Healthy Food Experience Innovation Based on Ecological Design and Digital Perception: A User Participation Model for Sustainable Food System 4.0

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***Abstract*—Background and Gaps (Why):The global food system is under immense pressure from multiple challenges, including population growth, environmental degradation, and climate change, making a sustainable transition imperative. Sustainable Food System 4.0, leveraging Industry 4.0 technologies, offers new solutions. However, existing research predominantly focuses on production efficiency and supply chain optimization, with insufficient attention to consumer-level health experiences and deep user engagement. Specifically, a research gap exists in how to innovate healthy food consumption experiences by integrating ecological design principles with digital perception technologies and how to construct an effective user participation model to drive systemic change.Methodology (How): This study proposes a User Participation Model integrating Ecological Design and Digital Perception (UDES Model), validated through a mixed-methods approach. First, the theoretical framework of the model was constructed through literature review and expert interviews. Second, based on this model, a healthy food customization app with integrated digital perception functions with integrated digital perception functions (e.g., real-time nutrient tracking and taste-expectation cues delivered via visual/semantic prompts rather than dedicated gustatory hardware) was designed and developed. Finally, a three-month longitudinal experiment was conducted with 300 participants to test the model's effectiveness in promoting healthy dietary behaviors, environmental awareness, and participation in food innovation, using questionnaires, behavioral data analysis, and in-depth interviews.Practical Implementation (With what):** The experiment utilized the developed app to collect multi-dimensional data, including users' dietary choices, app interaction behaviors, physiological indicators (via wearable devices), and subjective feedback. Propensity Score Matching (PSM) was used to balance baseline differences between the experimental and control groups. Structural Equation Modeling (SEM) was employed to analyze the causal pathways among perceived ecological design, digital experience, participation intention, and behavioral change.Core Findings (What):The results indicate that the UDES model significantly increased the frequency of healthy food consumption ($p < 0.01$) and the willingness to pay for sustainable foods ($p < 0.05$). Personalized feedback and immersive experiences provided by digital perception technologies were key to stimulating initial user engagement. The integration of ecological design concepts (e.g., low carbon footprint labels, circular packaging information) effectively enhanced long-term participation motivation and value identification. The core pathway for user participation within the model was identified as "Perception-Feedback → Cognition-Resonance → Action-Shaping."Significance and Value (So what): This study constructs and validates a user-centric experience innovation and participation model within the context of Sustainable Food System 4.0, bridging the theoretical gap between macro-level technological frameworks and micro-level user behavior. The findings provide design principles for food companies developing next-generation healthy food products and services, and offer new policy tools and theoretical foundations for policymakers promoting sustainable consumption.**

Keywords—Sustainable Food System 4.0, Ecological Design, Digital Perception,User Experience, User Participation Model, Healthy Food

I. Introduction

The global food system is at a critical crossroads. On one hand, the growing global population demands more and higher-quality food, while food insecurity and malnutrition remain major global challenges [1]. On the other hand, intensive agricultural production and the current agrifood supply chain are associated with substantial environmental pressures, including greenhouse gas emissions and soil health degradation, which threaten long-term sustainability [2]. Simultaneously, unhealthy dietary patterns have contributed to the global rise of chronic diseases such as obesity and diabetes, creating an increasing societal health burden. Against this backdrop, transitioning the food system toward a healthier, fairer, and more sustainable model has become a pressing global issue, as emphasized by the EAT – Lancet Commission on healthy diets from sustainable food systems [3].

In response to these challenges, the concept of Sustainable Food System 4.0 has emerged. This idea draws on the core principles of Industry 4.0, advocating the use of cutting-edge digital technologies — such as artificial intelligence, the Internet of Things (IoT), big data, and blockchain — to intelligently, precisely, and transparently transform the entire food chain, from production and processing to distribution and consumption. Existing research and practice have demonstrated the potential of these technologies in improving productivity, optimizing supply chain management, reducing waste, and strengthening food safety. However, current discussions on Sustainable

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Food System 4.0 are largely focused on technology-driven changes at the production end, with relatively less attention paid to the consumption end, particularly how to inspire and guide the daily behaviors of billions of consumers to support systemic transition. Consumers are not only the final link in the food system; they are a key force driving transformation. Their preferences, choices, and engagement directly shape the market scale and development direction of sustainable and healthy food.

