Healthy Food Design in a Co-creation Ecosystem: An Integrated Strategy for Education, Research, and Innovation in Sustainable Food System 4.0

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***Abstract*—As global population growth and health consciousness rise, traditional food systems face severe challenges in meeting demands for sustainability, nutrition, and personalization. Existing research predominantly explores food innovation from singular technological or managerial perspectives, lacking a systematic framework that integrates design thinking, multi-stakeholder collaboration, and capacity building. A significant research gap exists, particularly in how to construct a dynamic and efficient co-creation ecosystem to drive healthy food design. This paper aims to build a triple-helix integration strategy for education, research, and innovation, exploring, from the unique perspective of the design discipline, the methods and pathways for systematically promoting healthy food design through a co-creation ecosystem within the context of Sustainable Food System 4.0. The study employs a multi-case analysis and system dynamics modeling, selecting five leading global food innovation hubs as cases, combined with in-depth interview data from 150 industry experts and consumers, to construct a co-creation ecosystem model comprising four core subsystems: Technology Enablement, Multi-stakeholder Collaboration, Policy Guidance, and Capacity Building. The findings suggest that, across the selected cases and interviews, earlier integration of design thinking is associated with improved new product development (NPD) performance and higher perceived consumer acceptance. In addition, the system dynamics (SD) scenario analysis indicates that a digitally enabled co-creation ecosystem may shorten the end-to-end development cycle under the model assumptions. The reported improvement magnitudes are scenario-dependent and should be interpreted as indicative estimates rather than universally generalizable effects. This research not only provides a new theoretical framework for healthy food design but also offers actionable strategies for policymakers, educational institutions, and food enterprises to build efficient innovation ecosystems, holding significant theoretical and practical importance for promoting the sustainable transformation of the global food system.**

Keywords—Healthy Food Design, Co-creation Ecosystem, Sustainable Food System 4.0, Design Thinking, Integrated Strategy

I. Introduction

The global food system is at an unprecedented crossroads. On one hand,the world population is projected to approach 10 billion by 2050, with a sustained increase in demand for both the quantity and quality of food [1]. On the other hand, climate change, resource depletion, and environmental degradation pose severe challenges to traditional agriculture and food production models, casting doubt on their sustainability [2]. Concurrently, consumer expectations for food are undergoing a profound transformation, shifting from a mere pursuit of sustenance to a comprehensive focus on health, nutrition, safety, and personalized experiences [3]. This shift has fueled a tremendous demand for "healthy food," a term that refers not only to the nutritional value of the food itself but also to the transparency of its production process, its environmental friendliness, and its contribution to social well-being [4]. Against this backdrop, how to systematically promote healthy food innovation to meet increasingly diverse market demands while ensuring the sustainability of the food system has become a core global issue.

However, current food innovation practices are widely plagued by systemic fragmentation. Technological R&D, market demand, industrial policy, and consumer education are often disconnected, leading to low innovation efficiency, resource misallocation, and a high failure rate for new products in the market [5]. Although the concept of "Industry 4.0" has been introduced into the food sector, giving rise to the so-called "Food System 4.0" that emphasizes the use of digital technologies like the Internet of Things (IoT), big data, and artificial intelligence to enhance production efficiency and transparency [6], most research remains confined to the singular dimension of technological application, neglecting the synergistic value of multiple actors within the innovation ecosystem. In particular, the systemic role of the design discipline as a bridge connecting technological possibilities with human needs has been far from fully explored in food innovation. Therefore, the central question of this research is: How can a co-creation ecosystem that integrates education, research, and innovation be constructed, with design thinking as its core driving force, to systematically promote the design and development of healthy food within the framework of Sustainable Food System 4.0?

Currently, research on food innovation is primarily concentrated in several areas. First, it focuses on emerging food processing technologies, such as high-pressure processing, 3D printing, and cellular agriculture, aimed at improving nutrient retention and texture [7]. Second, it centers on consumer behavior, analyzing the acceptance of novel foods (e.g., plant-based products, insect protein) and its influencing factors [8]. Third, it explores the application of open innovation and value co-creation in the food industry, but mostly at a theoretical level or in small-scale case studies, lacking an operational systemic framework [9]. While these studies provide valuable insights for healthy food innovation, they generally suffer from the following shortcomings: firstly, a singular perspective, failing to effectively integrate

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multiple dimensions such as technology, consumers, design, business, and policy; secondly, a linear process, still following the traditional "R&D - production - marketing" model and lacking a dynamic, iterative co-creation mechanism; and finally, lagging capacity building, neglecting the importance of cultivating innovative talent with interdisciplinary knowledge and systems thinking for the sustainable development of the ecosystem [10].

To address these research gaps, this study aims to achieve the following objectives: first, to construct a theoretical model named the "Healthy Food Design Co-creation Ecosystem" (HFDCE) from the systemic perspective of the design discipline; second, to clarify the internal connections and integration mechanisms among the three pillars of education, research, aand third, to evaluate the plausibility and potential impacts of the proposed model through triangulated case evidence and system dynamics (SD) scenario analysis in enhancing the efficiency of healthy food design and promoting sustainable consumption. This study is scoped within the macro context of Sustainable Food System 4.0, focusing on the entire process of healthy food design and development, with a particular emphasis on a co-creation model centered on design thinking, without delving into the engineering details of specific food processing technologies.

The structure of this paper is as follows: The second section will systematically review the literature, summarizing the current state of sustainable food systems, co-creation theory, and the application of design thinking in food innovation. The third section will detail the multi-case analysis and system dynamics modeling methodology used in this study. The fourth section will present the core results obtained from the case analysis and model simulation. The fifth section will provide an in-depth discussion of the research findings and compare them with existing literature. Finally, the sixth section will summarize the core conclusions of the study, pointing out its theoretical contributions, practical implications, limitations, and future prospects.

