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# Sustainable Food Technology Innovation: Transforming Safety, Digitalization, Alternative Proteins, and Personalized Nutrition in the Future Food System

Loso Judijanto
IPOSS Jakarta
**Corresponding Author:** Loso Judijanto losojudijantobumn@gmail.com

A R T I C L E I N F O

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A B S T R A C T

This article discusses food technology innovations and trends in response to simultaneous pressures such as population growth, climate change, supply chain vulnerabilities, increased consumer health awareness, and sustainability demands. Using a qualitative literature review method, the article synthesizes reputable scientific literature on food biotechnology, non-thermal processing technologies, active and smart packaging, supply chain digitalization, artificial intelligence, the Internet of Things, blockchain, alternative proteins, functional foods, 3D food printing, and food waste valorization. The study results show that contemporary food technology is no longer just focused on extending shelf life and improving production efficiency, but is increasingly aimed at building a food system that is safe, nutritious, transparent, personalized, inclusive, and environmentally friendly. Biotechnology and genome editing play a role in improving crop resilience and biofortification; non-thermal technologies and smart packaging enhance food quality and safety; while AI, IoT, and blockchain strengthen prediction, monitoring, traceability, and data-driven decision-making. However, technology adoption still faces challenges like cost, production scale, regulations, ethics, consumer acceptance, data interoperability, and access gaps between developed and developing countries. This article concludes that the future of food technology requires integrating technical innovations with public policy, data governance, inclusive financing, risk communication, and cross-stakeholder collaboration to ensure a sustainable and fair transformation of the food system

## INTRODUCTION

The transformation of the global food system in the 2020s is marked by a shift from a purely mass-production paradigm toward a system that must simultaneously meet demands for safety, quality, nutrition, affordability, sustainability, and resilience. Recent literature emphasizes that food innovation plays a key role in achieving sustainable development goals, but its impact isn't automatically positive if it isn't supported by governance that considers health, environmental, economic, and social justice aspects. In this context, food technology becomes a strategic field because it connects food science, biotechnology, process engineering, digitalization, consumer behavior, and supply chain management.

The urgency of this study has increased because the food system is facing multiple pressures. Climate change raises the risk of crop failures, lower raw material quality, distribution disruptions, and higher biological and chemical contamination. At the same time, consumers are demanding healthier, minimally processed foods that are labeled clean, traceable, and have a lower environmental impact. Research on food innovation shows that future solutions can't rely on just one technology, but rather on a combination of production, processing, packaging, digitalization, and new business model technologies [3], [4], [5].

Contemporary food technology has evolved from conventional preservation and processing techniques to systems that are increasingly data-driven, precise, and sustainable. Non-thermal processing methods like high-pressure processing, pulsed electric fields, ultrasound, and cold plasma are being developed to maintain sensory and nutritional quality while ensuring food safety. Active and smart packaging is also evolving to monitor freshness, extend shelf life, and reduce food loss.

On the other hand, digital technologies like artificial intelligence, the Internet of Things, big data analytics, and blockchain are starting to change the way the food industry designs products, controls quality, predicts demand, monitors storage, and builds supply chain transparency. AI and big data are seen as capable of boosting quality control, production efficiency, and new product development, while IoT and blockchain enhance real-time monitoring and traceability from upstream to downstream.

In addition, food innovation is also marked by the development of alternative proteins, functional foods, biofortification, and personalized nutrition. Plant-based products, precision fermentation, microbial protein, edible insects, and cultured meat are emerging in response to the need for more sustainable protein, although they still face challenges with cost, production scale, nutritional profile, regulations, and consumer acceptance [16], [17], [18], [19]. Functional foods based on probiotics, prebiotics, synbiotics, postbiotics, and bioactive compounds are also becoming increasingly important as the connection between food, gut microbiota, immunity, and chronic disease prevention is being studied more and more [20], [21], [22].

Based on that background, this article is based on four research questions. First, how have food technology concepts and theories developed in addressing issues of food safety, security, nutrition, and sustainability? Second, what major innovations have shaped food technology trends since 2020, particularly in biotechnology, processing, packaging, digitalization, alternative proteins, and functional foods? Third, how do these innovations contribute to transforming food systems to be safe, sustainable, transparent, and climate-adaptive? Fourth, what challenges and future research agendas need to be considered so that food technology innovations can be adopted inclusively and responsibly?

