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REIMAGINING THE OUTLIERS: INTEGRATING UNCONVENTIONAL FOOD PROCESSING AND PRESERVATION PRACTICES WITH EMERGING TECHNOLOGIES FOR SUSTAINABLE INNOVATION

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Abstract
Sustainability challenges within the global food system demand novel thinking beyond conventional industrial models. This paper proposes a conceptual and theoretical re-examination of outliers; unconventional, overlooked, or seemingly abnormal practices in food processing and preservation as catalysts for sustainable innovation. Historically dismissed for their unpredictability and lack of standardization, such outlier practices, including spontaneous fermentations, natural drying, and plant-based preservation, are being re-evaluated through emerging technologies such as artificial intelligence, nanotechnology, precision fermentation, and green processing systems. This review integrates interdisciplinary perspectives from food science, sustainability studies, and technological innovation to develop the Outlier Integration Framework (OIF), a model that connects traditional and indigenous knowledge systems with advanced technological processes. The framework illustrates how blending unconventional wisdom with technological precision can generate low-impact, circular, and nutritionally efficient food systems. By positioning "abnormality" as an opportunity rather than a deviation, this study expands the theoretical foundations of sustainable food innovation. The paper concludes that the synthesis of outlier practices and emerging technologies represents not only a pathway toward more resilient food systems but also a paradigm shift in how food science perceives value, creativity, and sustainability.
Keywords: Outliers; Unconventional food processing; Preservation; Emerging technologies; Sustainable; Innovation.

Introduction
The global food system is under immense pressure to meet the nutritional needs of a rapidly growing population while addressing sustainability challenges such as climate change, food waste, and resource depletion. Conventional food processing and preservation methods though effective for mass production, often rely on energy-intensive, chemical-based, or waste-generating processes that compromise environmental and nutritional integrity (FAO, 2022). The emerging demand for sustainable, innovative, and inclusive approaches calls for a rethinking of what constitutes "standard" practice in food science. This rethinking opens the door to the exploration of outliers practices and ideas once considered unorthodox or unscientific that may hold transformative potential when reinterpreted through modern technological lenses.

The term outlier, commonly used in data analysis to describe elements deviating from the norm, offers a metaphorical lens for food systems. In food processing and preservation, outliers can be defined as unconventional techniques, materials, or microbial interactions that deviate from industrial conventions yet produce unique, sustainable, or culturally rooted outcomes (Adeyeye and Akanbi, 2021). Examples include spontaneous fermentations, indigenous drying techniques, natural curing, and the use of plant-based antimicrobial extracts. While these methods have been historically undervalued due to their variability and lack of mechanistic explanation, modern science is beginning to uncover their efficiency, safety, and ecological harmony. Emerging technologies such as artificial intelligence, nanotechnology, precision fermentation, cold plasma, and green preservation systems offer new opportunities to reinterpret these outlier practices. Integrating such technologies with traditional or

indigenous approaches can result in novel hybrid systems that are both sustainable and scalable (Bhat *et al.,* 2020). This synthesis aligns closely with global sustainability agendas, including the United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 12 (Responsible Consumption and Production).
However, despite growing attention, there remains a theoretical and conceptual gap in understanding how unconventional practices can be systematically integrated with emerging technologies to advance food sustainability. Much of the existing research either focuses on traditional food systems in isolation or examines technology-driven innovations without recognizing the adaptive potential of indigenous knowledge. To bridge this gap, this paper develops the Outlier Integration Framework (OIF)- a theoretical model that connects outlier practices in food processing and preservation with technological innovation pathways. This framework offers a holistic view of how creativity, culture, and science intersect to build resilient, efficient, and sustainable food systems.

The paper aims to:
1. conceptualize the notion of outliers within food processing and preservation.
2. review the role of emerging technologies in advancing sustainable innovation.
3. propose and discuss the Outlier Integration Framework as a theoretical model for sustainability transformation in food systems.
This interdisciplinary exploration contributes to both academic understanding and practical implementation by repositioning "abnormality" as a strategic driver of sustainable food innovation.

