration Zone in the Shandong Blue Economic Zone. Sentence-by-sentence textual analysis was conducted to ensure the diversity and validity of the source material, which included policy and planning documents, publicly available media information, field research notes, and expert interview records.

During the open coding stage, the research team analyzed the original materials line by line to identify and extract initial concepts related to digital–intelligent transformation. These included "deployment of real-time water quality monitoring equipment," "5G remote control system pilot," "automatic aquaculture data collection system," "launch of expert decision-support platform," "operation of digital seedling cultivation platform," and "launch of public science popularization platform." Preliminary categories were formed around themes such as environmental sensing, remote control, data collection, decision support, intelligent production, and ecological monitoring, as illustrated in Table 2.

Table 2. Examples of original concepts and preliminary categories identified during open coding.

Original Concept	Preliminary Category
Deployment of real-time water quality monitoring equipment	Environmental sensing
5G remote control system pilot	Remote control
Automatic aquaculture data collection system	Data collection
Launch of expert decision-support platform	Decision support
Operation of digital seedling cultivation platform	Intelligent production
Online assessment of marine carrying capacity	Ecological monitoring
Development of multi-department collaboration platform	Organizational linkage
Launch of public science popularization system	Social feedback

Note: Source: Author's own.

In the axial coding stage, the initial concepts were clustered, integrated, and linked into causal chains to identify their internal logic. Three axial categories emerged: digital infrastructure construction, which comprises environmental sensing, remote control, and data collection as foundational facilities; deployment of intelligent platform systems, which covers decision support, ecological monitoring, and intelligent production at the application level; and optimization of organizational coordination mechanisms, which emphasizes multi-department collaboration, social participation, and inter-organizational linkages.

The selective coding stage refined these categories into a vertical evolutionary relationship, forming the core pathway of the evolutionary model. This led to the identification of three evolutionary stages: the Technology and Facility Capacity Building Phase, the Digital Resource Integration and Application Deepening Phase, and the Multi-Stakeholder Collaboration and systemic Governance Phase. These stages represent a progression from digital infrastructure construction to platform interconnection, and ultimately to cross-regional industrial collaboration.

3.2. Construction of the Three-Stage Evolutionary Model

Based on the coding and category identification, a three-stage evolutionary model for the digital–intelligent transformation of marine ranches was developed. The model depicts a continuous process beginning with the "Technology and Facility Capability Building Phase," the "Digital Resource Integration and Application Deepening Phase," and the "Multi-stakeholder Collaboration and Systemic Governance Phase." It reflects the dynamic advancement of technological embedding, organizational change, and environmental adaptation.

The first stage focuses on intelligent upgrading through the introduction of 5G communication, IoT, cloud computing, and automated equipment, enabling remote monitoring and real-time data transmission. This supports intelligent environmental monitoring

and control, improving aquaculture efficiency and management standards. The second stage centers on integrating and deepening the use of digital resources. Big data, artificial intelligence, and blockchain are applied to ensure product quality and traceability, integrate aquaculture data, optimize production strategies, and support decision-making for ecological balance and sustainability. The final stage embeds marine ranches within broader regional collaborative systems, fostering integration with surrounding industries and creating synergies across industrial, innovation, and value chains to enhance regional economic performance.

Overall, the transformation process moves from foundational capacity building to system integration, and finally to coordinated multi-actor governance. The application of digital–intelligent technologies serves as a decisive driver, and continued innovation is expected to further expand the development potential of marine ranches.

3.3. Drivers and Objectives Under the Diversified Food Supply Strategy

The strategic connotations, practical drivers, and developmental orientations of each transformation stage are closely tied to China's national policy strategies, evolving technological environment, and enterprise-level challenges. The transformation is both an objective necessity and a process strongly shaped by policy guidance and systemic coordination.

Marine ranches, as a vital component of the marine food supply system, are undergoing transformation to meet both national food security requirements and the need for sustainable marine economic development. The diversified food supply strategy underscores the importance of diversifying food sources and optimizing dietary structures. As key providers of high-quality marine protein, marine ranches must pursue efficient, ecological, and sustainable growth, with digital–intelligent transformation serving as the pivotal pathway.