Accordingly, advanced technologies (e.g., AI analytics, digital twins, 3D food printing, or novel-food regulatory sandboxes) are discussed only as optional enablers observed in the cases, and are not prerequisites for applying the proposed framework in typical research or industry settings.

II. Literature Review

To construct an integrated framework for a healthy food design co-creation ecosystem, this section will systematically review relevant literature from three core areas: the development and challenges of Sustainable Food System 4.0, the application of co-creation theory in food innovation, and the potential of design thinking as an integration tool. Through a comprehensive analysis of existing research, this section aims to identify current research gaps and lay the theoretical foundation for the integrated strategy proposed in this paper.

A. *Sustainable Food System 4.0: Opportunities of Digitalization and Challenges of Systemic Integration*

"Food System 4.0" is an extension of the "Industry 4.0" concept into the food industry, with its core being the use of a series of disruptive digital technologies, such as the Internet of Things (IoT), big data, artificial intelligence (AI), blockchain, and digital twins, to transform the entire value chain from farm to fork [6, 11]. The application of these technologies aims to improve production efficiency, enhance food safety and traceability, reduce resource waste, and minimize the environmental footprint [12]. For example, IoT-based precision agriculture can optimize water and fertilizer use based on real-time data, while blockchain technology can provide consumers with immutable product origin information, thereby building trust [13]. These advancements offer unprecedented technological possibilities for achieving the United Nations Sustainable Development Goals (SDGs), particularly those related to zero hunger, good health and well-being, and responsible consumption and production [14].

However, despite the growing discussion at the technological level, existing research widely reveals a core problem: a lack of systemic integration. Most literature tends to discuss the application of a specific technology in isolation, failing to consider it within a complex socio-technical system composed of diverse stakeholders [15]. A food system is not just a physical process of production and distribution, but also a social ecosystem that includes producers, processors, retailers, consumers, research institutions, and policymakers [16]. The successful application of technology ultimately depends on its effective adoption, integration, and synergistic use by all actors in the ecosystem. Current research lacks in-depth theoretical guidance and practical models on how to cross organizational boundaries, coordinate the motivations and behaviors of different stakeholders, and co-create value. In particular, how to systematically integrate consumers' tacit needs and value preferences into technology-driven innovation processes remains a significant research gap [9]. This is precisely the entry point for this study's introduction of the "co-creation ecosystem" concept.

B. *Co-creation Theory and Food Innovation: From Linear Participation to Ecosystemic Synergy*

Co-creation theory, originating from Service-Dominant Logic, emphasizes that value is co-created in the interaction between firms and consumers (and other stakeholders), rather than being unilaterally created by the firm and delivered to passive consumers [17]. In the field of food product development, co-creation is seen as an effective strategy to cope with high market uncertainty and diverse consumer demands [18]. By involving consumers in the early stages of innovation (such as concept ideation and design), companies can more accurately grasp market needs and develop new products with greater appeal and acceptance, thereby reducing the risk of market failure [19].

Existing research on food co-creation mainly employs methods such as focus groups, online communities, and design workshops to involve consumers in the ideation, prototype testing, and marketing strategy formulation of new products [20]. These studies have confirmed the positive role of co-creation in enhancing product originality, feasibility, and value, especially in developing healthy foods for specific populations such as the elderly and children [21]. However, these practices are mostly project-based and one-off, failing to form a sustainable innovation mechanism. They often treat co-creation as a linear "information input" process, where insights are gathered from consumers and then subsequent development is carried out by internal corporate teams. This model has two major limitations: first, insufficient breadth and depth of participation, failing to fully integrate the knowledge and resources of other key actors in the supply chain (such as farmers, ingredient suppliers, and nutritionists); second, a lack of dynamic feedback and iteration, as the influence of external stakeholders sharply declines once the product enters the later stages of development, making it unable to adapt to a dynamic market environment. Therefore, it is necessary to elevate co-creation from a "project management tool" to an "ecosystem operation strategy," building a dynamic network that promotes continuous interaction, knowledge sharing, and value co-generation. This requires us to focus not only on consumers but also on the structure, relationships, and operational mechanisms of the entire ecosystem.

C. *Design Thinking: A Systemic Approach to Integrating Technology, Business, and User Needs*

Design Thinking is a human-centered, systemic innovation methodology for solving complex problems. It emphasizes the iterative cycle of Empathize, Define, Ideate, Prototype, and Test to effectively integrate technological feasibility, business viability, and human desirability [22]. Although Design Thinking was initially applied in product design and software development, its use as a general innovation framework has been successfully extended to various fields such as business strategy, public services, and organizational change [23].

In the field of food innovation, the potential of Design Thinking is gradually being recognized. It can help innovation teams shift from a traditional "technology-product" orientation to a "user-experience" orientation, systematically defining innovation opportunities by understanding consumers' life contexts, emotional needs, and latent pain points [24]. For example, through ethnographic research methods, design teams can gain deep insights into the real scenarios of home cooking, thereby designing healthy and convenient foods that better fit actual usage habits. Furthermore, the emphasis of Design Thinking on rapid prototyping and iterative testing allows for the low-cost, rapid validation of various concepts, effectively reducing uncertainty in the innovation process [25]. However, current research on applying Design Thinking to food innovation is still in its early stages, mostly consisting of conceptual discussions or small-scale teaching experiments. Few studies have systematically explored how to use Design Thinking as a core methodology to build and operate a complex food innovation ecosystem, especially how to use it to integrate the digital technologies of Food System 4.0, the diverse stakeholders in co-creation activities, and interdisciplinary educational and research resources. This provides a unique entry point for this study: positioning Design Thinking as a binder and catalyst to integrate the various elements of the co-creation ecosystem, thereby systematically driving healthy food design.