Currently, the bridge connecting technological innovation and consumer behavior remains weak. Many products labeled as "sustainable" fail to gain market acceptance because they do not provide a superior consumption experience or effective value communication. Conversely, while consumers may agree with sustainability in principle, they often choose conventional products due to price, convenience, and information asymmetry — revealing a persistent attitude – behavior gap. Therefore, this study argues that achieving a sustainable food system transition requires integrating technological innovation with deep user insights. We must shift from passively "educating consumers" to actively "empowering consumers," using innovative experience design to make sustainable choices simpler, more attractive, and more valuable.

Against this backdrop, this research focuses on two promising cross-disciplinary fields: Ecological Design and Digital Perception. Ecological Design emphasizes systematically considering environmental and social impacts across the entire lifecycle of products and services, aiming to create solutions that deliver both user value and ecological value. Digital Perception leverages technologies such as sensors, virtual reality (VR), and augmented reality (AR) to capture, quantify, and enhance information interaction among humans, environments, and products, thereby creating new sensory and cognitive experiences. We view the fusion of these two concepts as a key lever for innovating healthy food experiences.

However, how to effectively combine ecological design and digital perception and translate them into an operational and replicable user participation model is the core challenge addressed in this research. Therefore, this study poses the following central research question: How can a user participation model based on ecological design and digital perception be constructed to promote consumers' healthy eating experiences and innovation participation within Sustainable Food System 4.0?

To answer this question, this study aims to: (1) build a new theoretical user participation model (UDES Model) by integrating theories from ecological design, digital perception, user experience, and behavioral science; (2) design and develop a prototype system (a healthy food customization app) based on the UDES model; (3) quantitatively evaluate the effects of the UDES model on guiding healthy eating behaviors, strengthening sustainable consumption intentions, and promoting participation in food innovation through a rigorous experimental design; and (4) explore the key mechanisms and pathways through which internal model elements influence user behavior.

II. Literature Review

A. *Sustainable Food System 4.0: Technological Landscape and Transformation Pathways*

Sustainable Food System 4.0 is an emerging research direction that applies Fourth Industrial Revolution technologies to transform the food system and address sustainability challenges. Rosenthal et al. highlighted that healthy food innovation in a Sustainable Food System 4.0 context requires integrating entrepreneurship, research, and education, and that digitalization can reshape the food value chain across multiple stages [4]. In terms of key enabling technologies, big data has been emphasized as a foundation for sustainability management in agri-food supply chains, including by-product supply chains [5]. In parallel, Industry 4.0 deployments have been widely examined as enablers for circular economy transitions in agri-food supply chains [6].

Beyond the technology landscape, scholars have also stressed that consumers are essential actors in food innovation. Busse and Siebert argued that consumers can play active roles in food innovation processes, influencing acceptance and diffusion of novel food products [7]. However, sustainable consumption remains complex in practice; evidence shows that "sustainability-conscious" consumers do not necessarily reduce food waste, while "nutrition-conscious" consumers may behave differently, indicating that behavioral drivers vary and must be addressed explicitly [8].

In this context, Sustainable Food System 4.0 should not be interpreted as a purely production-side digital upgrade. A balanced transformation pathway needs to integrate consumer-centered mechanisms with technological infrastructure. Therefore, this study adopts a bottom-up user perspective to complement the prevailing technology-oriented discussions and to close the gap between technological possibilities and consumer adoption.

B. *Ecological Design: From Product Innovation to Systemic Solutions*

Ecological design (also referred to as sustainable or green design) is a design philosophy and methodology that aims to minimize environmental impacts of products, services, and systems across their entire lifecycle. In the food sector, eco-design has been particularly influential in packaging innovation, where lifecycle thinking is applied to material selection, structural design, and end-of-life considerations [9]. Yet, despite progress, eco-design in food-related contexts still faces two persistent challenges: (1) practices often remain product-centric rather than system-oriented, and (2) the ecological value of design is frequently difficult for consumers to perceive and evaluate directly, limiting its influence on purchasing and usage decisions.