The rapid growth of the digital economy has created favorable technological and market conditions, enabling precision aquaculture, intelligent management, and industrial upgrading. At the enterprise level, transformation responds to pressing challenges such as resource constraints, technical bottlenecks, and market competition by enhancing managerial efficiency, optimizing resource allocation, and boosting competitiveness. Strong policy support and theoretical research further reinforce the process, with national policies offering funding, tax incentives, and regulatory frameworks, and academic analysis confirming its necessity for sustainable development in the current era.

3.4. Development Directions

The objectives of digital–intelligent transformation in marine ranching extend beyond improving industrial efficiency and quality. The overarching aim is to establish a sustainable marine food supply system characterized by ecological integrity, precision, intelligence, and integration.

From an ecological perspective, transformation should safeguard marine ecosystem health and stability. Digital–intelligent technologies can optimize aquaculture techniques and environmental protection measures, enabling precise monitoring and management, minimizing ecological impacts, and ensuring sustainable resource use. Precision is achieved by applying big data and IoT technologies to targeted feeding, precise aquaculture, accurate monitoring and regulation, and targeted disease prevention and control. These approaches improve resource efficiency, reduce waste, and guarantee product quality and safety.

Intelligence is advanced through artificial intelligence and machine learning, fostering intelligent aquaculture, management, and decision support, which enhance operational efficiency and responsiveness while reducing costs and risks. Integration involves fostering both intra-industry and cross-industry collaboration, linking marine ranching with fisheries, tourism, and scientific research, and strengthening cooperation along the value chain. This

creates synergies across industrial, innovation, and value networks, contributing to a more complete and efficient marine food supply system.

By building a marine food supply system that is ecological, precise, intelligent, and integrated, marine ranches can better meet the demand for diverse, high-quality food products while promoting sustainable marine economic development. This approach also supports national food security strategies and the long-term goal of building a strong marine economy.

4. Discussion

4.1. Theoretical Interpretation and Research Implications

The findings of this study resonate to some extent with existing theoretical research on digital–intelligent transformation while also revealing new developmental logic. From the perspective of the Technology–Organization–Environment (TOE) framework, the results validate that digital transformation is influenced by the interaction of multidimensional factors, but further reveal the phased evolutionary characteristics of this influence. Unlike previous studies that predominantly focused on single-stage or static factors, this research constructs an evolutionary pathway progressing from "technology and facility capacity building" to "digital resource integration and application deepening," and ultimately to "multi-stakeholder collaboration and systemic governance." This pathway embodies the dynamic coupling relationship between technology-driven initiatives, organizational responses, and environmental adaptation.

Moreover, compared to related studies on dynamic capability theory and the socio-ecological-technological systems (SETS) framework, this research indicates that within the complex marine ranch system, the formation of transformative capabilities depends not only on internal learning and resource restructuring but also critically on multi-stakeholder collaboration and institutional linkage. Through platform-based mechanisms, governments, enterprises, research institutions, and fishing communities collectively promote knowledge diffusion, resource integration, and value co-creation, thereby driving the transition from localized digitization to systemic intelligence. This finding enriches existing research on the systemic understanding of industrial transformation processes.

Overall, this study theoretically extends the applicability of the TOE framework within complex socio-ecological-technical systems. By integrating grounded theory, it reveals the phased patterns and key mechanisms of digital–intelligent transformation. Practically, it provides actionable, phased pathways for governments, enterprises, and third-party service platforms. Based on these findings, the following sections propose specific policy and practice recommendations.

4.2. Policy Recommendations for China's Marine Ranch Digital–Intelligent Transformation

Building on the evolutionary mechanism outlined earlier, this section examines the policy support logic at both national and regional levels. It identifies existing challenges in marine ranch development policies, analyzes their deeper structural causes, and draws lessons from the successful experiences of other industries in China's digital–intelligent transformation, such as the industrial internet and smart agriculture. Recommendations are then proposed from the perspectives of government, enterprises, and third-party service platforms.