In summary, while existing literature has made significant progress in the respective fields of sustainable food systems, co-creation, and design thinking, it has also left a clear "integrative" research gap. It is on this basis that this study attempts to construct a "Healthy Food Design Co-creation Ecosystem" model that organically merges the three, and proposes corresponding integrated strategies for education, research, and innovation, with the hope of providing a new theoretical framework and practical path for promoting the sustainable transformation of the food system.

III. Related Work

Before constructing our integrated framework, it is necessary to review existing models and frameworks related to food innovation ecosystems to clarify the uniqueness and contribution of this study. Related work can be primarily categorized into three types: open innovation platforms, Living Labs models, and systemic transition frameworks.

Open innovation platforms are mechanisms established by companies to acquire external knowledge and ideas. In the food industry, many large multinational corporations such as Nestlé (through its HENRi platform) and Danone have adopted open innovation strategies, collaborating with startups, universities, and individual inventors to accelerate product development [26]. These platforms have been effective in breaking down internal innovation barriers and introducing disruptive technologies. However, their operating model is typically "hub-and-spoke," where the central firm dominates the innovation direction and resource allocation, and collaborations are often transactional and project-based. "Co-creation" in this model serves more the company's own strategy, lacking a systematic focus on the capacity building and value sharing of the entire ecosystem, and consumers are usually just information providers or testers, rather than equal co-creation partners [27].

Living Labs are another multi-stakeholder collaboration model that emphasizes continuous innovation activities in real-life environments, with the joint participation of users, researchers, companies, and the public sector [28]. The European Network of Living Labs has several successful cases focused on the food sector, such as developing nutritional products for the elderly or promoting sustainable dietary habits through living labs. Compared to open innovation platforms, Living Labs are more user-centric and emphasize iterative testing in real-world settings. However, their limitation is that many Living Labs are small in scale and geographically limited, making their successful experiences difficult to scale up and replicate [29]. Furthermore, the translation path between their research outcomes and commercialization is often unclear, lacking institutionalized connections with the broader industrial ecosystem and educational system.

Systemic transition frameworks explore the pathways of food system transformation from a more macro perspective. For example, the Food and Agriculture Organization of the United Nations (FAO) has proposed a framework for sustainable food and agriculture, and some academic studies have constructed Socio-Technical Transition Models [30]. These frameworks have strong explanatory power in identifying systemic barriers and analyzing multi-level driving factors (such as policy, market, and culture). They provide a macro perspective for understanding the complexity of food system transformation, but are often too abstract and lack specific methods and tools that can be directly applied by companies or innovation teams. In particular, these macro frameworks rarely focus on the active role of "design" in guiding and shaping the transition process, nor do they detail how to systematically cultivate the innovation capabilities required for the transition through education and research.

As shown in the table below, the "Healthy Food Design Co-creation Ecosystem" (HFDCE) model proposed in this study aims to address the shortcomings of the aforementioned related work while building on their strengths. Unlike open innovation platforms, HFDCE emphasizes a decentralized, multi-win ecosystem network. Compared to Living Labs, it focuses more on achieving scalability and institutionalized connections through digital platforms. In contrast to macro transition frameworks, it provides an operational methodology centered on design thinking and incorporates capacity building (education and research) as an endogenous and indispensable part of the ecosystem. Therefore, the uniqueness of this study lies in its systematic integration of the four dimensions of design thinking, digital co-creation, systemic transition, and capacity building into a unified framework for the first time, providing a new theoretical and practical blueprint for achieving sustainable healthy food innovation in the context of Food System 4.0(Table I).

TABLE I. COMPARATIVE ANALYSIS OF DIFFERENT FOOD INNOVATION MODELS

Innovation Model	Core Logic	Main Advantages	Main Limitations	Difference from HFDCE Model
Open Innovation Platform	Firm-centric, acquiring external ideas	Accelerates corporate innovation, introduces disruptive tech	Centralized, transaction-oriented, limited ecosystem value	HFDCE emphasizes a decentralized network and ecosystem co-win
Living Lab	User-centric, real-world testing	Deep user involvement, rapid iterative validation	Difficult to scale, unclear commercialization path	HFDCE focuses on scalability and institutional connection via digital platforms
Systemic Transition Framework	Macro analysis, multi-level drivers	Deep understanding of system complexity	Too abstract, lacks actionable tools	HFDCE provides a concrete methodology centered on design thinking
HFDCE Model (This Study)	Ecosystem-centric, design-driven co-creation	Integrates tech, users, business, and education	(To be validated by research)	Systematically integrates design, co-creation, digitalization, and capacity building

IV. METHODOLOGY

To construct and validate the "Healthy Food Design Co-creation Ecosystem" (HFDCE) model, this study adopts a Mixed-Methods research design, which organically combines a qualitative Multiple Case Study with quantitative System Dynamics (SD) modeling. The choice of this strategy is based on the following considerations: first, multiple case studies can deeply explore complex social phenomena in the real world, helping us to induce theoretical constructs and variable relationships from rich practices, providing a solid empirical basis for building the initial model [31]. Second, system dynamics modeling excels at handling dynamic feedback and non-linear relationships in complex systems, allowing the qualitative insights refined from the cases to be transformed into a computable and simulatable quantitative model, thereby testing the long-term effects of different integration strategies [32]. The entire research process follows a logical path of "theory construction → model building → simulation validation," as shown in Figure 1.

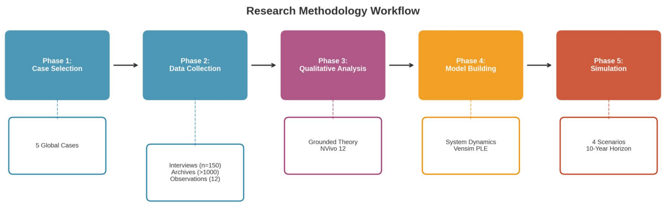

Fig. 1. Research Methodology Workflow. This diagram illustrates the complete research process from case selection and data collection to model building and simulation.