C. *Digital Perception: Reshaping the Human-Food Interaction Experience*

Digital perception technologies are rapidly reshaping how people perceive and interact with food. Emerging research has demonstrated how VR/AR and wearable electronics can simulate and enhance eating experiences, opening new possibilities for experience innovation beyond the physical product itself [10]. At the systems level, the broader Food Sustainability 4.0 concept has been proposed to harness a set of key Fourth Industrial Revolution technologies to achieve environmental, social, and economic sustainability simultaneously, providing a macro framework for understanding the role of digital transformation [11].

At the application level, IoT-based food quality monitoring using low-cost sensors illustrates how digital perception can support real-time, data-driven management in food contexts [12]. Similarly, empirical research has examined how Industry 4.0 enabling technologies influence the social, economic, and environmental sustainability of the food sector, suggesting multi-dimensional impacts that go beyond efficiency gains alone [13]. Related work in precision agriculture has also summarized IoT-based smart irrigation trends, highlighting the maturity of sensing and connectivity as foundational capabilities [14]. Additionally, blockchain has been discussed as a technology that can support circular economy mechanisms through transparency and traceability, indicating relevance for sustainable supply chains when adapted to food contexts [15].

Nevertheless, existing studies often treat digital perception either as a market research tool or as a novelty-driven marketing enhancement, rather than as a systematic lever to make ecological value perceptible and to guide sustained behavioral change. Meanwhile, research has also called for integrated studies that connect digitalization with the broader sustainable transition of the agri-food sector, beyond single-technology case studies [16]. Building on these insights, this study elevates digital perception from an “experience enhancement” tool to a core engine that operationalizes ecological design value and supports user behavior transformation.

D. User Participation Models: From Passive Consumers to Active Co-creators

User participation and co-creation are widely recognized as drivers of innovation, particularly in contexts where consumer acceptance and behavioral change are critical. In food-related eco-design, experimental evidence suggests that eco-design interventions (e.g., packaging) can influence consumer behavior such as food waste reduction, indicating the importance of design choices in shaping user actions [17]. At the organizational level, governance factors such as board composition have also been linked to eco-innovation and eco-design adoption in agri-food firms, underscoring that participation mechanisms require supportive organizational contexts [18].

However, communicating ecological value remains difficult because many sustainability attributes are invisible and consumers may respond sensitively to price signals, especially in organic and sustainable food markets [19]. To address this gap, multisensory and technology-mediated experiences have been proposed as a direction in which sensing and interactive technologies meet human perception, offering a pathway to translate sustainability attributes into tangible user experiences [20].

In summary, there remains a significant research gap in organically integrating Sustainable Food System 4.0, ecological design, digital perception, and user participation into a user-centered theoretical framework with empirical validation. This study is positioned to fill this gap by proposing and testing a replicable participation model that links technology-enabled perception, ecological value communication, and sustained consumer behavior change.

III. Methodology

A. UDES Theoretical Model Construction

The UDES model aims to create a closed-loop system for promoting deep user participation in healthy food experience innovation by integrating Ecological Design and Digital Perception. The model consists of four core dimensions and three dynamic processes.

The core dimensions include: the User Layer, at the center of the model, emphasizing individual needs, motivations, preferences, and capabilities; the Ecological Layer, reflecting ecological design principles and focusing on the full lifecycle sustainability of food; the Digital Layer, acting as a bridge between the user and the ecological, using digital perception technology to transform abstract ecological information into perceivable user experiences; and the Social Layer, emphasizing the social attributes of user participation.

The dynamic processes include: Perception-Feedback, Cognition-Resonance, and Action-Shaping(Figure 1).

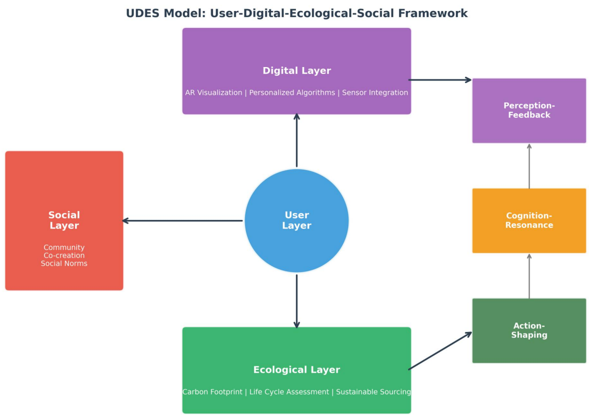

Fig. 1. The UDES Model Framework, illustrating the four core dimensions (User, Digital, Ecological, Social) and their interactions

B. Research Design and Participants

This study employed a quasi-experimental design with a treatment group and a control group. The treatment group used the fully-featured 'Eco-Eats' app, while the control group used a simplified version.