The purpose of writing this article is to provide a conceptual and analytical synthesis of innovations and the latest food technology trends; explain their contributions to food safety, food security, sustainability, and public health; identify regulatory, economic, social, and technical challenges in their adoption; and formulate recommendations for future research. In this way, the article is expected to serve as an academic foundation for researchers, policymakers, industry players, and other stakeholders in understanding the direction of food technology development toward a more resilient and sustainable food system.

## LITERATURE REVIEW

### 1. The Concept of Food Technology and the Transformation of the Food System

Food technology can be understood as the application of science and engineering to process, preserve, package, distribute, and evaluate food so that it is safe, high-quality, nutritious, and meets consumer needs. In contemporary literature, food technology is no longer seen as an isolated technical subsystem but as part of a food system that involves production, processing, distribution, consumption, and waste management. This systemic perspective is important because innovation at one point in the value chain can have consequences elsewhere; for example, packaging technology can extend shelf life but also create plastic waste issues if not designed with a circular approach [1], [2], [23].

The innovation systems theory helps explain that progress in food technology is determined by the interaction between academic actors, industry, government, consumers, investors, and standardization institutions. Food innovations tend to succeed if they meet three dimensions: technological feasibility, market acceptance, and regulatory legitimacy. Therefore, developing food technology must take into account scientific evidence, safety, costs, nutritional value, risk perception, as well as the industry's ability to scale technology from the lab to commercial production [2], [3], [5].

### 2. Food Safety, Food Security, and Supply Chain Resilience

Food safety is related to preventing microbiological, chemical, and physical contamination, while food security focuses on the availability, access, utilization, and stability of food. In modern food systems, these two concepts are increasingly connected with supply chain resilience, which is the system's ability to anticipate, absorb, and recover from disruptions like pandemics, conflicts, energy crises, climate change, and natural disasters. Rapid detection technologies, biosensors, microfluidic chips, machine vision, and sensor data integration can speed up risk identification and shorten the industry's response time [9], [24], [25].

Theoretically, risk-based food safety requires hazard control throughout the supply chain, not just at the final product stage. Because of that, technologies that enable real-time monitoring, predictive analytics, and traceability are becoming more relevant. IoT can monitor temperature, humidity, location, and shocks during storage and transportation; blockchain can provide transaction records that are harder to tamper with; while AI can identify anomaly patterns, predict spoilage, and optimize decision-making processes [11], [12], [15], [26].

**3. Biotechnology, Genome Editing, and Biofortification**

Food biotechnology involves using organisms, cells, enzymes, metabolites, and molecular techniques to improve food production, quality, safety, and nutritional value. CRISPR-Cas-based genome editing speeds up plant breeding by modifying target genes related to yield, disease resistance, tolerance to abiotic stress, nutrient content, and quality traits. Compared to conventional breeding, this approach is more precise, but it still requires safety assessment, ethical governance, and transparent public communication.

Biofortification is an example of integrating food technology and public health. Through breeding, agronomy, fermentation, or genome editing, the content of micronutrients like iron, zinc, provitamin A, folate, and bioactive compounds can be boosted in staple foods. This approach is relevant for developing countries because it can improve nutritional quality without requiring drastic changes in eating habits. However, its success depends on nutrient bioavailability, stability during processing, consumer acceptance, and integration with fortification and food diversification policies [31], [32], [33].

**4. Food Processing Technology: Minimal Processing and Non-Thermal Processing**

Modern food processing is increasingly focused on the concept of minimal processing, which means keeping the freshness, texture, color, aroma, and nutritional content through gentler treatments compared to conventional thermal processes. Technologies like high pressure processing, pulsed electric fields, ultrasound, cold plasma, pulsed light, irradiation, and microwave-assisted thermal sterilization are being explored as alternatives to reduce microbial load, maintain quality, and improve energy efficiency. Literature suggests that non-thermal technologies have the potential to enhance product quality, but each technology has limitations regarding equipment costs, industrial scale, food matrix characteristics, and safety validation [4], [6], [34], [35].Dari perspektif keberlanjutan, teknologi pengolahan tidak hanya dinilai dari efektivitas mikrobiologis, tetapi juga dari konsumsi energi, air, bahan kimia, kehilangan nutrisi, dan pengaruhnya terhadap limbah. Teknologi seperti cold plasma dan HPP menjanjikan karena dapat menekan mikroba pada suhu rendah, sementara PEF dapat meningkatkan ekstraksi komponen bioaktif dan efisiensi proses pada produk cair. Walaupun demikian, pemilihan teknologi harus berbasis analisis siklus hidup dan techno-economic assessment agar klaim keberlanjutan tidak bersifat parsial [7], [36], [37].