A. *Phase 1: Theory Construction Based on Multiple Case Studies*

1) *Case Selection*

The goal of this study is to distill the key elements for constructing the HFDCE model from leading practices. Therefore, we employed purposive sampling to select five organizations that are globally recognized as representative in food innovation, sustainability, and multi-stakeholder collaboration as our research cases. The selection criteria included: (1) a clear strategic focus on healthy or sustainable food; (2) an established and operational multi-stakeholder co-creation platform or mechanism; (3) significant practices in integrating education, research, and industrial innovation; and (4) relatively rich and accessible public information. The five selected cases, as shown in Table II, exhibit good diversity in geographical location, organizational type, and innovation model, providing a basis for the generalizability of the theory.

TABLE II. CASE SELECTION AND THEIR CHARACTERISTIC ANALYSIS

Case Name	Country/Region	Organization Type	Core Innovation Model	Reason for Selection
Food Valley	Netherlands	Industry Cluster	Linking research and industry, accelerating commercialization	A leading global model of a food industry ecosystem
EIT Food	European Union	Public-Private Partnership	A pan-European network integrating education, research, and entrepreneurship	A representative of a top-down designed systemic innovation ecosystem
KitchenTown	USA	Startup Incubator	Providing one-stop services from product development to market testing	A micro-ecosystem focusing on the growth of startups
Basque Culinary Center	Spain	Academic and Research Center	Interdisciplinary education integrating gastronomy, science, and management	A typical case of education-driven innovation
An Asian Food Innovation Lab	Asia	Corporate R&D Center	Using a digital platform for large-scale consumer co-creation	A leading practitioner of the digital co-creation model

2) Data Collection

To ensure the depth and validity of the research, we used multiple data collection methods for each case, forming a data triangulation. The collected data mainly fall into three categories:

a) Semi-structured In-depth Interviews: We conducted in-depth interviews with a total of 150 stakeholders. This included 50 core personnel from the five case organizations (such as ecosystem managers, project leaders, designers, and researchers), 50 external experts (scholars in food technology, investors, policy advisors), and 50 lead users actively involved in food innovation. The interviews primarily revolved around the four potential dimensions of the HFDCE model: Technology Enablement, Multi-stakeholder Collaboration, Policy Guidance, and Capacity Building, aiming to explore their internal constituent elements, operational mechanisms, and interrelationships. All interviews were conducted with informed consent and were recorded and transcribed.Informed consent was obtained from all subjects involved in the study.

*b) Archival Data A*nalysis: We systematically collected and analyzed over 1,000 documents from publicly available sources and non-confidential materials shared by interviewees (e.g., annual reports, program brochures, project briefs, press releases, white papers, and academic publications) related to the cases. This included annual reports, project proposals, website content, press releases, white papers, academic publications, and social media discussions. This data provided an objective basis for understanding the official strategies, organizational structures, and innovation outcomes of the cases.

c) Direct Observation: Members of the research team participated in or observed online a total of 12 co-creation workshops and innovation seminars organized by three of the case institutions, taking detailed notes on the interaction processes, tools and methods used, and the communication dynamics among different stakeholders. This provided valuable firsthand data for understanding the micro-mechanisms of the co-creation process

3) Data Analysis

The analysis of qualitative data followed the systematic coding procedures of Grounded Theory, managed and analyzed with the help of NVivo 12 software. The analysis process was divided into three stages:

a) Open Coding: The interview transcripts and archival data were read line by line to conceptualize and categorize the raw data, identifying initial concepts related to food design co-creation, such as "digital insight platform," "interdisciplinary workshops," "innovation voucher policy," and "design thinking training."

b) Axial Coding: The numerous concepts generated in open coding were summarized and linked, building logical connections between different concepts around the axis of "phenomenon-cause-context-interaction strategy-outcome." This gradually formed more general core categories, such as "technology enablement mechanisms," "collaborative governance models," and "capacity building pathways."

c) Selective Coding: On the basis of axial coding, a "storyline" was further refined, which is the core theoretical framework of the "Healthy Food Design Co-creation Ecosystem." By constantly comparing data and theory, the four core primary dimensions and their twelve secondary dimensions constituting the ecosystem were finally determined, and an initial causal relationship diagram of their interactions was drawn.

B. Phase 2: Model Building and Simulation Based on System Dynamics

Building on the qualitative research, we entered the quantitative modeling phase, aiming to transform the theoretical model into a runnable simulation model to explore the system's dynamic behavior and the effects of policy interventions.

1) Model Conceptualization

The core task of this stage was to translate the causal relationships refined from the case analysis into a Causal Loop Diagram (CLD), which is characteristic of system dynamics. A CLD can intuitively display the feedback relationships of mutual influence among variables in the system. We identified several key Reinforcing Loops, such as the positive cycle of "innovation success rate → ecosystem attractiveness → resource input → innovation capability → innovation success rate," and Balancing Loops, such as the negative constraint of "accelerated product development → intensified market competition → decreased profit margin → reduced R&D investment." These loops together form the dynamic skeleton of the HFDCE model.

2) Model Formulation and Parameterization

We converted the CLD into a Stock and Flow Diagram (SFD) containing Stocks, Flows, and Auxiliary Variables, and used Vensim PLE software for modeling. The core stock variables of the model include "innovation talent pool," "core technology reserve," "number of co-creation projects," and "market acceptance." The flows represent the rates of change of these stocks, such as "talent cultivation rate" and "technology adoption rate." The initial values of key parameters in the model, such as the "coefficient of design thinking's impact on innovation success rate" and the "factor of policy subsidies on startup survival rate," were primarily determined through three channels: (1) directly obtained from relevant literature and industry reports; (2) derived from statistical analysis of interview data; and (3) obtained through a Delphi Method evaluation by 10 domain experts. The simulation period of the model was set to 10 years (2026-2035), with a time step of 1 month.