At the national and regional levels, policies supporting marine ranch development have gradually been introduced. However, significant gaps remain in facilitating digital–intelligent transformation. The policy framework is still incomplete, with a lack of specialized plans and implementation guidelines targeting transformation, which limits enforcement. Funding support is insufficient given the capital-intensive nature of digital–intelligent upgrades. Technological R&D and dissemination lag behind the pace of techno-

logical change, and market cultivation is inadequate, with limited guidance and incentives for stakeholders to engage in transformation. These issues stem from an underestimation of the urgency and strategic importance of digital–intelligent transformation, as well as underdeveloped cross-departmental and cross-sectoral coordination mechanisms.

Other industries in China have made substantial progress in digital–intelligent transformation. The industrial internet and smart agriculture sectors, for example, have successfully combined government guidance with market-driven incentives, fostered deep integration of industry, academia, research, and application, and strengthened standardization systems. The marine ranching sector has also undertaken exploratory initiatives, such as establishing smart marine ranch demonstration zones and promoting intelligent aquaculture technologies.

From the government's perspective, strengthening policy frameworks is critical. This includes developing dedicated plans and guidelines for the digital–intelligent transformation of marine ranching, with clear objectives and pathways. Policy implementation should be supported by dedicated funding for key technology R&D and infrastructure construction. The government should also promote deeper integration between industry, academia, research, and application, encouraging collaboration between universities, research institutes, and enterprises to accelerate technological innovation and application. Furthermore, governments can play an active role in fostering market participation by guiding and supporting diverse stakeholders, thereby forming a multi-channel investment and engagement mechanism.

From the enterprise perspective, it is essential to reinforce their role as primary drivers of transformation. Enterprises should increase investment in digital–intelligent technologies to strengthen competitiveness. They should actively participate in platform construction and integration to achieve resource sharing and collaborative development, while also pursuing technological innovation to enhance independent innovation capacity. Additionally, enterprises can leverage digital–intelligent tools to expand market access, strengthen brand competitiveness, and increase market share.

From the perspective of third-party service platforms, efforts should focus on building a robust support ecosystem for digital–intelligent transformation. This includes offering technical consulting, talent training, and other value-added services, while actively participating in the formulation and dissemination of industry standards and norms. Third-party platforms can also facilitate upstream and downstream collaboration along the value chain, using digital–intelligent technologies to enable synergy, improve efficiency, and drive the overall upgrading of the sector.

4.3. Practical Measures for Advancing China's Marine Ranch Digital–Intelligent Transformation

Practical implementation requires coordinated action across government, enterprises, and service platforms. Governments should introduce clearer and more specific policy measures, enhance policy dissemination, and strengthen enforcement to ensure effective execution. Establishing a comprehensive safeguard mechanism will further improve the reliability of implementation.

Large-scale national marine ranches should be encouraged to play a leading role in platform development, leveraging their financial, technological, and managerial advantages. Deep integration of industry, academia, research, and application will enhance innovation capabilities and accelerate technological upgrading.

Small and medium-sized marine ranches should be guided and incentivized to participate in platform construction and integration. Through policy support and market-based incentives, these ranches can collaborate with larger enterprises to share resources, complement capabilities, and achieve coordinated growth.

Finally, strengthening the service ecosystem of marine ranch digital–intelligent platforms is essential for value chain coordination. This involves providing comprehensive, multi-level service support and fostering closer collaboration between upstream and downstream enterprises. By enhancing synergy across the value chain, the entire marine ranching sector can improve its competitiveness and readiness for sustainable, high-quality development.

To further enhance the operability and implementation effectiveness of the policy framework, this study deepens and expands policy recommendations across two dimensions: implementation pathways and evaluation mechanisms. At the strategic level, a phased action plan should be formulated, establishing quantifiable targets for digital–intelligent transformation—such as digital penetration rates, technology localization levels, and infrastructure coverage—while establishing a cross-departmental coordination mechanism. This mechanism should be jointly advanced by competent authorities including maritime affairs, science and technology, and ecological environment, forming a goal-oriented, highly coordinated policy execution system.

Regarding financial and industrial support, a combination of fiscal guidance and market-based mechanisms should be employed to establish incentive tools like specialized industrial funds or "scenario vouchers." These should prioritize supporting demonstration projects in key technology R&D, intelligent equipment deployment, and ecological monitoring. Fiscal leverage and project subsidy policies should stimulate enterprises and research institutions to actively engage in digital transformation practices, driving the implementation and diffusion of innovative outcomes.