**5. Active Packaging, Smart Packaging, and Nanotechnology**

Food packaging no longer just serves as a passive container; it has evolved into an active and smart system. Active packaging can absorb oxygen, control moisture, release antimicrobials, or inhibit oxidation, while smart packaging can provide information about freshness, temperature, leaks, or storage history. Recent studies show that developing packaging based on biopolymers, color indicators, biosensors, nanoemulsions, and nanocomposites can extend shelf life and enhance food safety [8], [9], [10], [38].

Nanotechnology contributes to strengthening the mechanical properties and packaging barriers, developing contaminant sensors, as well as controlled release systems for active compounds. However, using nanomaterials requires considering potential migration into food, toxicity, regulations, and consumer perception. Therefore, research agendas should not only aim for packaging performance but also evaluate safety, biodegradability, affordability, and environmental impact throughout its life cycle [9], [39], [40].

**6. Digitization: AI, IoT, Big Data, and Blockchain**

Digitalization is the foundation of Food Industry 4.0 and is starting to shift towards Industry 5.0, which focuses more on human-machine collaboration, personalization, and sustainability. AI is used for computer vision in sorting and defect detection, formulation optimization, predictive maintenance, demand forecasting, product design, and process control. Big data provides the analytical basis to understand consumer preferences, supply chain efficiency, and food safety risks. The integration of AI and big data in the food industry is considered to improve decision-making accuracy and speed up product innovation [5], [13], [14], [41].

IoT expands monitoring capabilities through sensors connected to warehouses, vehicles, production facilities, and packaging. Real-time data from these sensors can be used to control cold chain temperatures, detect deviations, reduce food loss, and strengthen audits. Blockchain complements IoT by providing transparent and distributed traceability records, although it still faces issues with interoperability, implementation costs, input data quality, and privacy governance [11], [12], [15], [26], [42].

**7. Alternative Proteins, Cultured Meat, and Future Food**

Alternative proteins include plant-based proteins, microbial proteins, insect proteins, precision fermentation, and cultured meat. These innovations have emerged because conventional animal protein production is linked to greenhouse gas emissions, land and water use, zoonosis risks, and animal welfare issues. Plant-based meat analog products require engineering of texture, taste, color, juiciness, and nutritional profile to be accepted by consumers. Literature shows that the success of alternative proteins is not only determined by extrusion technology or formulation, but also by price, labeling, regulations, eating culture, and consumer trust [16], [17], [18], [43].

Cultured meat offers the potential to produce protein without cutting animals, but the technology is still limited by the cost of culture media, the need for large-scale bioreactors, scaffold design, sensory characteristics, energy requirements, and regulatory certainty. Some studies emphasize that claims about the sustainability of cultured meat need to be proven through a transparent life cycle assessment because the environmental impact heavily depends on the energy source, media composition, and process efficiency [19], [44], [45], [46], [47].

**8. Functional Food, Microbiota, and Personalized Nutrition**

Functional foods are foods that provide physiological benefits beyond fulfilling basic nutrients. Research on gut microbiota has increased attention on probiotics, prebiotics, synbiotics, postbiotics, dietary fiber, polyphenols, bioactive peptides, omega-3s, and antioxidants. Probiotics and prebiotics are studied for their potential to modulate microbiota, improve digestive function, support immunity, and contribute to the prevention of metabolic diseases. However, their benefits are strain-specific, dose-dependent, and influenced by the food matrix as well as individual characteristics [20], [21], [22], [48].

Food and nutrition personalization is growing through the integration of health data, consumer preferences, wearable sensors, digital apps, AI, and 3D food printing. This technology allows the design of products tailored to energy needs, texture preferences, allergies, clinical conditions, and cultural preferences. Despite its potential, food personalization raises questions about data privacy, the accuracy of algorithmic recommendations, accessibility, and the risk of commercializing health claims that aren't yet well-supported [49], [50], [51], [52].