Conceptual Background and Literature Review

Outliers and Unconventional Practices in Food Systems

In the context of food processing and preservation, outliers refer to unconventional practices that deviate from industrial norms yet remain rooted in tradition, experimentation, or local adaptation. These methods often arise from indigenous knowledge systems, developed through generations of empirical learning and environmental interaction (Okoro *et al.,* 2020). While industrialization and modernization have standardized food processes, many of these unconventional methods persist at household and community levels, serving as models of resilience, minimalism, and sustainability.
Examples of outlier practices include spontaneous fermentation, where wild microorganisms drive fermentation without controlled inoculation and natural preservation methods such as sun drying, salting, smoking, or the use of plant-based antimicrobials (Adeyeye and Akanbi, 2021). These methods are often dismissed as "primitive" due to their unpredictability or variable sensory outcomes. However, research increasingly recognizes their potential for reducing energy consumption, enhancing product shelf life, and maintaining bioactive components (Bourdoux *et al.,* 2021). Spontaneous fermentation, for instance, fosters complex microbial diversity that can improve food safety and nutrient bioavailability while reducing dependence on synthetic additives.
The marginalization of such practices is partly due to the dominance of Western scientific paradigms that equate standardization with progress. Yet, as the food industry faces new sustainability pressures, these outliers are reemerging as valuable repositories of adaptive innovation. Re-examining them through contemporary science allows for the identification of bio-processes and preservation mechanisms that are both efficient and ecologically sound. Thus, outlier practices represent not anomalies to be discarded but innovation niches that can inform the development of sustainable food technologies.

Sustainability and Circular Bioeconomy in Food Innovation

Sustainability in food systems extends beyond environmental stewardship to encompass social equity, cultural integrity, and economic resilience. The circular bioeconomy model promotes the efficient use of biological resources by closing loops between production, processing, consumption, and waste management (Kuckertz *et al.,* 2020). Within this framework, waste streams from food processing are

revalorized into inputs for other processes, thereby minimizing resource loss and environmental impact.

Outlier practices naturally align with circular economy principles. Traditional drying or fermentation methods, for instance, rely on ambient energy sources such as sunlight and microbial metabolism, thereby reducing carbon footprints. Moreover, unconventional preservation agents such as extracts from fruit peels or plant leaves embody resource circularity by converting agricultural by-products into functional ingredients (Abdullah *et al.,* 2022). These practices exemplify sustainable innovation that does not require large-scale technological infrastructure yet achieves high ecological efficiency.

At the global level, incorporating these practices supports the United Nations Sustainable Development Goals, particularly SDG 12 on responsible consumption and production. By reinterpreting traditional wisdom through a scientific lens, researchers can transform cultural practices into scalable, technology-supported models of food sustainability. The combination of circular bioeconomy principles and indigenous knowledge thus creates a fertile ground for innovation that is not only green but also inclusive and culturally sensitive.

The Role of Emerging Technologies in Transforming Food Systems

Emerging technologies ranging from artificial intelligence (AI) and nanotechnology to precision fermentation and non-thermal processing, are redefining the frontiers of food science and sustainability. AI applications in food systems, for example, enable the modeling of complex fermentation dynamics, predicting optimal conditions for microbial growth and metabolite production (Singh *et al.,* 2023). Nanotechnology facilitates the development of active and intelligent packaging systems that respond to environmental stimuli, thereby extending shelf life and ensuring food safety (Ranjan *et al.,* 2019). Meanwhile, non-thermal preservation technologies like cold plasma, pulsed electric fields, and high-pressure processing minimize nutrient degradation while maintaining microbial stability (Kumar *et al.,* 2022).

The integration of these technologies with unconventional or traditional methods creates an innovation space where science and culture intersect. For instance, AI algorithms can analyze microbial succession patterns in spontaneous fermentations, enabling the optimization of flavor, texture, and safety. Similarly, nanomaterials derived from natural polymers can enhance traditional preservation systems by improving moisture control or antimicrobial activity. Precision fermentation technologies can replicate indigenous fermentation pathways in controlled environments, preserving cultural authenticity while ensuring standardization and safety.

However, the adoption of these technologies must be guided by sustainability ethics. Over-technologizing food systems can lead to resource inequities and cultural erosion. Therefore, the challenge lies in using emerging technologies not to replace traditional wisdom but to amplify it, transforming outlier practices into scientifically grounded, sustainable innovations. This synthesis forms the conceptual basis of the Outlier Integration Framework (OIF) developed in this study.

