OPEN ACCESS

Ecology EDITORIAL

The AI-material nexus rewiring the food supply chain: From molecule to market

Peihua Ma,[1,13,*] Xiaoxue Jia,[1] Fangzheng Zhou,[1] Yapeng Fang,[2] Yunfei Xie,[3] Mazen Alharbi,[4] Dachuang Zhang,[5] Yuan Li,[6] Yamin Bouzembrak,[7] Yizhou Ma,[7] Da Ma,[8] Cheng-I Wei,[9] Yixiang Wang,[10] Bei Fan,[1] Daming Fan,[3] Baoguo Sun,[11] Yang Shan,[12] and Fengzhong Wang[1,13,*]

[1]Institute of Food Science and Technology, Chinese Academy of Agricultural Sciences, Beijing 100193, China
[2]School of Agriculture & Biology, Shanghai Jiao Tong University, Shanghai 201100, China
[3]State Key Laboratory of Food Science & Technology, School of Food Science & Technology, Jiangnan University, Wuxi 214122, China
[4]King Abdulaziz City for Science and Technology (KACST), Riyadh 11442, Saudi Arabia
[5]Department of Food Science & Technology, Faculty of Science, National University of Singapore, Singapore 117543, Singapore
[6]Research Center of Food Colloids and Delivery of Functionality, College of Food Science & Nutritional Engineering, China Agricultural University, Beijing 100083, China
[7]Wageningen Food Safety Research, Akkermaalsbos 2, 6708 WB Wageningen; Information Technology Group, Wageningen University & Research, Wageningen 6706 KN, The Netherlands
[8]School of Food Science & Engineering, Jinan University, Guangzhou 510632, China
[9]Department of Nutrition & Food Science, College of Agriculture & Natural Resources, University of Maryland MD 20742, USA
[10]Yixiang Wang Department of Food Science & Agricultural Chemistry, McGill University, Ste Anne de Bellevue, Quebec H9X 3V9, Canada
[11]Baoguo Sun School of Food and Chemical Engineering, Beijing Technology and Business University, Beijing 100048, China
[12]Hunan Agricultural Product Processing Institute, Hunan Academy of Agricultural Sciences, Changsha 410125, China
[13]Institute of Food and Nutrition Development, Ministry of Agriculture and Rural Affairs, Beijing 100081, China
*Correspondence: mapeihua@caas.cn (P.M.); wangfengzhong@caas.cn (F.W.)
Received: April 23, 2026; Accepted: June 23, 2026; Published Online: June 29, 2026; https://doi.org/10.59717/j.xinn-life.2026.100232

Citation: Ma P., Jia X., Zhou F., et al. (2026). The AI-material nexus rewiring the food supply chain: From molecule to market. *The Innovation Life* **4**:100232.

From the Chinese proverb "Food is the staff of life" to George Bernard Shaw's declaration "There is no sincerer love than the love of food", food has always been more than sustenance: it is a foundation of civilization and an enduring human bond. Yet the systems that deliver food are under growing strain. Efficiency bottlenecks, climate shocks, conflict, and mounting loss underscore the urgent need for reinvention. Current systems waste more than 1.3 billion tons of food each year and contribute roughly 34% of global greenhouse gas emissions.[1] Incremental reform is therefore insufficient; structural transformation is needed in how food is grown, processed, distributed, and consumed. The convergence of artificial intelligence (AI) and advanced materials science offers a route to rewire the food supply chain from molecule to market. In this Editorial, we call for a concerted cross-disciplinary push to fuse AI, materials science, and food science, unlocking intelligent, adaptive, and regenerative food systems. We frame the AI-material nexus as a closed-loop system in which AI enables sensing, prediction, optimization, and generative design, while materials translate digital intelligence into physical functions for preservation, safety, nutrition, logistics, and waste valorization. This framework is summarized in Figure 1, which links AI functions, material functions, supply-chain stages, technology readiness, and responsible deployment considerations from molecule to market.

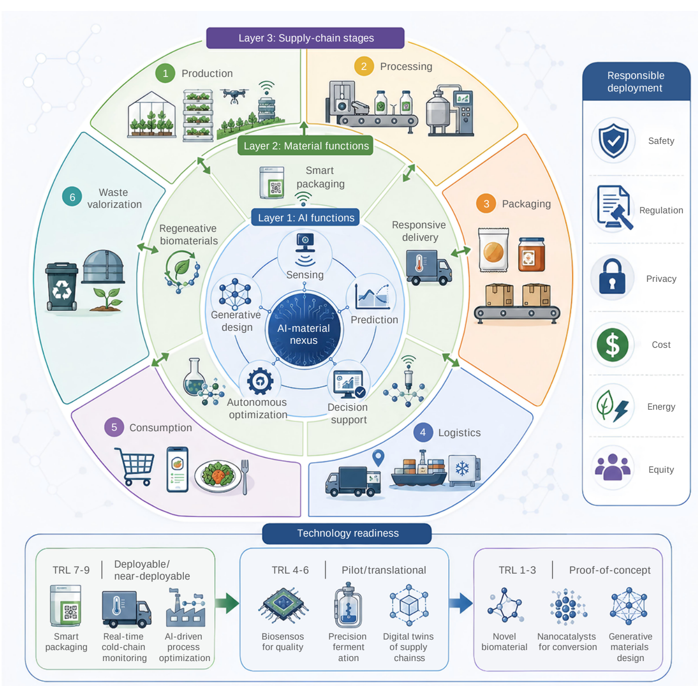

Figure 1. AI-material nexus for rewiring the food supply chain The schematic summarizes how AI functions, material functions, supply-chain stages, technology-readiness levels, and responsible deployment considerations connect from molecule to market.