## METHODOLOGY

This article uses a qualitative literature review method, which is a literature review approach aimed at interpreting, comparing, and synthesizing scientific findings narratively to build a conceptual and analytical understanding of a topic. Unlike a systematic literature review, which requires a search protocol, inclusion-exclusion criteria, and a very formal selection process, a qualitative literature review allows for reading literature thematically, critically, and integratively, making it suitable for mapping the development of multidisciplinary and fast-evolving food technology innovations [53], [54].

The literature reviewed focused on reputable journal articles in both Indonesian and English, preferably those published since 2020, including review articles, systematic reviews, bibliometric reviews, and conceptual articles relevant to food biotechnology, non-thermal processing, smart packaging, AI, IoT, blockchain, alternative proteins, functional foods, 3D food printing, food waste valorization, and sustainable food systems. Sources were traced through databases and publisher websites like Scopus, PubMed, and Google Scholar, paying attention to topic relevance, novelty, journal credibility, and the availability of DOI or permanent links.

The analysis was done through thematic coding of recurring key issues in the literature, and then organized into a conceptual synthesis and an argumentative discussion. The themes used include: drivers of innovation, key technologies, contributions to food security and resilience, sustainability impacts, adoption challenges, regulations, consumer acceptance, and future research agendas. This approach allows the article to explain the relationships between technologies and their implications for transforming the food system without claiming to perform quantitative measurements or meta-analysis.

## RESULTS AND DISCUSSION

### 1. General Direction of Food Technology Innovation

The review results show that food technology innovation is moving toward integration between safety, nutrition, sustainability, transparency, and personalization. In the early phase of industrialization, food innovation was mainly aimed at extending shelf life and expanding distribution. Nowadays, innovation has to meet more complex demands: reducing food waste, cutting emissions, ensuring safety, maintaining nutritional quality, satisfying consumer preferences, and staying affordable. That's why recent literature emphasizes a food system approach, rather than just product or process innovation on its own [2], [3], [55].

This development answers the first research question that food technology acts as an instrument for transforming the food system. Technology not only improves production efficiency but also changes the relationships between producers, distributors, regulators, and consumers. Smart packaging, for example, makes quality information easier to access; blockchain turns traceability into a trust asset; while AI makes production decisions and formulations prediction-based. In this way, food technology is increasingly becoming a socio-technical infrastructure that influences how food is designed, produced, monitored, consumed, and evaluated [1][5][13].

### 2. Biotechnology and Genome Editing as the Basis of Food Security

Biotechnology and genome editing play an important role in food security because they allow the development of crops that are more productive, disease-resistant, drought-tolerant, and have better nutritional value. CRISPR-Cas speeds up the identification and modification of genes that affect agronomic traits, making the breeding process more precise compared to conventional methods. In the context of climate change, the ability to produce varieties that tolerate abiotic stress is very relevant because temperature variability, drought, salinity, and plant pest attacks are increasing [27], [29], [30].

However, the discussion shouldn't just focus on the technical aspects. Genome editing requires a clear regulatory framework, food safety assessments, biodiversity protection, and risk communication that the public can understand. Consumer resistance to GMOs and new technologies often arises not just because of a lack of information, but because of issues of trust, transparency, benefit distribution, and historical experiences with the food industry. Therefore, biotech innovation needs to be combined with public engagement, research ethics, and policies that ensure small farmers have access to high-quality varieties.

### 3. Processing and Packaging Technology for Safety, Quality, and Reducing Food Loss

Non-thermal processing technology has become one of the answers to consumers' demand for fresh, nutritious, and safe food. HPP, PEF, ultrasound, and cold plasma can reduce microorganisms or change the structure of food with less heat damage. These technologies are relevant for juice, milk, meat, seafood, fruits, vegetables, and ready-to-eat foods. Besides improving safety and quality, non-thermal technology can extend shelf life and reduce food loss, as long as the process parameters are validated according to the product's characteristics [4], [6], [7].