Conceptualizing "Outliers" in Food Processing and Preservation

The concept of outliers originates from statistics, describing data points that deviate markedly from the mean or expected pattern (Barnett and Lewis, 1994). In food systems research, the metaphor of "outliers" can be extended beyond quantitative anomalies to encompass unconventional or marginal practices that diverge from industrial norms. These may include localized fermentation systems, plant-based curing agents, wild microbial consortia, or energy-minimal preservation methods. Though often excluded from mainstream processing due to perceived inconsistency or lack of industrial scalability, such outliers may embody hidden efficiencies, resilience mechanisms, and sustainability attributes (Akinola *et al.,* 2023).

Historically, food science has favored standardization achieving uniform taste, texture, and safety through tightly controlled parameters. However, recent sustainability discourses emphasize the ecological and socio-cultural costs of over-standardization, including biodiversity loss, cultural

erosion, and environmental degradation (FAO, 2022). Consequently, there is growing interest in revisiting indigenous and context-specific knowledge systems once regarded as "abnormal." When studied through modern scientific frameworks, these systems reveal alternative processing logics grounded in local resource efficiency, circular use, and microbial ecology (Eromosele and Okonkwo, 2021). Hence, the outlier perspective redefines abnormality as a reservoir of untapped innovation potential.

Sustainability and the Transformation of Food Systems

Sustainability in food systems integrates environmental integrity, economic viability, and social equity (Rockström *et al.,* 2020). The processing and preservation subsectors play pivotal roles in this transition by determining the life-cycle impacts of food from raw material utilization to waste generation and energy consumption. Conventional methods such as thermal sterilization, chemical preservation, and extensive cold storage, while effective in prolonging shelf life, often demand substantial energy input and contribute to carbon emissions (Ghosh *et al.,* 2019). To meet global sustainability targets, innovative processing approaches must achieve a balance between food safety, nutritional retention, and minimal environmental burden.

In this context, sustainability can no longer be viewed solely as a set of operational adjustments; it demands a paradigmatic shift in how knowledge and innovation are sourced. The inclusion of outlier practices those derived from traditional, indigenous, or bioinspired systems, introduces a diversity of approaches aligned with natural ecosystems. For instance, natural fermentation without artificial inoculation has been shown to enhance probiotic diversity, flavor complexity, and energy efficiency (Okoro *et al.,* 2022). Similarly, solar drying and plant-extract-based preservation embody low-carbon alternatives that complement technological innovations. The integration of such practices reinforces the multidimensional nature of sustainability, spanning cultural, ecological, and technological dimensions.

Emerging Technologies as Catalysts of Transformation

Emerging technologies in food processing and preservation represent critical enablers for reinterpreting traditional and outlier practices within a modern framework. Technologies such as nanotechnology, artificial intelligence (AI), cold plasma, pulsed electric fields, and 3D food printing have demonstrated potential to revolutionize safety, efficiency, and quality control (Bhat *et al.,* 2020). These innovations contribute to precision, real-time monitoring, and reduced resource consumption. For example, nanostructured materials can enhance antimicrobial efficiency in natural preservatives, while AI-based predictive modeling can optimize fermentation kinetics once considered uncontrollable (Yadav and Jha, 2021).

Moreover, the Fourth Industrial Revolution (4IR) characterized by digital integration and automation, offers tools for scaling indigenous and small-scale processing models without eroding their ecological or cultural identities. By combining sensor technologies, machine learning, and blockchain traceability, food systems can authenticate traditional processes while ensuring safety compliance and transparency (OECD, 2021). The challenge lies not in replacing traditional systems but in embedding them within smart, adaptive frameworks that preserve their contextual value.

Theoretical Intersection: Outliers, Innovation, and Sustainability

The intersection between outliers, innovation, and sustainability can be understood through the lens of socio-technical transitions theory (Geels, 2002). This theory posits that systemic change occurs when niche innovations (e.g., unconventional or marginalized practices) align with broader regime pressures and landscape trends. Outlier practices in food systems can thus be viewed as niche innovations that, when empowered by emerging technologies, challenge dominant industrial paradigms. Their success depends on institutional support, research integration, and public acceptance.

Additionally, systems thinking and circular economy frameworks reinforce the logic of outlier integration by emphasizing interdependence, feedback loops, and waste valorization. Practices once dismissed as inefficient such as the re-fermentation of by-products or microbial biofilm utilization, can become key strategies for achieving zero-waste processing (Asiedu and Boateng, 2020). When combined with precision technology, these methods offer a path toward adaptive sustainability: a state in which food systems dynamically evolve through learning, diversity, and innovation.