Regarding human resources and institutional development, a comprehensive interdisciplinary talent cultivation system should be established to advance composite disciplines like "marine intelligence" and "marine data science." Concurrently, vocational education and skills training must be strengthened to meet the personnel demands for digital operations and intelligent management in marine ranching. A standardized performance evaluation system should be implemented, setting key performance indicators (KPIs) such as smart equipment application rates, carbon emission intensity reduction rates, and collaborative governance efficiency to enable dynamic monitoring and continuous improvement throughout policy execution.

This systemic implementation framework will shift policy orientation from "overall planning" to "precise execution," thereby providing a measurable, traceable, and replicable governance pathway for the sustained deepening of the digital–intelligent transformation of marine ranching.

5. Conclusions

This study focused on the digital–intelligent transformation of marine ranches under the strategic orientation of a diversified food supply. Centered on the interaction pathways among the technological, organizational, and environmental dimensions, it developed a three-stage evolution model comprising the "Technology and Facility Capacity Building Phase–Digital Resource Integration and Application Deepening Phase–Multi-stakeholder Collaboration and Systemic Governance Phase," and systemically revealed the dynamic mechanisms through which marine ranches progress from digitalization to intelligentization.

Within the methodological framework, the study was grounded in the Technology–Organization–Environment (TOE) framework and combined with a procedural grounded theory approach. Drawing on field investigation data, policy documents, and interview records from national-level marine ranches in the Shandong Blue Economic Zone, it employed open coding, axial coding, and selective coding to extract the critical technological foundations, platform systems, and institutional mechanisms influencing the transformation process. The findings indicated that the digital–intelligent transformation of marine

ranches is not merely a linear process of technological iteration and upgrading; rather, it constitutes a systemic transformation path driven by multi-actor participation, platform-based governance, and environmental adaptability.

At the theoretical level, this study enriches the applicability boundaries of the TOE framework within the context of social–ecological–technical systems (SETS), addressing the lack of analytical research on the digital–intelligent transformation mechanisms of marine ranches in existing literature. At the practical level, the policy recommendations proposed from the perspectives of governmental guidance, enterprise empowerment, and platform services are highly targeted and operational, providing valuable references for the digital–intelligent transformation of marine ranches in other coastal regions.

Although this study has constructed a phased model for the digital–intelligent transformation of marine ranches based on systemic grounded theory, certain limitations remain: (1) The research primarily relies on qualitative analysis. While cross-validation using multi-source data enhances the reliability of conclusions, subsequent studies should employ quantitative methods to empirically validate the identified evolutionary pathways, thereby further improving the model's robustness and universality. (2) Regional variations in resource endowments, policy environments, and industrial foundations may result in heterogeneous transformation processes and stage characteristics. Future cross-regional comparative studies could explore differentiated mechanisms under diverse institutional and resource contexts. (3) While this paper proposes policy directions and practical recommendations, there remains scope for expansion in implementation strategies and measurable performance indicators. Future research could further examine the synergistic impacts of intelligent transformation on ecological performance and social value, thereby establishing a more systemic integrated evaluation framework to enhance the policy transferability and practical guidance value of research findings.

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Appendix A. Interviewee Background and Data Summary

This appendix provides anonymized background information on interviewees and summarizes the qualitative data used for grounded theory analysis. All interviews were conducted within the National Marine Pasture Demonstration Zone of Shandong Blue Economy Zone, a key practical model for China's digital–intelligent transformation of marine pastures. Respondents included enterprise managers, technical experts, government officials, researchers, and representatives from fishery cooperatives. All participants voluntarily engaged and provided informed consent for the use of anonymized interview content in academic research. All audio recordings were transcribed and verified by the

authors. Content involving sensitive or proprietary information was removed during compilation to ensure confidentiality and ethical compliance.

A total of 14 valid interview transcripts were obtained, amounting to approximately 180,000 words after transcription. In addition to interview data, 26 policy and planning documents issued between 2018 and 2024, 12 relevant project reports, and 146 publicly available news reports and media materials were collected. This diverse dataset provides crucial grounding for grounded theory coding and cross-validation, facilitating a comprehensive understanding of the digital–intelligent transformation process of marine ranching.