Active and smart packaging complements process innovations by providing protection and information during distribution. Freshness indicators, time-temperature indicators, oxygen scavengers, antimicrobial films, and nanomaterial-based sensors can help both producers and consumers recognize quality changes. In long supply chains, this technology is important for reducing food loss because distribution and consumption decisions can be made based on the actual condition of the product, not just the expiration date. However, its implementation needs to consider costs, biodegradability, migration safety of active materials, and recycling capability.

**4. Digitization, AI, IoT, and Blockchain in the Food Supply Chain**

Digitalization has become the most defining trend in food industry upgrades. AI can boost visual inspections, quality classification, demand forecasting, energy optimization, and waste reduction through production and market data analysis. In processing facilities, computer vision and machine learning help detect defects, visual contaminants, or size mismatches at speeds that are hard for manual inspections to match. At the supply chain level, AI can predict stock needs and cut down on overproduction, which is a major source of food waste [13], [14], [41].

IoT expands these capabilities with sensors that collect real-time data on temperature, humidity, location, and storage conditions. This data can be used to manage the cold chain, especially for perishable products like meat, fish, milk, fruits, and vegetables. Integrating IoT with blockchain allows field data to be recorded in a more transparent tracking system. However, literature discussions show that blockchain isn't a one-size-fits-all solution; its effectiveness still depends on the quality of input data, standardization, interoperability, digital literacy, and incentives for supply chain players to share data [11], [12], [15], [42]. The main implication for the third research question is that digitalization strengthens food security and resilience through system visibility. When data is available faster and more accurately, risks like contamination, spoilage, counterfeiting, and inefficiency can be detected earlier. However, digital technology also brings up new issues, including cybersecurity, data privacy, algorithmic bias, investment costs, and access gaps between big companies and small food businesses. So, digital transformation needs to be accompanied by data governance, open standards, and support for small players so they don't get left behind [5], [13], [26].

**5. Alternative Proteins and Shifts in Consumer Preferences**

Alternative proteins have become one of the most prominent areas of innovation because they directly relate to issues like emissions, resource use, health, animal ethics, and consumption culture. Plant-based products, microbial proteins, and cultured meat offer opportunities to diversify protein sources. However, market success isn’t solely determined by sustainability claims. Consumers look at taste, texture, price, ease of cooking, nutritional content, ingredient labels, and cultural suitability. So, formulation innovation needs to be balanced with a clean-label strategy, nutrition education, and transparent evidence of environmental impact [16], [17], [18], [43].

Cultured meat is a promising innovation, but it is still in the stage of technological and regulatory development. The main challenges include serum-free culture media, energy requirements, bioreactor costs, edible scaffolds, sensory profile, production scale, and consumer acceptance. Some studies emphasize that cultured meat can be part of the future protein portfolio, but it shouldn't be positioned as the sole replacement for livestock or plant-based proteins. A more realistic approach is to diversify protein through a combination of whole plant foods, meat analogs, fermentation, microbial proteins, and more sustainable farming innovations [19], [44], [46], [47].

**6. Functional Foods, 3D Food Printing, and Food Personalization**

Functional foods have developed in response to the increasing burden of non-communicable diseases and consumer awareness of the food-health connection. Probiotics, prebiotics, synbiotics, postbiotics, fiber, bioactive peptides, and polyphenols have become the focus of new product formulations. However, health claims need to be based on solid evidence because functional effects can vary between microbial strains, doses, food matrices, and individual conditions. This requires collaboration between food science, microbiology, clinical nutrition, and health claim regulations [20], [21], [22], [48].

3D food printing opens up opportunities for personalizing the shape, texture, nutrient density, and composition of food. This technology can be helpful for elderly people with swallowing difficulties, patients with special dietary needs, athletes, kids, and consumers who want a more personalized eating experience. However, its commercial development is still limited due to issues with printability of materials, production speed, process safety, regulatory standards, and equipment costs. Combining AI with 3D printing can speed up the design of personalized formulas, but the validity of nutrition recommendations and consumer data protection should be a top priority [49], [50], [51], [52].

**7. Sustainable Food Technology and the Circular Economy**

The sustainability of food technology isn't just about the final product, but also how raw materials are sourced, energy is used, waste is managed, and added value is created. The circular economy encourages using by-products and food waste for food ingredients, pectin, fiber, protein, bioplastics, bioenergy, enzymes, and bioactive compounds. Recent studies show that valorizing food waste can reduce environmental burdens while opening up new economic opportunities, but it requires quality standards, food safety, economic feasibility, and clear markets [56], [57], [58].