AI IN FOOD SUPPLY CHAIN: TOWARD PROACTIVE INTELLIGENCE

AI is already permeating the food supply chain, but its disruptive potential lies not merely in efficiency gains. Its deeper value is a paradigm shift from reactive response to proactive design.[2]

In agricultural production, AI-assisted robotics, sensing, logistics, and controlled-environment systems can reduce inputs, improve quality control, and decrease food loss, although performance remains highly dependent on crop type, infrastructure, cost, and deployment context. Climate-resilient agriculture is another frontier. By integrating satellite data, soil diagnostics, and climate models, AI systems can forecast regional yield losses 60 to 90 days in advance, empowering farmers to implement adaptive planting strategies that reduce climate-induced losses by up to 40%.[3] In harvesting, soft robotics coupled with multimodal sensing are enabling millimeter-precision, bruise-free collection of delicate fruits and vegetables. These advances can triple harvesting efficiency and drive postharvest losses from about 15% to below 2%. AI is also transforming processing. Generative algorithms enable the design of molecular structures with desired functions; for instance, high-sweetness but low-metabolic-burden sweeteners and pH-responsive antimicrobial materials may be developed at lower cost. In quality control, AI-enhanced hyperspectral imaging and nanosensors enable pathogen detection at parts-per-trillion sensitivities in under five minutes across the supply chain, potentially preventing millions of tons of food loss annually and lowering foodborne illness risk by more than half. Logistics systems are evolving in parallel. Autonomous delivery fleets coordinated by AI-driven logistics engines can work with intelligent, phase-change thermal materials to reduce spoilage by 50% while curbing carbon emissions. At the consumer end, multimodal AI models integrating personal genomics, metabolomics, and behavior are redefining food from a generic commodity to a personalized service through individualized nutrition and dynamic meal planning.

These technologies differ greatly in maturity. AI-enabled quality inspection, logistics optimization, and precision spraying are closer to deployment; smart packaging sensors, autonomous materials laboratories, and cultured-meat scaffolds are largely translational; CO_2-to-starch conversion, DNA-origami sensors, and omics-guided personalized nutrition remain proof-of-concept or long-term directions. Progress also brings challenges: high capital and energy needs may limit adoption; AI-developed materials need safety checks; personalized nutrition raises privacy risks; and unequal access may widen gaps. Responsible development thus calls for coordinated regulation, open data rules, transparent validation, and inclusive deployment.

AI × MATERIALS SCIENCE: TRIGGERING THE NEXT CRITICAL THRESHOLD

The integration of AI and materials science is catalyzing structural transformation across the food supply system. The core shift is from piecemeal optimization to an intelligent materials paradigm capable of closing the loop from energy input to waste regeneration.

In vertical agriculture, machine learning-driven spectral membranes, such as gradient bandgap perovskite/polymer composites, can precisely regulate photon migration, boost light utilization by 45%, and lower energy demand by half.[2] This may help urban high-density farming move toward both energy self-sufficiency and economic viability. Packaging is also being reinvented. Neural networks coupled with embodied AI are powering autonomous materials laboratories, enabling closed-loop molecular generation, property prediction, and synthesis. AI-guided materials design can accelerate biodegradable packaging, while smart labels based on MOFs, conductive hydrogels, or other responsive materials enable in situ monitoring of freshness markers such as ethylene, biogenic amines, and ATP. By linking biochemical signals to logistics decisions, packaging can shift from passive protection to condition-based quality control and waste reduction.

Food safety is being redefined at the molecular scale. Generative AI can guide highly specific nanoframeworks, such as DNA-origami-MOF hybrids, capable of recognizing microbial proteins such as Salmonella spp. flagellin with single-step detection at sensitivities as low as 0.1 CFU/mL. These portable "sample-in, answer-out" diagnostics could deliver lab-grade performance at points of production and distribution, embedding traceability tools at the edge of the supply chain. In functional food development, reinforcement learning is guiding targeted delivery systems based on responsive carrier topologies; some systems achieve intestinal release efficiencies exceeding 90% in vitro. When tailored to individual omics profiles, AI can generate personalized, clean-label formulations and advance nutrition from population supplementation to dynamic individual adaptation. Waste streams are also being recast as bioeconomic inputs. Machine learning can help design efficient cellulases and selective COF adsorbents that convert fruit pomace and lipid residues into high-value molecules such as lactic acid and squalene. Waste is no longer only an end point but the origin of new value chains. This is not a simple technology stack but a triadic revolution powered by the materials genome, generative AI, and food engineering.[4] Importantly, the AI-material nexus should not be equated only with capital-intensive robotics, vertical farms, or omics-based nutrition. For resource-limited settings, near-term priorities should include mobile diagnostics, low-cost freshness indicators, reusable cold-chain materials, open-source decision tools, and cooperative service models that reduce the burden on individual smallholders.