Identified Knowledge Gaps

Despite promising trends, the literature reveals notable gaps. Few theoretical models explicitly link unconventional food practices to emerging technologies in the context of sustainability. Existing studies often address them separately; ethnobotanical research focuses on cultural dimensions, while techno-innovation studies emphasize scalability and control. There is a need for an integrative framework that synthesizes these dimensions and provides a roadmap for transformation. This conceptual vacuum justifies the development of the Outlier Integration Framework (OIF) presented in the next section.

The Outlier Integration Framework (OIF)

Conceptual Foundation of the Framework

The Outlier Integration Framework (OIF) is a theoretical model that seeks to systematize how unconventional, traditional, or "outlier" food processing and preservation practices can be integrated with emerging technologies to foster innovation and sustainability. It builds on the premise that sustainability transitions in food systems do not solely depend on technological breakthroughs, but on the reinterpretation and revalorization of knowledge once considered marginal. The framework therefore acts as a bridge between indigenous wisdom and modern science, embedding cultural, ecological, and digital dimensions into a unified process of innovation.

OIF draws its intellectual foundation from three major theoretical constructs:

1. Socio-technical transitions theory, which explains how niche innovations can challenge and transform dominant regimes when contextual enablers align (Geels, 2002).
2. Systems thinking, which frames food processing as an interconnected web of actors, resources, and feedback mechanisms rather than isolated technologies (Senge, 2006).
3. Circular economy and adaptive sustainability theory, which emphasize waste minimization, resource regeneration, and continuous learning (Asiedu and Boateng, 2020)

Together, these constructs situate outlier practices as strategic entry points for transformation sources of diversity that stimulate creative experimentation and adaptive resilience within food systems.

Structural Components of the OIF

The Outlier Integration Framework comprises four interrelated components:

1. Outlier Identification and Characterization
2. Technological Alignment and Enhancement
3. System Integration and Circular Linkages
4. Sustainability Feedback and Adaptive Learning

Each component represents a progressive stage through which outlier practices evolve into mainstream, sustainable innovations.

Outlier Identification and Characterization

This stage involves the recognition of unconventional or marginalized food processing and preservation practices that display unique cultural, ecological, or functional traits. These may include spontaneous fermentation, sun-drying, smoking, natural antimicrobials, or organic acid-based preservation methods. Characterization focuses on defining their physicochemical, microbiological, and socio-economic properties, while acknowledging their cultural origins. Modern analytical tools

such as metabolomics, genomic sequencing, and sensory mapping can scientifically validate the principles underlying these outliers (Eromosele and Okonkwo, 2021).

Technological Alignment and Enhancement

Once identified, the next stage aligns these outliers with emerging technologies capable of enhancing safety, consistency, and scalability. This alignment involves adapting traditional techniques to incorporate smart or green innovations such as nanostructured coatings, pulsed electric field preservation, AI-assisted fermentation monitoring, and biodegradable packaging (Yadav and Jha, 2021). The goal is not to replace the indigenous logic but to amplify its efficiency and sustainability through precision tools. For instance, cold plasma treatment may extend the shelf life of traditionally fermented foods without altering their microbiota balance, thereby retaining cultural authenticity.

System Integration and Circular Linkages

The third component focuses on embedding the technologically enhanced outlier practice into broader food system networks. This includes establishing circular linkages between production, processing, and waste management. For example, by-products from traditional fermentation can serve as raw materials for bioenergy generation or natural enzyme production. The integration process benefits from digital infrastructure such as blockchain for traceability or IoT sensors for quality control that ensures transparency and resource optimization (OECD, 2021). Thus, OIF fosters a multi-scalar integration process connecting local producers, innovators, and policymakers within a sustainability ecosystem.

Sustainability Feedback and Adaptive Learning

The final component captures the dynamic feedback mechanism that allows continuous improvement of the integrated system. This involves assessing environmental, social, and economic performance indicators, supported by life-cycle assessment (LCA) and sustainability analytics. Adaptive learning enables stakeholders to refine processes based on real-time data, local feedback, and scientific evaluation. It embodies the principle that sustainability is not a fixed outcome but an evolving practice. By embedding feedback loops, OIF ensures that innovations remain context-sensitive and ecologically grounded.