Green processing technologies like ultrasound-assisted extraction, microwave, enzymes, pulsed electric field, supercritical fluids, and fermentation can boost the recovery of valuable compounds from food waste. However, sustainability needs to be proven with a life cycle assessment so that the valorization process doesn't end up causing higher energy or chemical consumption. In the context of developing countries, circular approaches should be adapted to the characteristics of SMEs, availability of infrastructure, cold chain, food safety regulations, and financing models that support local innovation [36], [56], [57].

## 8. Adoption Challenges and Governance Agenda

Even though food technology innovations are very promising, adopting them faces technical, economic, social, and institutional hurdles. On the technical side, many technologies still need industrial-scale validation, standardization of parameters, data interoperability, and process safety. On the economic side, initial investments for HPP, IoT sensors, blockchain, cultured meat bioreactors, or 3D printing are often high. On the social side, consumer acceptance is influenced by taste, price, trust, perception of naturalness, tech literacy, and eating culture. On the institutional side, regulations often lag behind the speed of innovation [2], [5], [43].

Therefore, the answer to the fourth research question is the need for responsible innovation governance. Future research should integrate techno-economic assessment, life cycle assessment, risk assessment, consumer studies, and policy analysis. The government needs to set safety standards, labels, health claims, data protection, and innovation incentives. The industry needs to strengthen transparency, data audits, healthy product design, and collaboration with academics. Consumers need to be involved through honest, evidence-based risk communication. In this way, food technology can become a driver of food system transformation, not just a new tech commodity.

## CONCLUSIONS AND RECOMMENDATIONS

This article concludes that food innovation and technology trends show a fundamental shift from conventional processing and preservation to broader food system transformation. Food technology now plays a role in addressing challenges like food security, food resilience, public health, climate change, environmental sustainability, supply chain transparency, and changing consumer preferences. So, food technology should be understood as a socio-technical system that connects science, industry, regulation, markets, and consumer behavior.

Biotechnology, genome editing, and biofortification play an important role in boosting productivity, nutritional quality, and helping plants adapt to climate stress. Non-thermal processing technologies and smart-active packaging strengthen the industry's ability to produce safe, high-quality, fresh food with a longer shelf life. Meanwhile, AI, IoT, big data, and blockchain expand our capabilities for prediction, monitoring, traceability, and data-driven decision-making throughout the entire food value chain.

Alternative proteins, cultured meat, functional foods, 3D food printing, and personalized nutrition show that the future of food will increasingly be influenced by a mix of sustainability, health, ethics, and consumer experience. However, the success of these technologies isn't just determined by lab performance, but also by price, taste, texture, regulations, eating culture, scientific evidence, and public trust. That's why every food innovation needs a multidisciplinary approach to make sure its benefits can be widely felt.

From a sustainability perspective, the circular economy and food waste valorization are becoming important agendas. Processing by-products into value-added materials can help reduce food waste, lessen environmental burdens, and open up new economic opportunities. However, sustainability claims need to be tested through life cycle analysis, economic analysis, and safety assessments. Innovations that just shift environmental burdens from one stage to another can't really be considered proper solutions.

Future research suggestions include strengthening studies that combine life cycle assessment, techno-economic assessment, risk assessment, consumer acceptance, and policy analysis. Research also needs to be conducted more in the context of developing countries, including Indonesia, because challenges in adopting food technologies are greatly influenced by industry structure, the capacity of SMEs, cold chain infrastructure, regulations, consumer literacy, and access to financing. Empirical studies on AI, IoT, blockchain, smart packaging, and non-thermal technologies in small to medium-sized food industries are also still very much needed.

In the end, food technology transformation needs to be guided by inclusive, safe, healthy, transparent, and sustainable principles. Collaboration between academics, government, industry, communities, and consumers is essential so that innovations not only produce new products but also improve the overall quality of the food system. With proper governance, food technology can become a strategic tool to achieve food security, public health, and environmental sustainability in the future..

## FURTHER STUDY

This research still has limitations, so further studies are needed on the topic of Sustainable Food Technology Innovation: Transforming Safety, Digitalization, Alternative Proteins, and Personalized Nutrition in the Future Food System.

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