ENABLING CROSS-DISCIPLINARY SYNERGY

The coming era of AI-driven materials innovation holds the promise of a fully reimagined food supply chain, but only if disciplinary barriers are dismantled.[5] We propose concrete measures to integrate computer science, agriculture, food science, materials science, and the social sciences.

Expand evaluation and incentive systems

Incentive structures must evolve. Academic recognition, funding criteria, and performance evaluation should reward interdisciplinary work that bridges AI, food systems, and materials innovation. Recognizing and incentivizing AI-materials-agriculture breakthroughs will ensure that interdisciplinary work achieves both visibility and sustainability.[1]

Build integrated research platforms

Joint projects and dedicated centers should convene AI researchers, materials scientists, and food technologists. Such hubs can incubate disruptive innovations for grand societal and scientific challenges. Implementation should proceed in stages. In the next 3 years, journals, funders, regulators, universities, and industry should require clearer technology-readiness reporting, build shared validation datasets, and establish pilot AI-material food laboratories. Over 10 years, these efforts should mature into regional demonstration hubs, harmonized safety standards, and affordable deployment models for both high-resource industries and small-scale producers.

Embed social science and ethics

Ethics and social dimensions must be embedded early. Regulatory frameworks for AI-designed ingredients, standards for cultured meat certification, and transparency tools for algorithmic personalization should be co-developed with ethicists, policymakers, consumers, and industry. Funders should mandate explicit inclusion of ethical and equity considerations to align technological advances with public values and sustainability.[5]

Train cross-boundary researchers

Education must prioritize cross-disciplinary fluency. Materials chemists trained in systems thinking may discover new avenues for social impact; conversely, data scientists and food technologists must learn to co-design with materials, biological systems, and users. Cross-training programs and joint mentorship will cultivate teams fluent in AI, new materials, and agricultural science.[2]

Pursue disruptive creativity

True breakthroughs arise from unconventional combinations. Interdisciplinary research must encourage calculated risk-taking and creative collisions, fusing AI and advanced materials to dismantle traditional supply-chain paradigms and accelerate the sustainable food revolution.

OUTLOOK: FROM SILENT REVOLUTION TO RESILIENCE FUTURE

The food system of the 21st century must achieve resilience in the face of climate volatility, population growth, resource constraints, geopolitical tensions, trade disruptions, armed conflicts, and global supply-chain fragility. AI-driven materials innovation is not a marginal enhancement but a structural rewiring, creating adaptive supply chains that sense, respond, and regenerate.[3] By uniting disciplines, embracing ethical frameworks, and fostering disruptive creativity, we can build a food system that delivers not only efficiency but also nutritional equity and planetary health.

This quiet revolution is now underway: from molecule to market, from scarcity to resilience, and from reactive supply to proactive design. The future of food is being rewritten not in isolated laboratories, but through the synthesis of intelligence, materials, and humanity itself.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

AI tools were used exclusively for language editing and image refinement suggestion, with all scientific content and conclusions remaining the sole responsibility of the authors, and all AI-related rights, disclosures, and compliance terms permitted under the publisher's policy are fully acknowledged and upheld.

REFERENCES

1. Wang L., Garland G.M., Ge T., et al. (2025). Integrated strategies for enhancing agrifood productivity, lowering greenhouse gas emissions, and improving soil health. *The Innovation* **6**:101006. DOI:10.1016/j.xinn.2025.101006
2. El Jarroudi M., Kouadio L., Delfosse P., et al. (2024). Leveraging edge artificial intelligence for sustainable agriculture. *Nat. Sustain.* **7**:846–854. DOI:10.1038/s41893-024-01352-4
3. Balashankar A., Subramanian L. and Fraiberger S.P. (2023). Predicting food crises using news streams. *Sci. Adv.* **9**:eabm3449. DOI:10.1126/sciadv.abm3449
4. Zhao Y., Zhu Z., Chen B., et al. (2023). Toward parallel intelligence: An interdisciplinary solution for complex systems. *The Innovation* **4**:100521. DOI:10.1016/j.xinn.2023.100521
5. Tzachor A., Devare M., King B., et al. (2022). Responsible artificial intelligence in agriculture requires systemic understanding of risks and externalities. *Nat. Mach. Intell.* **4**:104–109. DOI:10.1038/s42256-022-00440-4

FUNDING AND ACKNOWLEDGMENTS

This work was funded by Basic Research Center, Innovation Program of Chinese Academy of Agricultural Sciences (CAAS-BRC-202610). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

AUTHOR CONTRIBUTIONS

All authors have read the final manuscript and approved it for publication.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

No new data were created or analyzed in this study.