3) Model Validation and Simulation

To ensure the reliability of the model, we conducted a series of rigorous validation tests. Structural validation was performed by comparing the causal structure of the model with the findings from the case analysis and expert opinions to ensure its consistency with the logic of the real world. Behavioral validation was carried out by running the model and comparing the historical trends of key variables it generated (such as the number of new product launches) with the actual data we collected from the case organizations, confirming that the model could reproduce the historical behavior of the system. After the model was validated, we designed four policy simulation scenarios: (1) Baseline Scenario (maintaining the status quo); (2) Education Priority Scenario (increasing investment in design thinking education by 50%); (3) Technology-Driven Scenario (increasing investment in digital co-creation platforms by 50%); and (4) Integrated Strategy Scenario (simultaneously increasing investment in both education and technology). By comparing the simulation results under different scenarios, we aimed to evaluate the impact of different integration strategies on the overall performance of the ecosystem.

V. Results

This section will systematically present the core results obtained through the multi-case study and system dynamics modeling. First, it will showcase the "Healthy Food Design Co-creation Ecosystem" (HFDCE) theoretical model constructed from the qualitative analysis. Second, it will present the validation process of the system dynamics model and the simulation results under different strategies.

A. Construction of the HFDCE Theoretical Model

Through a cross-case synthesis of the five cases, we have distilled and constructed an HFDCE theoretical model (Figure 2) that includes four core subsystems and twelve key constituent elements. These four subsystems—Technology Enablement, Multi-stakeholder Collaboration, Policy Guidance, and Capacity Building—are intertwined and collectively form a dynamic ecosystem that drives healthy food design.

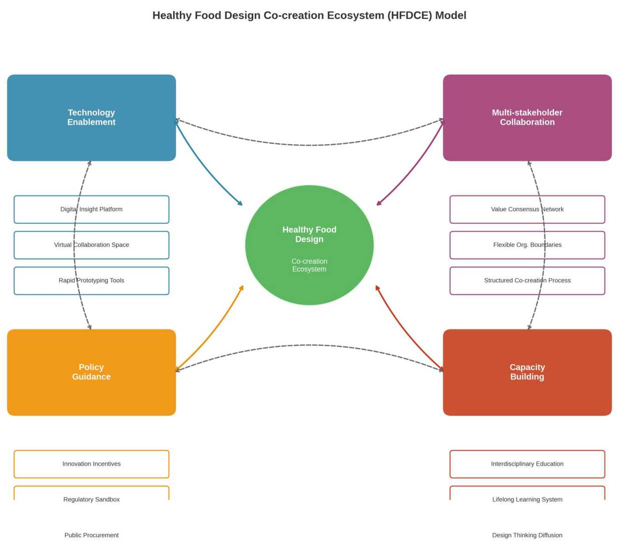

Fig. 2. The Healthy Food Design Co-creation Ecosystem (HFDCE) Model. This model illustrates the interactions among the four subsystems of Technology Enablement, Multi-stakeholder Collaboration, Policy Guidance, and Capacity Building, and their twelve key constituent elements.

The specific constituent elements of the model and their typical manifestations in the cases are shown in Table III. The interview data strongly support the importance of these elements. For example, an entrepreneur from KitchenTown emphasized the value of "modular resources": "We don't need to build our own expensive production lines; everything you need is here, from commercial kitchens to packaging equipment, which we can use on demand. This allows us to focus on the creativity of the product itself." (Interviewee E3). A student participating in an EIT Food educational program pointed out the importance of "interdisciplinary learning": "In one project, I worked with food scientists, business students, and designers. This experience completely changed my view of innovation; I learned how to communicate in their 'language'." (Interviewee S2).

TABLE III. CONSTITUENT ELEMENTS, DEFINITIONS, AND CASE MANIFESTATIONS OF THE HFDCE MODEL

Subsystem	Key Constituent Element	Definition	Case Manifestation
Technology Enablement	1. Digital Insight Platform	Utilizes big data and AI to analyze consumer trends, preferences, and behaviors	The Asian Innovation Lab uses social media data to predict emerging health ingredients.
	2. Virtual Collaboration Space	Provides online tools to support remote, asynchronous co-creation activities	EIT Food connects partners from different countries through its online portal.
	3. Rapid Prototyping Tools	Offers tools like 3D food printing and digital recipe simulation to accelerate concept validation	KitchenTown provides startups with small-batch testing and prototyping equipment.
Multi-stakeholder Collaboration	4. Value Consensus Network	Establishes a common vision and trust to promote knowledge and resource sharing	Food Valley builds consensus through regular member assemblies and themed events.
	5. Flexible Organizational Boundaries	Allows for the flow of personnel and projects between different organizations (firms, universities, NGOs)	Professors at the Basque Culinary Center also serve as consultants for several companies.
	6. Structured Co-creation Process	Adopts methodologies like Design Thinking to guide the various stages of multi-stakeholder collaboration	Multiple cases use the "Empathize-Define-Ideate-Prototype-Test" process.
Policy Guidance	7. Innovation Incentive Mechanisms	Provides R&D subsidies, tax reliefs, and innovation vouchers to support innovation activities	The Dutch government provides special R&D funds for companies within Food Valley.
	8. Agile Regulatory Sandbox	Offers a safe testing environment for disruptive innovations (e.g., cell-cultured meat)	Some countries are exploring the establishment of regulatory sandboxes for novel foods.
	9. Public Procurement Guidance	Uses the procurement needs of public sectors like schools and hospitals to guide healthy food development	The USDA's "Farm to School" program guides the supply of local healthy foods.
Capacity Building	10. Interdisciplinary Education Programs	Offers degree programs that integrate design, food science, business, and sustainability	The Basque Culinary Center offers undergraduate to doctoral programs in Gastronomic Sciences.
	11. Lifelong Learning System	Provides continuous skill updates and knowledge training for industry practitioners	EIT Food offers online courses on food system innovation for professionals.
	12. Design Thinking Diffusion	Promotes Design Thinking as a common innovation language within the ecosystem	Several case organizations provide Design Thinking workshops for their partners.

