

Review

Progress and Prospective in the Development of Stored Grain Ecosystems in China: From Composition, Structure, and Smart Construction to Wisdom Methodology

Yunshandan Wu ^{1,†} , Wenfu Wu ^{1,2,†}, Kai Chen ¹, Ji Zhang ¹, Zhe Liu ¹ and Yaqiu Zhang ^{1,*}

¹ College of Biological and Agricultural Engineering, Jilin University, Changchun 130022, China; wysd22@mails.jlu.edu.cn (Y.W.); wuwf@jlu.edu.cn (W.W.); chenkaiz20@mails.jlu.edu.cn (K.C.); zhangji21@mails.jlu.edu.cn (J.Z.); liuzhe20088@jlu.edu.cn (Z.L.)

² School of Grain Science and Technology, Jilin Business and Technology College, Changchun 130507, China

* Correspondence: yaqiu@jlu.edu.cn; Tel.: +86-043185692518

† These authors contributed equally to this work.

Abstract: Food security is intrinsically linked to maintaining optimal physical health and promoting active lifestyles. Stored Grain Ecosystems (SGEs) are complex systems comprising a range of grains, microorganisms, and environmental elements. To ensure sustainable grain storage and promote food-friendly SGEs, careful regulation and monitoring of these factors are vital. This review traces the evolution of the Eco-concept of stored grain in China, focusing on micro- and macro-structural composition, the Multi-field/Re-coupling structure, and Smart Construction of SGEs, while introducing the four development lines and Wisdom Methodology of SGEs. The current status and challenges of SGEs in China are also discussed. The Eco-concept of stored grain in China has progressed through the initial exploration period, formation and practice periods, and has now entered its fourth stage, marked by a shift to include interactions of multiple biological fields. This evolution extends beyond the traditional binary relationship and offers emerging technologies greater scope for scientific and intelligent theoretical analysis of grain storage practices. The Wisdom Methodology employs a multifaceted, Mechanism and Data-driven approach, incorporating four driving methods, and is now widely recognized as a leading strategy for researching Smart Grain Systems. Digital Twin technology enables precise simulations and mappings of real-world SGEs in a virtual environment, supporting accurate assessments and early warnings for issues concerning grain conditions. Driven by Mechanism and Data, Digital Twin solutions are a pioneering trend and emerging hotspot with vast potential for enhancing the intelligence and wisdom of future grain storage processes. Overall, this review provides valuable guidance to practitioners for advancing high-quality Smart Grain Systems, enhancing sustainable and intelligent grain storage practices.

Keywords: food security; stored grain ecosystems; Eco-concept; multi-field/re-coupling structure; smart construction; grain storage; wisdom methodology; mechanism and data; smart grain systems; digital twin



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1. Introduction

The present period has brought forth significant transformations in conjunction with a major epidemic, which has led to heightened uncertainty in global food markets. This circumstance has presented a formidable challenge to the sustenance of food security in China. Addressing national food security requires setting our sights on multiple factors affecting the safety of Stored Grain Ecosystems (SGEs), encompassing both abiotic and biotic factors [1,2]. Abiotic factors, such as temperature, humidity, moisture, micro airflow, and pressure, can exert considerable impacts on the safety of stored grain [3,4]. Biotic factors, including fungal, bacterial, viral pathogens, and pests, also play pivotal roles. Temperature, humidity, and microbial growth stand among significant considerations in

grain storage safety [4–6]. These factors interact with each other, leading to diverse impacts on the safety of SGEs.

Throughout storage, it is not uncommon for the temperature and moisture levels of stored grain to exceed recommended thresholds, leading to the accumulation of heat and moisture within grain piles. This can result in the formation of fungus, hot spots, and even condensation. Excessive moisture and temperature levels within the grain provide ideal conditions for pests, fungal, and bacterial, leading to rapid reproduction and growth, and ultimately compromising food quality [6,7]. Infestations caused by pests can also lead to significant economic losses for agricultural producers and food processing industries [8]. These challenges underscore the critical importance of implementing efficient monitoring and regulatory measures to mitigate the adverse outcomes of degraded grain storage.

In order to trace the evolution of the Eco-concept of stored grain in China, this review extensively analyzes literature published between 1982 and 2023. This paper focuses on the composition, structure, and smart construction of Stored Grain Ecosystems (SGEs), which includes the Multi-field/Re-coupling relationship, the four main development lines, and Wisdom Methodology. Drawing from these concepts, this paper presents a comprehensive analysis of the current status and challenges facing SGEs in China. The aim of this endeavor is to advance high-quality Smart Grain Systems, promote sustainable and eco-friendly grain storage practices, and foster the application and development of the Digital Twin, Mechanism and Data Multi-driven strategy in SGEs. This approach enables more precise assessments and timely warnings for stored grain conditions, leading the future of grain storage towards a more scientific, informative, intelligent, and wise path.