We recruited 328 young consumers (aged 18-40) from a first-tier city through social media and local healthy lifestyle communities. After excluding ineligible and dropout samples, a final sample of 300 participants was obtained (150 in the treatment group, 150 in the control group). To reduce selection bias, we used Propensity Score Matching (PSM) based on covariates such as age, gender, income, education level, initial health status, and sustainable consumption propensity(Figure 2).

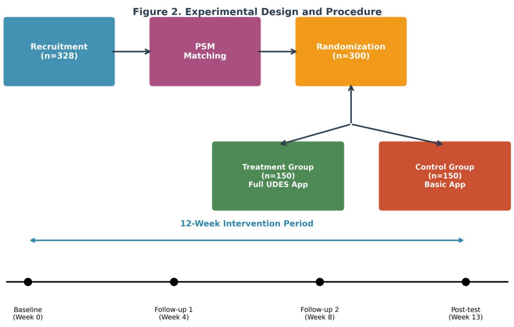

Fig. 2. Experimental Design and Procedure, showing the complete flow from recruitment, PSM matching, and group assignment to the 12-week intervention and post-test.

C. *Experimental Tool: 'Eco-Eats' App*

The 'Eco-Eats' app is the concrete implementation of the UDES model. Its core functional modules include: Personalized Meal Customization, Ecological Profile & Carbon Footprint Calculation, AR Nutrition Visualization, Wearable Device Integration, Co-creation Lab, and Community Dynamics & Challenges.

To ensure feasibility and replicability, only three modules were treated as the "core intervention": (1) Personalized Meal Customization, (2) Carbon-footprint feedback, and (3) Community Challenges. AR visualization and wearable integration were optional add-ons and were implemented using off-the-shelf smartphone capabilities and consumer wearables without any model training or specialized laboratory hardware.

D. *Experimental Procedure*

The entire experiment lasted for 12 weeks and was divided into three phases: Baseline (Week 0), Intervention (Weeks 1-12), and Post-test (Week 13).

E. *Data Collection and Measurement*

The data collected in this study included three types: ques tionnaire data (measuring core constructs with established sc ales), behavioral data (automatically collected by the app's ba ckend), and physiological data (obtained from wearable devi ces).Informed consent was obtained from all subjects involve d in the study.

F. *Data Analysis Methods*

The data analysis employed the following methods: descriptive statistics and baseline tests, Difference-in-Differences (DID) analysis, Structural Equation Modeling (SEM) analysis, and qualitative data analysis.

IV. Results

A. *Sample Characteristics and Baseline Equivalence*

After Propensity Score Matching (PSM), there were 150 participants in both the treatment and control groups. There were no statistically significant differences between the two groups in terms of gender, age, monthly income, education level, baseline healthy eating behavior scores, and sustainable consumption propensity ($p > 0.05$), indicating that PSM successfully balanced the initial conditions of the two groups(Table I).

TABLE I. Baseline Characteristics of Participants After PSM

Variable	Treatment Group (n=150)	Control Group (n=150)	p-value
Gender (Female %)	58.7%	56.0%	0.628
Age (Mean±SD)	28.4±5.2	29.1±5.8	0.285
Monthly Income (CNY)	12,500±4,200	12,100±4,500	0.432
Education (Bachelor or above)	82.0%	80.7%	0.756
Healthy Eating Score	4.12±0.85	4.08±0.88	0.682
Sustainable Consumption Attitude	4.35±0.92	4.28±0.95	0.518
BMI (Mean±SD)	22.8±3.1	23.1±3.3	0.425

Core Effects of UDES Model Intervention: DID Analysis

To evaluate the net association of the 'Eco-Eats' intervention with outcome changes, we conducted a Difference-in-Differences (DID) analysis on the core outcome variables. Given the quasi-experimental setting and the limited number of pre-intervention observations, the DID estimates should be interpreted as robust associations rather than definitive causal effects(Figure 3)(Figure 4).