Mechanistic Pathways of Transformation

The OIF operates through three core transformation pathways:

1. Reinterpretation- Re-examining “abnormal” practices through modern science to reveal their underlying efficiency.
2. Reconfiguration- Merging traditional knowledge with contemporary technologies to create hybrid innovations.
3. Reinstitutionalization- Embedding these hybrid systems within policy, education, and industrial frameworks to achieve lasting impact.

These pathways are iterative and nonlinear, reflecting the real-world complexity of food systems. The framework promotes inclusive innovation, where knowledge flows bidirectionally between scientific institutions and local communities.

Theoretical Positioning of the OIF

The OIF contributes to sustainability and innovation theory in three ways. First, it introduces abnormality as a valid source of innovation, contradicting the industrial notion that standardization equates to progress. Second, it advances the conceptual discourse on integrative innovation, where social, cultural, and technological systems co-evolve toward shared sustainability outcomes. Third, it establishes a learning-based model for adaptive sustainability, emphasizing feedback-driven refinement rather than linear transfer of technology.

Philosophically, the OIF challenges the epistemic divide between indigenous knowledge and modern science. It repositions local practices not as primitive relics but as evolving systems of empirical wisdom capable of informing next-generation food innovation. This theoretical synthesis not only broadens the epistemological base of food science but also democratizes innovation by validating plural knowledge systems.

Practical Illustrations

The framework can be illustrated through multiple practical contexts:

- Fermented foods: Traditional fermentation of African locust bean (*Parkia biglobosa*) into iru can be optimized using AI-based microbial profiling and predictive modeling, ensuring safety and uniformity while preserving cultural identity.
- Natural drying systems: Indigenous solar drying methods for fruits and vegetables can be integrated with smart temperature sensors and nanofilm covers to reduce contamination and enhance nutrient retention.
- Plant-based preservation: Extracts from *Moringa oleifera* or *Zingiber officinale* used traditionally as natural antimicrobials can be stabilized using nanocarrier systems for commercial application. Such cases exemplify how the OIF moves beyond theory into actionable sustainability transitions.

Theoretical Implications and Policy Relevance

Theoretical Implications for Food Science and Innovation

The Outlier Integration Framework (OIF) offers a fresh theoretical lens for understanding innovation in food systems. By introducing "outliers" as legitimate sources of scientific inquiry, it challenges the conventional hierarchy of knowledge that privileges laboratory-based technologies over community-driven experimentation. In doing so, it broadens the epistemological foundation of food science to encompass diverse, pluralistic sources of innovation.

From a theoretical standpoint, the OIF advances three major implications:

1. **Epistemic Expansion of Innovation Theory** – The framework expands innovation theory beyond the linear "R&D-to-market" pipeline, promoting a plural innovation ecology that values local adaptation and endogenous creativity. It situates innovation as an emergent property of interaction between traditional practices and scientific tools (Senge, 2006).

2. **Bridging Micro and Macro Systems Thinking** – OIF synthesizes micro-level practices (e.g., local processing methods) with macro-level systems (e.g., industrial standards, global trade, and sustainability metrics). This multi-scale integration addresses the persistent gap between laboratory-scale innovations and community-scale realities, thus enhancing contextual applicability (Geels, 2002).

3**. Adaptive Sustainability Paradigm** – The OIF redefines sustainability as an adaptive process rather than a static end goal. By embedding continuous feedback and learning cycles, it transforms food innovation into a dynamic process responsive to ecological and socio-economic change. This concept aligns with adaptive management principles in environmental science, fostering resilience and long-term viability (Rockström *et al.,* 2020).

Theoretically, the OIF bridges technological determinism and cultural realism, emphasizing co-evolution rather than domination. It reorients food innovation toward inclusivity, where both scientific expertise and indigenous ingenuity co-construct sustainable futures.

Policy Relevance for Sustainable Food Systems

The OIF also holds significant implications for policy formulation at local, national, and global levels. As food security and climate adaptation policies increasingly emphasize sustainability, frameworks

that integrate technological and cultural innovation become crucial. The OIF provides policymakers with a roadmap for inclusive, evidence-based interventions.