2. A Brief History of the Development Process of the Eco-Concept of Stored Grain in China

Tansley, the British ecologist, first introduced and defined the concept of Ecosystem as the integration of the Environmental system and the Biological system [9]. This framework has been a driving force behind relevant agricultural research for scientists and technicians around the world.

The Eco-concept of stored grain in China underwent an initial phase of development from the 1940s to the 1970s, characterized by early exploration of ecological concepts. During the 1970s, Li [10] introduced the Stored Grain Ecosystem Theory in China, summarizing the characteristics and research methods of SGEs. Li [10] proposed that stored grain forms a complex, interdependent system of biotic and abiotic organic compounds that operates within a closed ecosystem. To ensure optimal preservation, all aspects of the system's contradictions must be comprehensively analyzed and coordinated, driving the system towards beneficial outcomes. This contribution underlines the importance of considering ecological principles in the management of grain storage systems and remains fundamental to academic research in this field.

The formation of the Eco-concept in grain storage research marked a significant period from the 1980s to the 1990s. Jiang [11] conducted extensive research and analysis of the Eco-concept of stored grain. Building on this foundation, Jin, Z., Yu, Y., Pan, C., et al. [12] proposed the Stored Grain Ecosystem Theory as the cornerstone of green grain storage. This theory emphasized the critical importance of governing the science and technology of grain storage through a framework of economic and technological ethics, as well as strategic considerations for sustainable development. Their work underscores the value of the Eco-concept as a pivotal element in current investigations into grain storage and the pursuit of ecologically sound practices.

The first decade of the 21st century marked the practical application period of the Eco-concept in grain storage research. During this time, the innovative “Four-in-One” grain storage technology was systematically developed and applied in China [13]. This technology combines intelligent mechanical ventilation, low-dose circulating fumigation, intelligent grain condition detection, and efficient grain cooling to resolve issues related to the long-term safe storage of large grain silos. This period represents a significant

milestone in the application and practice of the Eco-concept in grain storage, demonstrating the value and transformative power of integrating sound ecological principles into agricultural practices.

The period from 2010 to the present day has seen the consolidation of the Eco-concept through the integration of emerging Information Technology and Biotechnology. This period has been marked by a shift in the Eco-concept of stored grain to include interactions of multiple biological fields [14]. One example of this integration is the digital and cloud map monitoring system for stored grain, which enables real-time monitoring of stored grain across different locations [15]. Wu, W., Zhang, J., Xu, W. et al. [16] have proposed a groundbreaking multi-field-coupled graphical detection system for grain storage based on Nuclear Magnetic Resonance (NMR), signaling a new era in the study of SGEs. The system offers simultaneous, realistic, and accurate detection of grain temperature, humidity, and moisture, thereby revolutionizing the way these vital parameters are measured in the field. The cloud map generation software allows the presentation of the distribution of temperature, humidity, and moisture within the grain pile, providing a comprehensive analysis of the ecologically complex coupling relationship of the stored grain. This is the first instance of low-field Magnetic Resonance Imaging (MRI) technology being utilized in the context of the Stored Grain Ecosystem Theory, setting the stage for new technical means of exploring the interrelationships and complexity of grain storage. Wu, W., Wang, W., Li, S. et al. [17] have introduced the concept of Granary Philosophy, which has advanced the Eco-concept of stored grain and facilitated the exploration of intelligent grain storage technologies. The Granary Philosophy is an in-depth reflection on grain storage practices, with implications extending to other fields. It emphasizes the principles of “one divided into two, two divided into three, three born change” and utilizes a Mechanism and Data Multi-driven strategy as a Wisdom Methodology. This forward-thinking approach aims to enhance the understanding of current scientific and technological achievements and guide the exploration of Smart Grain Systems in the new era.

These innovative works are expected to have significant implications for the broader agricultural industry, offering a more efficient and eco-friendly approach to grain storage and management. The proposal and implementation of these advanced technologies and methodologies exemplify a growing commitment to environmentally sustainable and socially responsible practices in agriculture. As the global population continues to grow, such innovative approaches will be increasingly necessary to ensure food security and sustainable development, making this work of both immediate and long-term importance.

3. Deepening of the Eco-Concept of Stored Grain in China

3.1. Composition of SGEs

The period of post-harvest storage in grains comprises complex SGEs that can be duly characterized from both macrostructural and microstructural perspectives.

Macroscopically (Figure 1), the SGEs comprise the Grain Ecological Subsystem and the Environmental Ecological Subsystem, with factors in each subsystem impacting and intersecting to determine the overall stability of the systems. The Grain Ecological Subsystem encompasses stored grain within the confines of the granary enclosure, affected by abiotic factors such as temperature, humidity, pressure, and micro airflow, as well as biotic factors such as microorganisms, pests, rats, and birds. The Environmental Ecological Subsystem encompasses the external space surrounding the granary enclosure, where conditions such as solar radiation, temperature, humidity, climatic factors, and biological factors can significantly impact the state of the stored grain [18]. The interaction between these subsystems can affect the safety of the stored grain, and there may be delays and lags due to the thermal inertia of the enclosure. Understanding these complex interactions is crucial for maintaining the quality and safety of stored grain.