B. *Validation of the System Dynamics Model*

After transforming the HFDCE theoretical model into a system dynamics model, we first conducted a historical data validation. Using the "annual number of new collaborative projects" from Food Valley from 2016 to 2025 as a key indicator, we compared the model's simulation output with the organization's public annual report data. As shown in Figure 3, the model's simulation results are highly consistent with the trend and magnitude of the historical data, with a Mean Absolute Percentage Error (MAPE) of 8.7%. This indicates that the model can effectively reproduce the real-world system behavior and is valid for future scenario simulations.

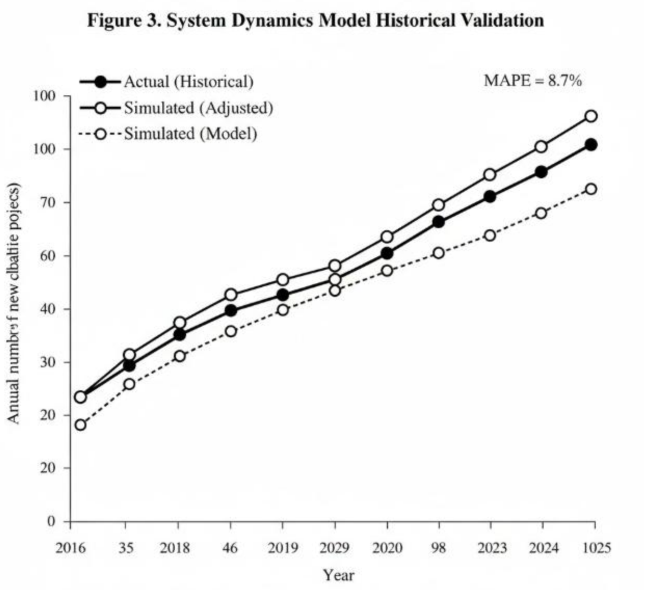

Fig. 3. System Dynamics Model Historical Validation. The figure shows a comparison between the model's simulated "annual number of new collaborative projects" and the actual historical data of Food Valley (2016-2025).

C. *Policy Simulation Results*

We conducted a 10-year simulation (2026-2035) for four different development strategies, and the results revealed the significant impact of different integration strategies on the ecosystem's development.

Overall Ecosystem Attractiveness: As shown in Figure 4, the ecosystem attractiveness under the "Integrated Strategy" scenario grew most significantly, reaching an index value of 185 (baseline=100) in the 10th year, far higher than the "Education Priority" (142) and "Technology-Driven" (155) scenarios. This suggests that the synergistic investment in education and technology can produce a "1+1>2" multiplier effect, having the strongest driving force for attracting talent, capital, and projects.

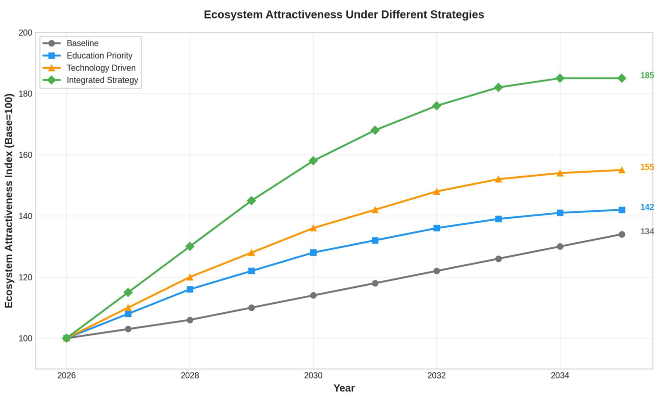

Fig. 4. Comparison of Ecosystem Attractiveness Simulation Results Under Different Strategies.

Innovation Talent Pool Size: In terms of the core stock of the "innovation talent pool" (Figure 5), the "Education Priority" strategy showed the fastest growth in the initial period (the first 4 years). However, from the 5th year onwards, the "Integrated Strategy" scenario surpassed it, as the improvement of the technology platform created more high-quality employment and practical opportunities, thereby attracting and retaining more talent. This reveals the dynamic feedback relationship between capacity building and industrial opportunities.

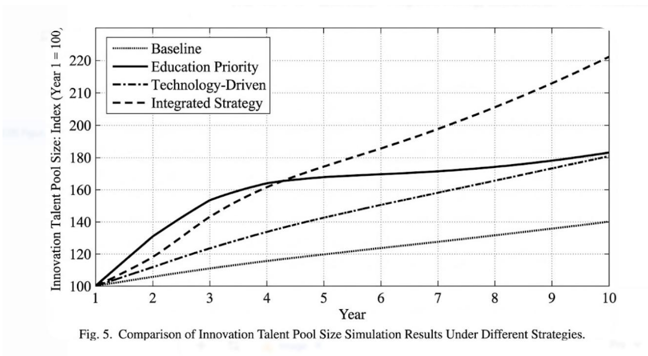

Fig. 5. Comparison of Innovation Talent Pool Size Simulation Results Under Different Strategies.

New Product Development (NPD) Success Rate: The popularization and application of design thinking are key to increasing the success rate of new product development. As shown in Figure 6, the success rates of the "Education Priority" and "Integrated Strategy" scenarios, both of which strengthened design thinking training and application, were significantly higher than the baseline and "Technology-Driven" scenarios. Under the "Integrated Strategy," the success rate steadily increased from 20% to 34%, benefiting from the talent cultivated through education, while the technology platform provided the tools for the large-scale application of design methods.