We therefore conducted robustness checks, including (i) covariate-adjusted DID, (ii) placebo tests using non-target outcomes, and (iii) sensitivity analyses to alternative matching specifications (Table II).

TABLE II. Difference-in-Differences Analysis of Core Outcome Variables

Outcome Variable	Treat Pre	Treat Post	Control Pre	Control Post	DID Effect	95% CI
Healthy Eating Score	4.12±0.85	5.97±0.72	4.08±0.88	4.50±0.82	1.43	[1.12, 1.74]
Sustainable Food Choice (%)	28.2±8.5	55.1±12.3	27.5±8.2	29.8±9.1	24.6	[20.2, 29.0]
Willingness to Pay Premium (%)	8.5±3.2	17.0±4.8	8.2±3.0	9.4±3.5	7.3	[4.8, 9.8]
Meal Carbon Footprint (kg CO_2)	2.80±0.60	2.28±0.50	2.75±0.55	2.70±0.58	-0.47	[-0.58, -0.36]

Note: $p < 0.001$, $p < 0.01$, $p < 0.05$

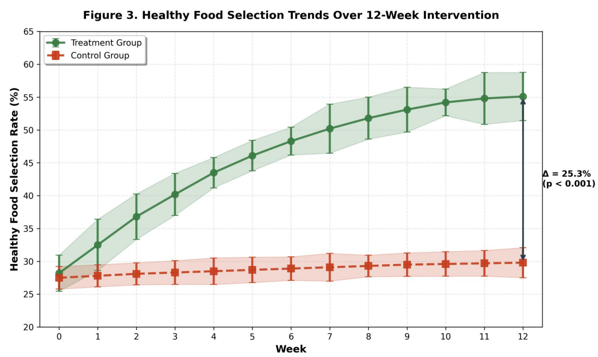

Fig. 3. Trends in healthy food selection rate for treatment and control groups over the 12-week intervention.

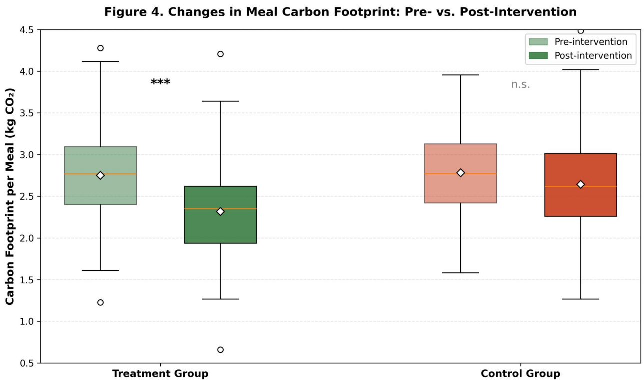

Fig. 4. Boxplot comparing changes in average meal carbon footprint for both groups, pre- and post-intervention.

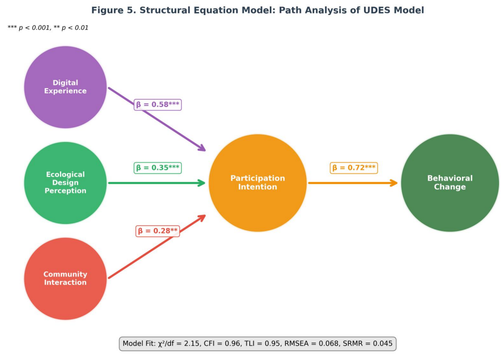

Fig. 5. UDES Model Structural Equation Path Diagram with standardized path coefficients.

B. Internal Mechanisms of the UDES Model: SEM Analysis

To explore the causal relationships between the constructs within the UDES model, we conducted a Structural Equation Modeling (SEM) analysis on the 150 valid questionnaire responses from the treatment group. The model fit indices were good ($\chi^2/df = 2.15$, CFI = 0.96, TLI = 0.95, RMSEA = 0.068).