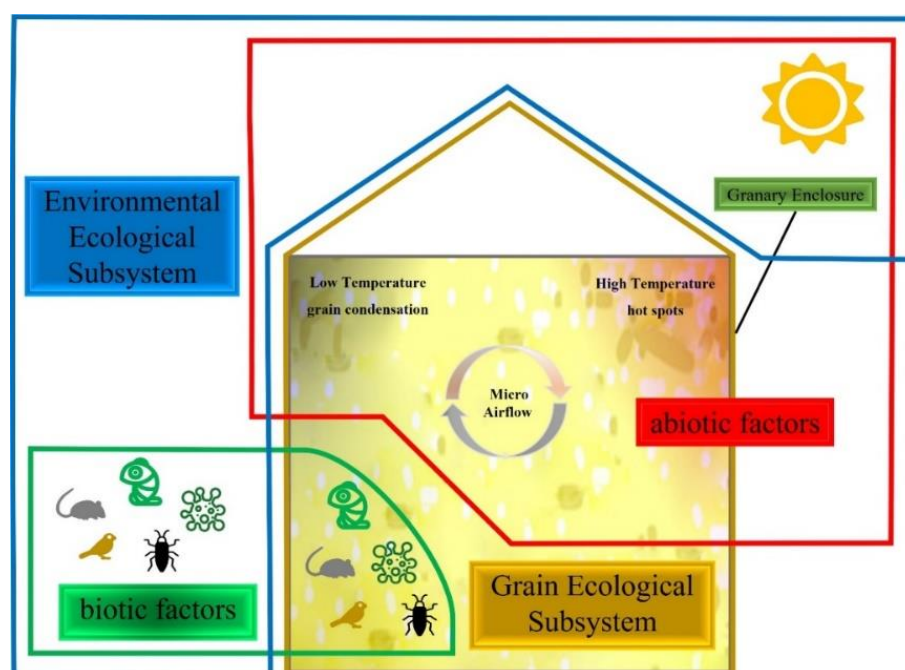


Figure 1. Macrostructure of Stored Grain Ecosystem (Figure 1 is adapted from Refs. [2,14]). The SGEs comprise the Grain Ecological Subsystem and the Environmental Ecological Subsystem, with factors in each subsystem impacting and intersecting to determine the overall stability of the systems.

At a microscopic level (Figure 2), the SGE is a triadic microstructure that involves the interactions among temperature, moisture, and humidity [17]. This triadic structure presents the most critical contradiction within the SGEs and has an inter-coupling relationship with micro airflow, microorganisms, pests, and impurities in the stored grain. The physical mechanism of this triadic microstructure is primarily reflected in the innovative “Four-in-One” grain storage technology, which employs a CAE model as its core. The micro-element, micro-environment, and micro-element in concomitant can form an internal microstructure, and they interact with each other through fields.

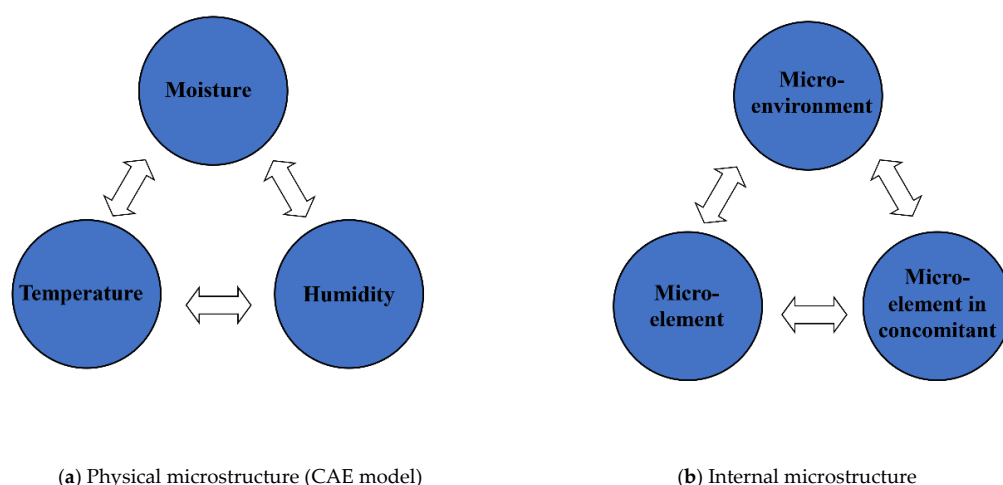


Figure 2. Microstructure of Stored Grain Ecosystems [17]. (a) Physical microstructure (CAE model); (b) internal microstructure.