(a) **Knowledge Integration Policies**
Governments and research agencies can adopt policies that promote transdisciplinary collaboration between food technologists, social scientists, and indigenous communities. Establishing innovation clusters or living labs based on the OIF can encourage co-development of sustainable food technologies while preserving local heritage. For example, Nigeria's agro-industrial policy could institutionalize community–university innovation partnerships to refine and commercialize indigenous preservation methods.

(b) **Digital and Technological Infrastructure**
The OIF underscores the role of emerging technologies such as AI, blockchain, and sensor systems in modernizing outlier practices without displacing their cultural essence. Governments can enhance digital infrastructure in rural areas to enable local processors to access smart technologies and data analytics. This democratization of technology ensures that innovation flows inclusively from the grassroots to the global market (OECD, 2021).

(c) **Education and Capacity Development**
Integrating OIF concepts into tertiary and technical education curricula can inspire a new generation of food scientists who value cross-cultural innovation. Academic institutions can design interdisciplinary programs on sustainable food systems innovation that combine food technology, anthropology, and environmental science. Capacity-building initiatives should emphasize co-learning and participatory research to strengthen local ownership of innovation outcomes (FAO, 2022).

Implications for Global Sustainability Agendas
The OIF aligns with and contributes to several United Nations Sustainable Development Goals (SDGs), particularly:
- SDG 2 (Zero Hunger): by enhancing food availability and nutritional security through sustainable preservation and processing.
- SDG 9 (Industry, Innovation, and Infrastructure): by encouraging the creation of inclusive, sustainable food industries rooted in local knowledge.
- SDG 12 (Responsible Consumption and Production): by promoting circular, waste-minimizing practices in the food chain.
- SDG 13 (Climate Action): through reduced energy intensity and integration of adaptive, low-emission technologies.
By embedding innovation within ecological and cultural systems, the OIF advances a holistic sustainability paradigm that transcends technical efficiency to embrace equity, resilience, and cultural continuity. It thus supports a transformative sustainability agenda, one that moves beyond incremental improvements toward systemic change in the global food landscape.

Conclusion
The growing complexity of global food challenges from climate change and resource depletion to food waste and nutritional insecurity demands innovation paradigms that transcend conventional technological boundaries. The Outlier Integration Framework (OIF) developed in this paper provides a conceptual foundation for such transformation by reimagining outliers; unconventional, indigenous, or marginal practices as powerful drivers of sustainability-oriented innovation.
By synthesizing socio-technical transitions theory, systems thinking, and circular economy principles, the OIF articulates how traditional food processing and preservation methods can be reinterpreted, technologically enhanced, and systemically integrated into modern food value chains. The framework

advances both theoretical and practical understanding by challenging the dominant notion that progress must emerge solely from high-tech innovation. Instead, it demonstrates that sustainability and resilience can also arise from rediscovering and reconfiguring what was once deemed "abnormal" or outdated.

From a practical standpoint, the OIF establishes a pathway for developing hybrid innovation processes that integrate indigenous wisdom with emerging technologies like AI, nanoscience, and biotechnology. These hybrid systems promise not only ecological efficiency but also economic inclusiveness, ensuring that innovation benefits flow equitably across both industrial and local actors. Such integration resonates strongly with current global transitions toward nature-based solutions and regenerative food systems.

In conclusion, the Outlier Integration Framework offers not merely a theoretical construct but a transformative vision for the future of food science and sustainability. It demonstrates that what society once labeled as abnormal may, in fact, hold the key to ecological balance, resilience, and inclusive progress. By turning outliers into opportunities, the OIF provides a blueprint for building food systems that are not only technologically advanced but also culturally grounded, environmentally conscious, and socially just.

Recommendations

However, the framework also raises important questions for future inquiry. Empirical validation remains a crucial next step. Researchers should explore case studies that apply the OIF to specific food systems, evaluating measurable sustainability outcomes such as carbon reduction, waste minimization, and socio-economic empowerment. Additionally, cross-disciplinary studies involving food technologists, environmental economists, and social scientists can further refine the model's applicability and robustness.

Future research should also investigate the digitalization of outlier practices; how tools like machine learning, blockchain, and IoT can document, preserve, and scale indigenous processing knowledge without eroding cultural authenticity. Similarly, ethical and governance dimensions warrant deeper exploration: Who owns innovation derived from traditional practices? How can intellectual property frameworks evolve to ensure fair benefit sharing? Addressing these questions will be vital to achieving ethical and equitable innovation in the global food sector.

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