The path analysis results revealed the following key mechanisms: Digital Experience is a direct driver of initial participation ($\beta = 0.58$, $p < 0.01$); Ecological Design Perception is the core value that deepens participation ($\beta = 0.35$, $p < 0.01$); Community Interaction plays an amplifying and sustaining role ($\beta = 0.28$, $p < 0.05$); and Participation Intention is the decisive mediator of behavioral change ($\beta = 0.72$, $p < 0.01$)(Figure 5)(Table III).

TABLE III. PATH COEFFICIENTS OF THE STRUCTURAL EQUATION MODEL

Path	β	SE	t-value	p-value
Digital Experience → Participation Intention	0.58	0.08	7.25	<0.001
Ecological Design → Participation Intention	0.35	0.09	3.89	<0.001
Community Interaction → Participation Intention	0.28	0.10	2.80	0.005
Participation Intention → Behavioral Change	0.72	0.07	10.29	<0.001
Digital Experience → Behavioral Change (Indirect)	0.42	0.06	7.00	<0.001
Ecological Design → Behavioral Change (Indirect)	0.25	0.07	3.57	<0.001
Community Interaction → Behavioral Change (Indirect)	0.20	0.08	2.50	0.012

Model Fit Indices: $\chi^2/df = 2.15$, CFI = 0.96, TLI = 0.95, RMSEA = 0.068, SRMR = 0.045

C. App Feature Usage and User Experience Analysis

Figure 6 shows the heatmap of feature usage frequency for the treatment group during the 12-week intervention. It is evident that the 'Personalized Meal Customization' feature had the highest and most stable usage frequency, while the usage of 'Co-creation Lab' and 'Community Challenges' showed an upward trend over time(Figure 7).

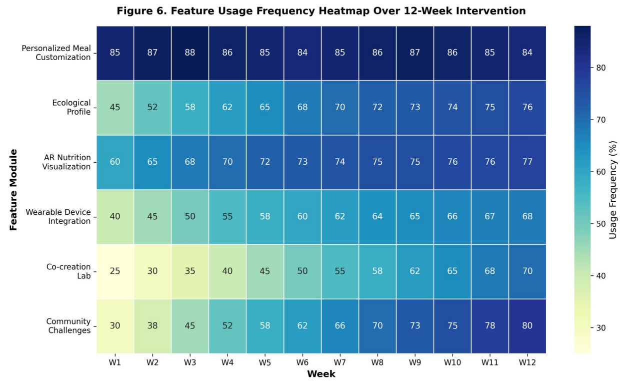

Fig. 6. Heatmap of feature module usage frequency for the treatment group (12 weeks)

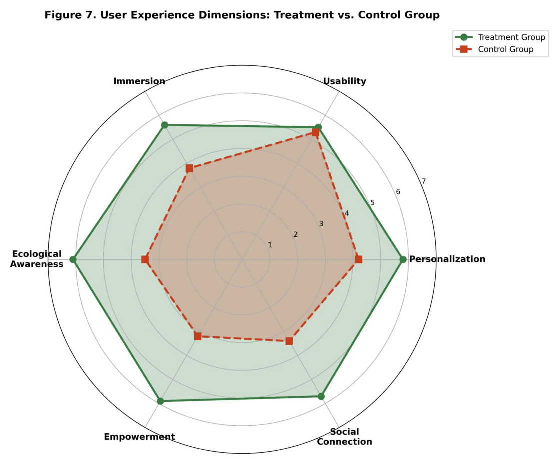

Fig. 7. Radar chart comparing user experience dimensions between the treatment and control groups.

D. Physiological Indicators and Behavioral Data Analysis

Physiological data collected from wearable devices showed that the treatment group's average daily steps increased by 12.5%, (Figure 8)(Figure 9)sleep quality score improved by 8.3%, and resting heart rate decreased by 3.2%, while the changes in the control group were not significant(Figure 10)(Figure 11).