3.2. Structure of SGEs

In the first decade of the 21st century, China entered the third development cycle of the Eco-concept of stored grain, culminating in the systematic and scientific application of the

innovative “Four-in-One” grain storage technology. This period saw significant progress in achieving industrialization and modernization for both the Eco-concept and industrial applications of grain storage. As the Food Internet of Things and Fourth Industrial Revolution gather pace, the Eco-concept of stored grain is entering a new phase of development, integrating with emerging Information Technology and Biotechnology [14]. Examples of this integration include the incorporation of multiple biological fields in stored grain research, the development of digital and cloud map monitoring systems for grain storage, and the construction of real-time dynamic supervision systems for grain storage [15,19]. These state-of-the-art technologies hold the potential to radically transform the way we manage the storage and preservation of our food resources, promoting greater efficiency and sustainability.

In their work, Wu, W., Wang, W., Li, S. et al. [17] have proposed a Multi-field/Re-coupling relationship to the study of SGEs, which deepens and broadens our understanding of this complex system. It has been revealed that SGEs are characterized by a coupling relationship with both external and internal environments, as shown in Figure 3. The internal Micro-environment of the stored grain is composed of a superposition of Micro-element environment, Micro-element environment in concomitant, along with Cluster environments. It is important to distinguish between the Micro-environment, which refers to the impact of the Macro-environment, and the Micro-element environment, which pertains to the effect of a Micro-element. The Microstructure and Micro-environment inside stored grain interact via various fields, including the Micro-element field, the Field in companion, and the Cluster field. A comprehensive understanding of these interactions is essential for more effective management and preservation of stored grains.

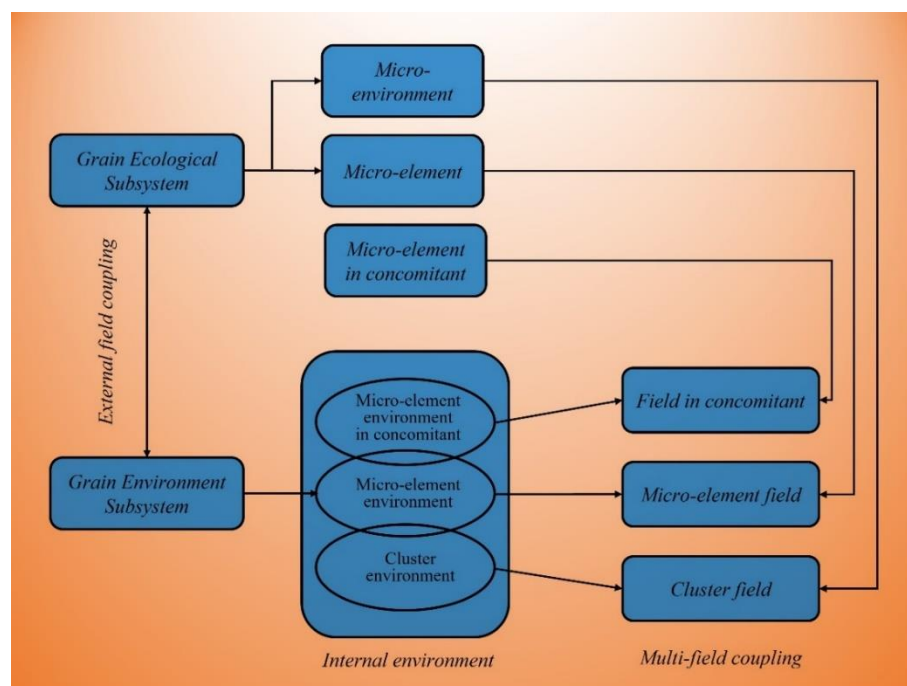


Figure 3. Multi-field/Re-coupling relationship of Grain Storage Ecosystems [17]. SGEs are characterized by a coupling relationship with both external and internal environments.

3.3. Smart Construction of SGEs

Since 2010, the field of SGEs has experienced remarkable growth and maturation, fueled by rapid advancements in the Internet of Things, Information Technology, Big Data, Artificial Intelligence, and Smart Construction Concept [20–25]. These technological breakthroughs have provided a continuous impetus for SGEs to shift towards a more diverse, extensive, scientifically based, and intelligent direction. Furthermore, recognizing

the multiple and complex interactions within SGEs, the coupling relationship has been expanded from the traditional binary arrangement to a multilayered one, as depicted in Figure 4. This development marks a significant step towards a more sophisticated and integrated understanding of this dynamic and intricate system.