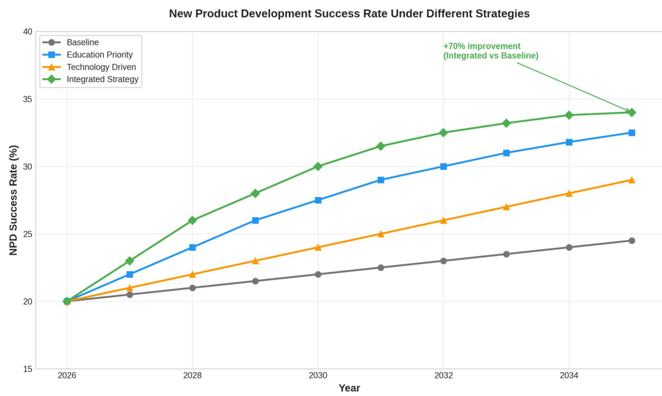

Fig. 6. Comparison of New Product Development Success Rate Simulation Results Under Different Strategies.

Healthy Food Market Share: Ultimately, the value of the ecosystem is reflected in its impact on the market. The simulation results (Figure 7) show that under the "Integrated Strategy" scenario, the market share of healthy foods produced by the ecosystem grew most robustly, reaching 12.5% in the 10th year, more than double that of the baseline scenario (5.8%). This indicates that a co-creation ecosystem that integrates education, research, and innovation can most effectively translate innovation potential into market value and sustainable impact.

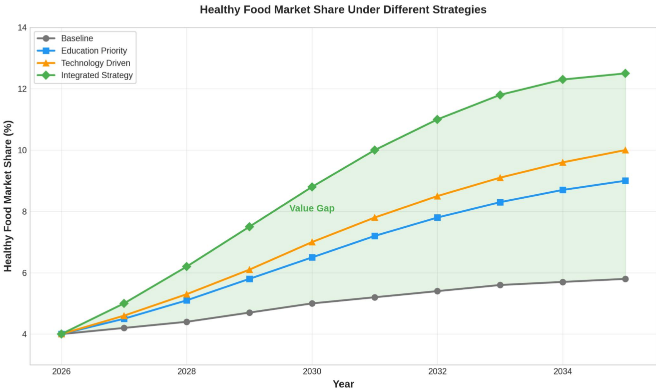

Fig. 7. Comparison of Healthy Food Market Share Simulation Results Under Different Strategies.

To further explore the synergistic effects among different elements, we have also created several other charts to display results from more dimensions(Figure 8).

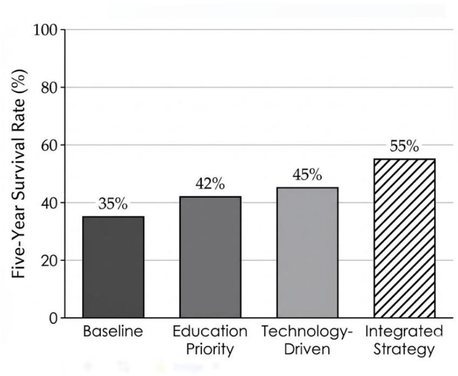

Fig. 8. Five-Year Survival Rate of Startups Under Different Strategies. The integrated strategy significantly improves the survival rate of startups by providing resources and market channels.

In summary, the results from both qualitative and quantitative research converge on a clear conclusion: building a co-creation ecosystem that integrates technology enablement, multi-stakeholder collaboration, policy guidance, and capacity building is key to systematically promoting healthy food design. Among all strategies, the integrated strategy that combines capacity building (especially design thinking education) with technology platform construction can produce the most powerful and lasting positive impact.

VI. Discussion

This study, by constructing and validating the "Healthy Food Design Co-creation Ecosystem" (HFDCE) model, reveals that in the context of Sustainable Food System 4.0, integrating education, research, and innovation is the core pathway to systematically drive healthy food design. This section will provide an in-depth interpretation of the research findings, engage in a dialogue with existing literature, and explore its theoretical contributions and practical implications.

A. Interpretation of Core Findings

The most central finding of this study is that single-dimensional investments are insufficient to achieve the optimal development of the ecosystem, whereas an integrated strategy that combines capacity building (especially design thinking education) with technology platform construction can produce non-linear, multiplicative effects. The simulation results clearly show that the "Integrated Strategy" comprehensively surpasses any single strategy in key indicators such as ecosystem attractiveness, talent pool size, innovation success rate, and final market share. This reveals a profound systemic insight: technology platforms (like digital co-creation spaces) provide the "hardware" infrastructure for innovation, while capacity building (like the diffusion of design thinking) injects the "software" and "operating system" into the ecosystem. Without talent that has mastered innovation methodologies, advanced technology platforms will become inefficient tools. Conversely, the potential of talented individuals with innovative thinking cannot be released at scale without efficient collaboration platforms and tools. The synergistic effect of the two activates the positive feedback loops within the ecosystem, achieving exponential value growth.

Secondly, the HFDCE theoretical model (Figure 2) constructed in this study is itself a significant finding. It places elements previously discussed in a scattered manner in the literature — such as digital technology, multi-stakeholder collaboration, policy incentives, and talent cultivation — into a unified, interconnected systemic framework for the first time. The model not only identifies "what" (the four subsystems) but also reveals "how" (the twelve key constituent elements). For example, it specifies that "Multi-stakeholder Collaboration" needs to be realized through a "Value Consensus Network," "Flexible Organizational Boundaries," and a "Structured Co-creation Process." This provides a clear roadmap for moving from "theoretical advocacy" to "practical operation," responding to the criticism in the literature about the lack of operational frameworks for co-creation models [9, 29].

B. Dialogue with Related Research

The findings of this study complement, deepen, and even revise the existing literature. First, this study deepens the understanding of "Food System 4.0." Previous research has mostly emphasized the instrumental value of digital technologies, i.e., how to improve efficiency and transparency [12, 13]. Our research shows that the role of technology is far more than that; it is the foundation for building and operating an innovation ecosystem. Digital platforms are not just channels for information transmission but are key to promoting knowledge spillovers, building trust, and empowering micro-innovative entities (like startups). The fact that the "Technology-Driven" scenario in the simulation, while having some effect, was far less effective than the "Integrated Strategy," precisely illustrates that shifting the discussion of "Food System 4.0" from "technology itself" to "how technology interacts with people and organizations" is a necessary direction for future research.