Table A1. Distribution of interview participants by stakeholder group.

Stakeholder Group	Representative Roles	Count
Enterprises	Managers, operators	4
Technology sector	Engineers, platform designers	3
Government agencies	Regulators, policy officers	2
Academia	Professors, researchers	2
Cooperatives	Leaders, fishers	2
Third-party services	Association staff	1
Total	14	

Note: Source: Author's own.

Table A2. Anonymized interviewee list.

Code	Role/Position	Organization Type	City (Shandong)	Years of Experience	Mode	Duration (min)
I1	Deputy GM	National marine ranch operator	Qingdao	12	In-person	60
I2	Operations Director	Marine ranch operator	Weihai	10	In-person	55
I3	Senior Engineer	Smart aquaculture equipment vendor	Qingdao	8	In-person	45
I4	Data Platform PM	Digital platform provider	Yantai	6	Online	50
I5	Section Chief	Municipal ocean & fisheries bureau	Rizhao	14	In-person	60
I6	Policy Officer	Provincial ocean administration	Jinan	9	Online	40
I7	Associate Professor	Marine research institute	Qingdao	11	In-person	55
I8	Post-doc Researcher	University research team	Yantai	4	Online	45
I9	Ranch Site Manager	Marine ranch operator	Weihai	7	In-person	60
I10	Chief Technician	Seedling & breeding center	Qingdao	13	In-person	50
I11	Co-op Leader	Fishers' cooperative	Rizhao	15	In-person	40
I12	Fisher Representative	Fishers' cooperative	Weihai	18	In-person	35
I13	Secretary-General	Industry association/third-party	Qingdao	9	Online	45
I14	Digital Twin Specialist	Tech vendor (aquaculture DT)	Yantai	5	Online	50

Note: Source: Author's own.

Appendix B. Semi-Structured Interview Guide

Appendix B.1. Instructions

This interview aims to understand the current conditions and experiences of marine ranches in China's coastal regions during their digital–intelligent transformation. It explores the key factors influencing this transformation, its primary characteristics, and the

interactions among different stakeholders. The outline employs open-ended questions to guide interviewees in describing their experiences based on personal insights and practical situations. The research team will flexibly adjust the sequence and depth of questions during the interview to gain a deeper understanding of the real-world scenarios and critical events occurring throughout the transformation process.

Appendix B.2. Core Interview Questions

I. Overall Changes and Transformation Context

1. In recent years, what notable changes have occurred in your organization regarding the construction, management, or production of marine ranches?
2. What do you believe are the primary reasons for these changes?
3. Looking back at your work over the past few years, which events or decisions made you feel that "the shift had begun"?

II. Technology and Management Practices

4. In your daily work, what new technologies or practices have been adopted? Please share your experiences of using them.
5. What specific challenges have you encountered in applying these technologies or improving management? How were they addressed or adjusted?
6. How do you think these new technologies or practices have impacted work efficiency, quality, or costs?
7. Based on your observations, what conditions most facilitate the widespread adoption of these new technologies?

III. Organization and Collaboration

8. During the implementation of these changes, have there been new adjustments to your organization's structure, personnel division of labor, or internal communication?
9. In collaborations with research institutions, government departments, or partners, what experiences are worth summarizing? What areas still require improvement?

IV. External Environment and Policy Support

10. How have policy, market, or funding environments impacted your organization's transformation?
11. Within the current external environment, which factors most effectively promote or hinder innovation?

V. Outcomes and Problem Reflection

12. What do you consider the most significant change or achievement brought about by digital–intelligent transformation?
13. Which objectives remain unmet? What are the primary reasons?
14. Overall, what do you perceive as the main bottlenecks or risks in your current work?

VI. Future Direction and Recommendations

15. Looking ahead one to three years, what do you believe should be the key focus for marine ranch development?
16. To further advance the transformation, what areas of support or resources would you like to receive?
17. What practices or experiences from your organization could serve as reference for other regions?

Appendix B.3. Interview Guidelines

This interview centers on facts and experiences, focusing on understanding specific practices, key milestones, and lessons learned during the transformation process. The research team will systemically code the interview content in subsequent analysis to identify influencing factors and phase characteristics.

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