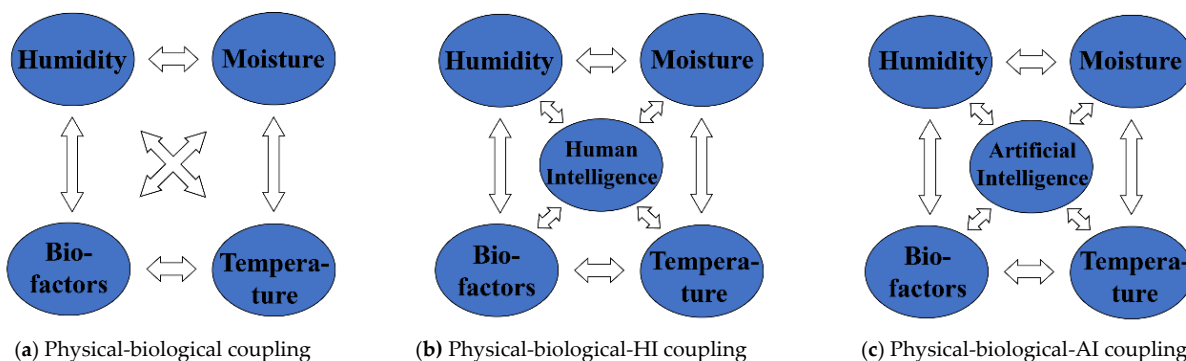


Figure 4. Smart Construction of Stored Grain Ecosystems [17]. The technological breakthroughs have provided a continuous impetus for SGEs to shift towards a more diverse, extensive, scientifically based, and intelligent direction: (a) Physical-biological coupling; (b) physical-biological-HI coupling; (c) physical-biological-AI coupling.

The binary relationship within SGEs primarily concerns the heat and mass transfer that takes place within the porous grain media. This relationship has proven to be a valuable tool in addressing scientific research and engineering practice problems. For example, Khankari, K.K., Patankar, S.V., Morey, R.V. et al. [26] used numerical simulation methods to study the movement of grain moisture within this system. The results showed that temperature variations play a significant role in driving grain moisture movement. In a similar study, Ghosh, P.K., Jayas, D.S., Smith, E.A. et al. [27] investigated the moisture transfer patterns of individual wheat grains under temperature gradients, providing insights into predicting moisture development patterns during the drying process of wheat.

Expanding the binary relationship between temperature and moisture to a triadic relationship that also includes humidity within the SGEs provides a solution to more complex engineering problems. By utilizing the CAE equation and the absolute water potential map, it becomes possible to predict the growth of fungi and the occurrence of condensation in stored grain [17]. Such predictive capabilities are critical for ensuring the safe storage of grain and can help mitigate potential losses due to spoilage. Uneven temperature distribution within grain piles leads to the formation of an airflow driven by temperature differences, which in turn causes grain condensation. During heat transfer, water vapor within the pores of the grain pile is transported from higher temperature regions to lower temperature regions, resulting in partial moisture accumulation and the creation of low temperature zones and high humidity zones within the pile [28]. Therefore, the moisture content of stored grain is a critical factor for ensuring its safety. In a test, Wang, X. [29] added high moisture corn (18.2% w.b) into the center of a low moisture corn grain pile (14% w.b) and stored it at a constant temperature of 30 °C for 40 days. The test results revealed a significant increase in the multiplication of *Aspergillus* and *Aspergillus flavus* in the grain pile due to the high moisture content, which generated substantial heat. These findings highlight the importance of careful consideration of moisture levels in stored grain to prevent spoilage and ensure the preservation of grain quality.

The quadratic coupling relationship between biological and physical factors in SGEs represents a significant breakthrough in the advancement of Eco-concepts for grain storage, achieved through the integration of biotechnology, emerging science, and technology. Cui, H. [15] established real-time dynamic supervision through the use of digital and cloud map monitoring systems for grain storage. The digital supervision intelligent method employs a Mechanism-Data co-driven technique for monitoring stored grain. This approach

utilizes seven intelligent strategies which are drawn from a wealth of grain big data information [30]. This allows for the provision of efficient and rapid machine-assisted judgments, enabling the effective utilization of data in grain storage management.

The fifth and sixth element coupling relationships within SGEs can be enhanced through the synergy of Human Intelligence and Artificial Intelligence [17]. The expansion of the Eco-concept of stored grain employs emerging technologies such as Big Data, Internet of Things, Intelligent Perception, Meta-Universe and Digital Twin, along with a hybrid strategy combining qualitative and quantitative analysis. Such practices require careful handling of the interrelationships between Mechanistic Formulae and Data-Driven approaches, Complexity and Simplicity, Determinism and Perturbation, among others. Consequently, it provides scientific, intelligent theoretical analysis methods, and tools that can significantly improve grain storage practice. The fourth industrial revolution presents a new developmental opportunity for traditional industries like the grain industry to embrace such technological solutions, while the effective use of these new scientific methods remains a potential challenge and fruitful mission for the grain industry to move towards sustainable growth.