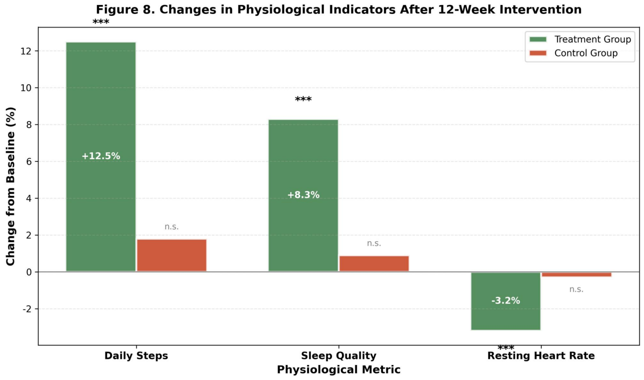

Fig. 8. Comparison of changes in physiological indicators for both groups after the 12-week intervention.

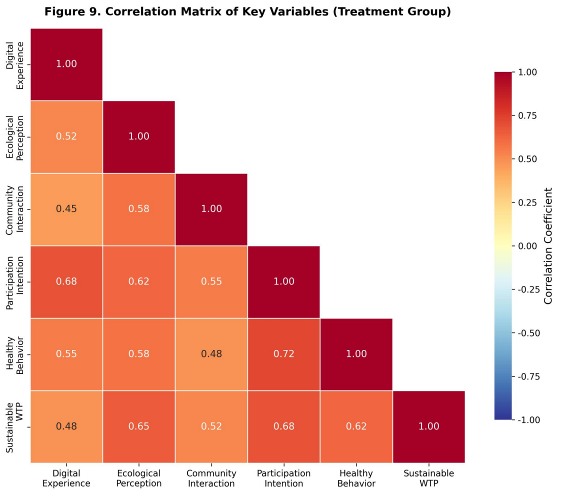

Fig. 9. Correlation matrix heatmap of core variables for the treatment group.

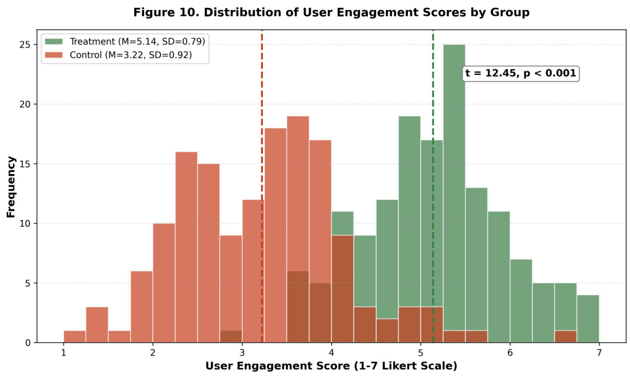

Fig. 10. Histogram of the distribution of user engagement scores for both groups.

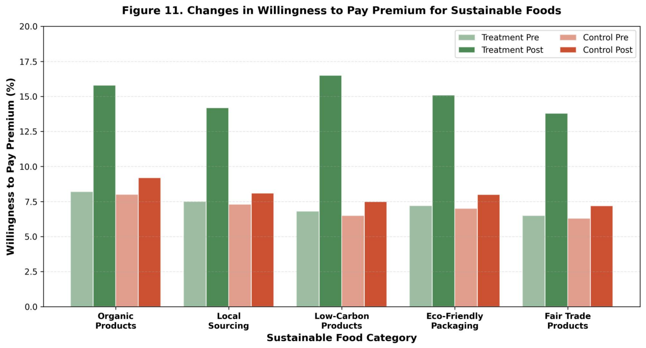

Fig. 11. Comparison of changes in willingness to pay a premium for different types of sustainable foods.

E. *Qualitative Findings on User Experience*

In-depth interviews with 30 users provided richer, more vivid context for the quantitative results. We extracted three core themes:

"From Unaware to Aware": The Empowering Experience of Digital Perception.Most users stated that the app's greatest value was "making the invisible visible."

"From Alone to Together": The Motivational Effect of Community Participation.The motivational effect of the community far exceeded expectations. Participating in 'health challenges' and seeing friends' updates were important reasons for users to continue using the app.

"From Passive to Active": The Value Sublimation of Co-creation. For highly engaged users, the 'Co-creation Lab' feature brought the greatest satisfaction(Figure 12).