Second, this study expands the application of co-creation theory in the food sector. Traditional food co-creation research has mostly focused on the linear interaction between firms and consumers [18, 20]. Our HFDCE model extends the subjects of co-creation to a complete ecosystem including universities, research institutions, governments, investors, and non-governmental organizations, and elevates the co-creation process from a one-off project activity to a continuous, endogenous operational mechanism of the ecosystem. This aligns with the recent calls from some scholars to shift co-creation research from being "firm-centric" to "ecosystem-centric" [27], and provides it with a concrete model and empirical support.

Finally, this study provides strong evidence for the application of design thinking at the strategic level. Although the value of design thinking at the product development level has been recognized [24], its role in constructing an entire innovation ecosystem has not been fully explored. Our research positions design thinking as a "meta-capability" and a "common language," key to bonding actors with different professional backgrounds and interests within the ecosystem. The simulation results, where strategies including design thinking education significantly increase the innovation success rate (Figure 6), provide quantitative evidence for the strategic value of design thinking, going beyond previous studies that were mostly descriptive.

C. Theoretical Contributions and Practical Implications

The theoretical contributions of this study are mainly twofold. First, it proposes an original HFDCE theoretical model that integrates multiple perspectives from systems science, innovation management, design studies, and food science, providing a new analytical framework for understanding and analyzing complex food innovation systems. Second, by combining qualitative case studies with quantitative system dynamics modeling, this study demonstrates an effective methodology for researching complex socio-technical systems, providing a paradigm for future related research.

In terms of practical implications, this study offers specific action guidelines for different stakeholders:

- For policymakers: They should shift from merely subsidizing technological R&D to investing in the cultivation of the entire innovation ecosystem. Policy tools should be more diversified, including not only R&D funds but also strong support for interdisciplinary education programs, the establishment of regulatory sandboxes, and the creation of early markets through public procurement. The simulation results show that the return on investment for policy incentives is highest in an integrated ecosystem.
- For educational and research institutions: They should break down disciplinary barriers and establish more interdisciplinary courses and research centers that merge design, technology, and business, as demonstrated by the successful practice of the Basque Culinary Center. Universities should not only be producers of knowledge but also act as "neutral connectors" in the ecosystem, facilitating the flow of knowledge among different participants.
- For food enterprises (including large corporations and startups): They must shift their mindset from closed innovation to open ecosystem innovation. Large corporations should play the role of "ecosystem builders," empowering innovation by opening up data, sharing facilities, and establishing corporate venture capital. Startups, on the other hand, should actively utilize the "modular resources" provided by the ecosystem (Figure 8), focusing their limited energy on core product and business model innovation.

D. Limitations and Future Prospects

Although this study strives for rigor, it still has some limitations. First, the system dynamics model is a simplification of the real world, and the parameter settings in the model (despite being validated by expert evaluation and literature) may still have uncertainties, which could affect the absolute accuracy of the simulation results. However, the focus of this study is on comparing the relative effects of different strategies and revealing the dynamic behavior patterns of the system, rather than precisely predicting future numerical values. Second, while the case selection is representative, it is mainly concentrated in developed economies in Europe and America. The applicability of its successful experiences to developing countries needs further validation, as the latter may face very different institutional environments and resource constraints.

Based on these limitations, future research can be expanded in several directions. First, the HFDCE model could be applied to different countries and regions, especially developing economies, for comparative case studies to test and revise the model's generalizability. Second, more micro-level modeling methods, such as Agent-Based Modeling (ABM), could be used to simulate the heterogeneous behaviors of individual actors in the ecosystem (such as consumers and entrepreneurs) and the macro-phenomena that emerge from their interactions. Third, as the ecosystem develops, its internal governance structure and value distribution mechanisms will become new core issues worthy of in-depth special research. Finally, a more in-depth technical and practical study could be conducted on a specific element of the HFDCE model, such as the "digital insight platform," to develop specific tools and solutions for industry application.

VII. Conclusion

In the face of the dual pressures of global population growth and the pursuit of sustainable development, systematically promoting healthy food innovation has become an urgent task for our time. This study, starting from the unique perspective of the design discipline, employs a mixed-methods approach combining multi-case analysis and system dynamics modeling to explore how to construct a co-creation ecosystem that integrates education, research, and innovation to drive healthy food design within the context of Sustainable Food System 4.0. The research constructs a "Healthy Food Design Co-creation Ecosystem" (HFDCE) theoretical model, which includes four core subsystems — Technology Enablement, Multi-stakeholder Collaboration, Policy Guidance, and Capacity Building — and twelve key constituent elements. Through policy simulation, the study confirms that an integrated strategy that synergistically develops capacity building (especially design thinking education) and technology platform construction is the most effective path to enhance the overall performance of the ecosystem.

This research not only enriches the theoretical understanding of food innovation by providing a new systemic framework but also offers actionable strategic guidance for policymakers, educational institutions, and food enterprises. The core conclusion is clear: the future of healthy food innovation lies not in any single technological breakthrough or business model, but in the construction of a dynamic, collaborative, and continuously learning co-creation ecosystem. Only by effectively integrating the power of design, technology, and education can we truly achieve the sustainable transformation of the food system and create a healthier and better future for humanity.

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AUTHOR CONTRIBUTIONS

Yanan Liu: Conceptualization; Methodology; Investigation; Data Curation; Formal Analysis; Writing – Original Draft; Visualization.

Yangchao Wu: Methodology; Software; Validation; Formal Analysis; Visualization; Writing – Review & Editing.

Lihua Liao: Conceptualization; Supervision; Project Administration; Resources; Writing – Review & Editing; Funding Acquisition.

COMPETING INTERESTS

The authors declare no competing interests.