4. The Main Line and Wisdom Methodology for the Development of SGEs

4.1. The Development Line of SGEs

Currently, four primary research methodologies are utilized in the study of Stored Grain Ecosystem Theory: knowledge-driven, theory-driven, experiment-driven, and data-driven. The employment of these methodologies has significantly contributed to the advancement of Stored Grain Ecosystem Theory.

The knowledge-driven approach relies on the utilization of the extensive expertise and skills of trained frontline workers to enhance grain storage efficiency and reduce losses. This approach encompasses a variety of valuable resources such as case studies, experiences, and common knowledge, and it continues to play a pivotal role in the current operations of grain storage management in China.

The second approach is driven by experimentation, with the goal of constructing an accurate model. This method involves exerting precise control over the parametric conditions in the laboratory, measuring trace samples, and formulating precise formulas. It can be represented by the CAE Unidirectional Model or Concise CAE Multi-directional Model, which serve as the core components of the innovative “Four-in-One” grain storage technology [17]. These models are instrumental in driving the modernization of grain storage practices in China.

The third approach is theory-driven and relies on linear multi-field coupling. This model is based on partial differential equations, such as momentum, energy, and mass conservation, to numerically describe the SGEs. It offers a detailed simulation analysis of stored grain conditions and variations in rules from a mechanistic standpoint, under both manual and non-manual interventions. Some typical models that fall under this category include Heat and Mass Transfer Model [26,31,32]. Additionally, Numerical Simulation technology serves as a bridge between small and large-scale SGE studies, and it addresses the variability that exists between scales. By incorporating the medium flow field [33] and biological field, it becomes possible to study the interactive coupling of multiple factors. This approach provides a window for observing and predicting long-term stored conditions in large-scale real systems within short-term periods.

Data-driven approaches employing Big Data Mining and Machine Deep Learning have emerged as effective tools for optimizing management in the absence of clear mechanistic models. The application of data-driven AI technology is enhancing the post-grain production industry in China by improving its management skills. For instance, an automatic optimal control algorithm has been successfully implemented, resulting in a remarkable increase in efficiency by over 20% over similar drying systems [18,34,35].

4.2. The Wisdom Methodology of SGEs

The SGEs represent a highly complex system, and accordingly, research methods utilized for the system's analysis encompass both advantages and limitations.

Theory-driven is suitable for numerical simulation, but it can encounter challenges when dealing with complex and variable physical parameters and boundary conditions. Numerical simulation methods leverage sophisticated mathematical models and algorithms to solve intricate equations that capture real-world phenomena. However, it is crucial to acknowledge that the implementation of numerical simulations entails intricate mathematical computations. The precision and dependability of simulation outcomes are influenced by the complexity and intricacy of these computations.

Experimental approaches, although suitable for achieving a high degree of precision in expression, may have limited applicability when scaled up from trace samples to larger granaries. Such limitations have led to questions about the reliability and practicality of these methods when used at larger scales.

Data-driven is good at approximating the real phase but lacks mechanistic support. Moreover, because the data volume is huge, there are inevitably problems such as low data quality and unsatisfactory utilization, even some minor probability events will be ignored.

Despite its practical usefulness, knowledge-driven approaches are limited in terms of accurate and scientific transmission due to the significant variation in knowledge level among individuals. Furthermore, the accumulation of knowledge necessary to build a comprehensive knowledge system typically requires a significant investment of time and effort.

"Integrated Dual Analysis of Quantitative and Qualitative" provides a research method for analyzing the SGEs in China [36]. Based on the definitions of the composition, structure, Smart Construction, and main development lines of the SGEs, Wu, W., Wang, W., Li, S. et al. [17] developed a Wisdom Methodology for studying this ecosystem (Figure 5). The Wisdom Methodology integrates four types of research methods to identify new approaches for solving complex problems within SGEs.