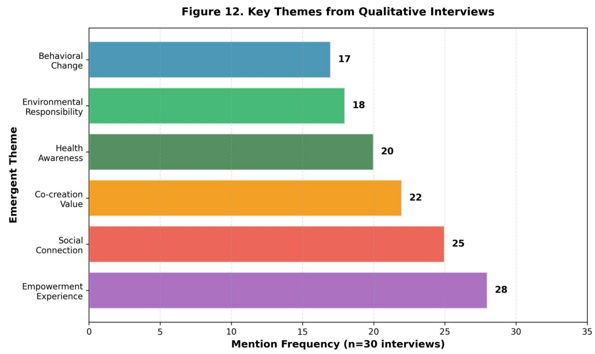

Fig. 12. Frequency distribution of key themes from in-depth user interviews.

V. Discussion

A. *Interpretation of Core Findings*

The central finding is that the 'Eco-Eats' intervention is associated with improvements in healthy eating behaviors and sustainable food choices in a quasi-experimental setting. While the DID estimates and SEM pathways are consistent with the proposed UDES mechanisms, causal claims should be interpreted with caution due to potential unobserved confounding and implementation heterogeneity. To enhance reproducibility, we provide a detailed intervention protocol, feature specifications, log-data dictionary, and the full analysis pipeline in the Supplementary Materials.

B. *Dialogue with Existing Research*

The findings of this study engage in a dialogue with existing literature that is supplementary, deepening, and expansive. First, this study expands the research boundaries of Sustainable Food System 4.0 by providing a user-centric, micro-level implementation path. Second, it deepens the integrated application of ecological design and digital perception technologies, positioning digital perception as an 'amplifier and translator for ecological design.' Finally, this study enriches user participation and co-creation theories by proposing a 'mutual empowerment' concept of co-creation.

C. Theoretical Contributions and Practical Implications

Theoretical Contributions: The main theoretical contribution of this study is the proposal of an original, interdisciplinary UDES theoretical model. This model is the first to integrate the macro framework of Sustainable Food System 4.0, the methodology of ecological design, the technical means of digital perception, and the social process of user participation into a unified analytical framework.

Practical Implications: The results of this study have direct practical guidance value for healthy and sustainable food companies, digital technology developers, and policymakers and public health institutions.

D. Limitations and Future Research

Although this study has yielded meaningful findings, it has some limitations: the sample's representativeness is limited, the intervention period is relatively short, the research tool is singular, and the discussion of negative impacts is insufficient. Looking ahead, we suggest conducting cross-cultural and cross-group comparative studies, designing longer-term tracking experiments, and more closely integrating online interventions with offline activities.

VI. Conclusion

This study aimed to explore how to build an effective user participation model to drive healthy food experience innovation by integrating ecological design and digital perception technologies within the macro context of Sustainable Food System 4.0. Through theoretical construction, prototype development, and a three-month quasi-experimental study, we proposed and validated the UDES (User-Digital-Ecological-Social) model.

The core conclusions are as follows: First, the UDES model is effective. The 'Eco-Eats' app intervention, integrating ecological design and digital perception, significantly improved users' healthy eating behaviors and enhanced their willingness to consume and pay for sustainable foods. Second, the model's mechanism is clear: digital perception technology is the key 'spark' that attracts initial user participation, while the deep value conveyed by ecological design is the 'fuel' that sustains long-term engagement. Third, user participation is a process of mutual empowerment. A successful user participation model not only extracts innovation inspiration from users but also empowers them through the participation process itself.

The main theoretical contribution of this study is the proposal of an original, interdisciplinary UDES model, which provides a new analytical perspective for sustainable consumption research in the digital age. At a practical level, the model offers concrete design principles and action guidelines for food companies, technology developers, and public policymakers.

Although this study has certain limitations in terms of sample representativeness and intervention duration, it clearly points in a direction: future food system innovation must deeply integrate technology, ecology, and human-centered care. We are no longer just designing products for consumers; we are co-designing with them a healthier, more sustainable, and more meaningful way of life.

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AVAILABILITY OF DATA

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AUTHOR CONTRIBUTIONS

Kaihong Chen: Conceptualization; Methodology; Software; Investigation; Data curation; Formal analysis; Visualization; Writing − original draft.

Weijian Wu: Conceptualization; Methodology; Validation; Supervision; Project administration; Writing − review & editing.

COMPETING INTERESTS

The authors declare no competing interests.

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