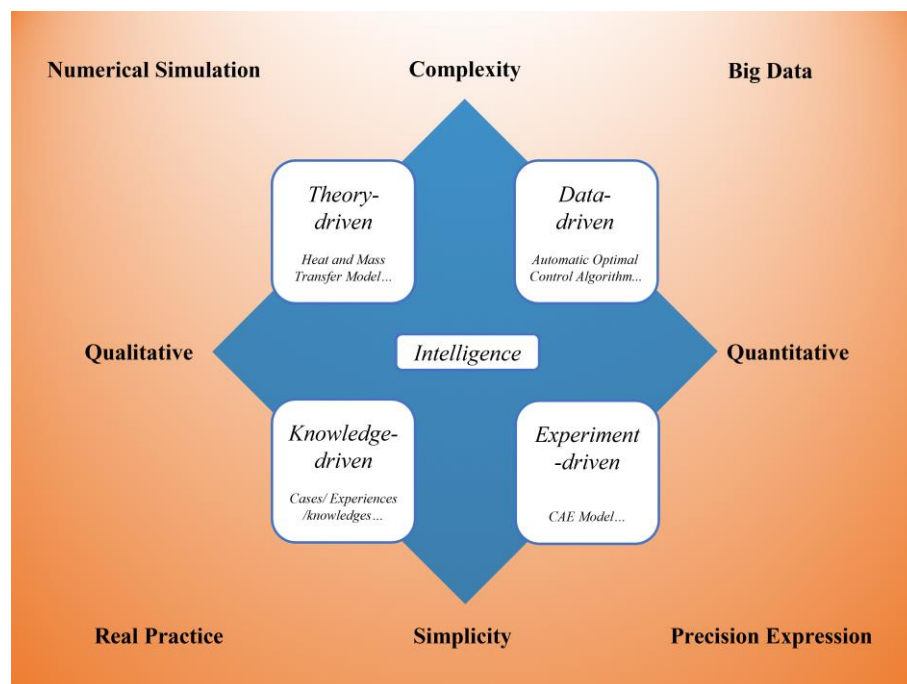


Figure 5. Wisdom Methodology of Stored Grain Ecosystems [17]. The Wisdom Methodology integrates four types of research methods to identify new approaches for solving complex problems within SGEs.

4.3. Practical Examples of SGEs Wisdom Methodology

The Mechanism and Data Multi-driven intelligent strategy draws inspiration from the wisdom methodology of SGEs and stands as the most promising approach for comprehensively exploring the intricacies of the Smart Grain Systems. Table 1 presents the practical examples of the SGEs Wisdom Methodology.

Table 1. Practical examples of SGEs Wisdom Methodology.

Examples	Main Content	Wisdom Methodology	References
Example 1	Ref. [15] developed an advanced method for digitally supervising grain reserves.	Mechanism and Data Multi-driven.	[15]
Example 2	Refs. [15,30,37] devised seven intelligent strategies, including 6R, O, AID, ABC, SIN, U, and CAE, and these strategies are driven by the principles of supervision developed in example 1.	Mechanism and Data Multi-driven.	[15,30,37]
Example 3	Ref. [37] developed a comprehensive manual for intelligent analysis of grain conditions, and this enables efficient and accurate application of intelligent strategies devised in example 2, facilitating the digital supervision method developed in example 1.	Mechanism and Data Multi-driven.	[37]
Example 4	The “digital and cloud map monitoring system of stored grain” system developed and applied during a State Council-led pilot project that examined grain storage in 10 provinces. The system demonstrated impressive accuracy, with an over 70% success rate in issuing early warnings.	Mechanism and Data Multi-driven.	[15,30,38]
Example 5	Refs. [29,39] investigated temperature and humidity levels during grain storage, identifying the specific zones where condensation or fungal growth may arise, as well as forecasting their incidence up to two weeks or even two months in advance	Mechanism and Data Multi-driven.	[29,39]

An exemplary application of the Wisdom Methodology is demonstrated in the digital supervision of stored grain using intelligent techniques. Cui, H. [15] developed an advanced method for digitally supervising grain reserves, which analyzes the continuity of single fields over time and space, alongside periodicity around the time axis and the coordination principles of Multi-field Coupling. Seven intelligent strategies, including 6R, O, AID, ABC, SIN, U, and CAE were devised to operate in conjunction with the graphical characteristic data of grain information, and these strategies are driven by the principles of supervision [15,30,37], as shown in Table 2. The implementation of these strategies directly addresses the challenges associated with processing original data, such as low efficiency and significant errors. To overcome these issues, Lu, Y., Li, X., Wu, W. [37] conducted focused research on the typical grain silos in different grain storage ecological regions in China. By extracting the relevant original grain storage data for major grain varieties, they developed a comprehensive manual for intelligent analysis of grain conditions. This enables efficient and accurate application of intelligent strategies, facilitating the digital supervision of stored grain quantity and quality, and realizes that the transformation from relying on human defense to adopting technical defense measures signifies a significant advancement in the field. Using the “digital and cloud map monitoring system of stored grain” developed by Cui, H., Wu, W [15,30], over 230,000 data points on grain information were scrutinized, and close to 1800 early warning signals related to temperature changes were gleaned during a State Council-led pilot project that examined grain storage in 10 provinces. The system demonstrated impressive accuracy, with an over 70% success rate in issuing early warnings [30].

Table 2. Seven intelligent strategies explanations [15,37].

Strategy	Principles	Model Parameters	Explanations
SIN	Climate model	Climatic temperature	Based on the relationship between the elevation, longitude, and latitude of each city, as well as the local air temperature curve, and the magnitude of change in the grain temperature inside the silo, a comparative judgment is made to determine whether the grain temperature inside the silo is abnormal.
AID	Periodicity	Grain temperature, cumulative grain temperature, and quality models	A: Characterization of the magnitude of the food storage factor, including the range of variation, mean, variance; I: Detection of stored grain cumulative temperature as a method of judging and evaluating grain condition; D: Differential characterization of grain storage factors, where differential characterization examines grain temperature characteristics from both temporal and spatial perspectives.
ABC	Contiguity	Grain temperature	Quadratic polynomial model.
6R	Contiguity	Grain temperature	Using the principle of mathematical statistics, the correlation of each grain temperature cross-section layer in the grain silo on the time axis and the mutual correlation in space are calculated and analyzed to determine the location of anomalies and realize the monitoring of grain conditions.
O	Coordinative	Cloud map isotherm closure	Ratio of isotherm length to cloud map perimeter.
U	Coordinative	Cloud map isotherm openness	Proportion of the area of the temperature field cloud map that is lower than the temperature value T_0 in the whole cloud map.
CAE	Equilibrium model	Ternary relationship between temperature, humidity, and moisture	The equation fitted by using the EMC/ERH desorption and adsorption data of the measured grain is called the CAE equation.

Moreover, by implementing a Mechanism and Data Co-driven strategy to investigate temperature and humidity levels during grain storage, it becomes feasible to identify the specific zones where condensation or fungal growth may arise, as well as forecast their incidence up to two weeks or even two months in advance [29,39]. This provides ample time for relevant personnel to take targeted preventive and remedial action.

5. The Opportunities and Challenges for the Development of SGEs

Traditionally, research into SGEs has been hindered by limitations associated with single theoretical research methods, experimental research scalability, and the inability to extend scientific and technological breakthroughs. Fortunately, the emergence of Artificial Intelligence, Information Technology, Digitalization, Industrial Internet of Things, and Numerical Simulation technology has created new opportunities to overcome these challenges. A paradigm shift is called for in the approach towards researching SGEs, with renewed focus on multifaceted, scientifically efficient, multidisciplinary and interdisciplinary, intelligent, and wisdom-based methodologies. Given the diversity and complexity of the factors that influence SGEs, innovation in Multi-field Coupling theory is crucial. It is imperative to explore innovative, scientifically justifiable, advanced, accurate, effective, and high-precision modeling approaches to portray, describe, and forecast the condition of large grain storage facilities under complex multi-field effects, to guarantee efficient operation and secure grain storage.

In recent years, there has been a growing focus on advancing Digital Twin and computer Numerical Simulation techniques, as Digital Twin technology serves as a crucial link between the physical and digital worlds. In the context of Stored Grain Ecosystem Theory,

the potential of Digital Twin technology to shift simulation models from single-condition, single-physical field, static modeling to dynamic modeling of complex conditions and multi-physical fields is highly promising.

The complexities of SGEs, the demands and difficulties of Digital Twin technology, and the Wisdom Methodology of SGEs have led us to believe that the fusion of calculation and measurement driven by the combination of Mechanism and Data analysis will become a new trend and hot topic for research in this field. This innovative approach comprises two key steps. First, the construction of a real-time twin model (grain bin) with coupling characteristics of multi-physical fields, multi-disciplines, multi-scales, and multi-dimensions using the mechanistic model and basic data book of grain intelligence analysis. This model enables accurate simulation and mapping of the form and performance of the real physical system in the virtual world, reflecting its external behavior and internal evolution law in space, mapping online or offline in time, reproducing in real time or history, and predicting future storing states [40,41]. Second, the twin model (grain bin) simulates, analyzes, summarizes, and optimizes the real grain storage conditions to achieve intelligent and optimal control and operation, ultimately realizing high-quality grain storage.

6. Conclusions

The evolution of the Eco-concept of stored grain in China has progressed through four phases: the initial exploration period, the formation period, the practice period, and the latest phase marked by a shift towards a more diverse, extensive, scientific, and intelligent orientation. This transformation expands beyond the traditional binary relationship and provides emerging technologies with enhanced access to scientific and intelligent theoretical analysis of grain storage practices. The Wisdom Methodology for Stored Grain Ecosystems (SGEs) offers a unique framework for innovatively addressing the most complex issues in this field, incorporating four distinct driving methods, such as the Mechanism and Data analysis method. Consequently, the Wisdom Methodology is now widely recognized as a leading strategy for researching Smart Grain Systems.

The advancement of the Stored Grain Ecosystem Theory hinges on the development of more accurate methods for portraying, describing, and predicting the state of grain in large-scale storage facilities subjected to multi-field effects. Digital Twins, which employ the “fusion of calculation and measurement” approach and are co-driven by Mechanism and Data, represent a new trend and a hotspot that hold great potential for advancing the intelligence and wisdom of future grain storage processes. By integrating these innovative technologies and novel approaches, grain storage can become more sustainable, while minimizing potential risks and uncertainties through precise monitoring and control strategies. This review serves as a valuable source of guidance for practitioners in advancing high-quality Smart Grain Systems and improving sustainable and intelligent grain storage practices.

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