Agri-Food Future: Strategic Insights Into Innovation, Sustainability, and Global Food Security

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Abstract

The Agri-Food (AF) sectors are confronting unprecedented challenges driven by climate change, resource scarcity, demographic pressures, and shifting consumer demands. Feeding a projected 9.7 billion people necessitates a 50–60% increase in food production under conditions of heightened climatic volatility, water scarcity, and deteriorating soil fertility. Addressing these constraints requires a paradigm shift anchored in scientific innovation, technological disruption, and sustainable transformation. This paper presents a holistic strategic assessment of critical trajectories shaping the AF ecosystem, including precision agriculture, artificial intelligence (AI), digital twins, blockchain-enabled supply chains, and next-generation biotechnology. Advances in CRISPR-Cas9 genome editing, synthetic biology, precision fermentation, and cultured proteins are redefining the protein landscape, while regenerative agriculture and circular economy principles provide sustainable pathways for soil restoration, carbon sequestration, and waste valorization. The convergence of Internet of Things, quantum computing, and predictive analytics enable data-driven systems optimizing resource allocation at molecular and ecosystem scales. Parallel innovations in food science and technology, post-harvest preservation, functional food design, animal genomics, and climate-resilient livestock are advancing food security and nutritional health. Economy aspects should be considered as they will also play a pivotal role. Adaptive education programs integrating AI, bioinformatics, and systems engineering, coupled with robust policy frameworks, R&D incentives and public-private partnerships, are essential for cultivating the next generation of AF talent and accelerating innovation adoption. This integrative assessment identifies transformative opportunities across scientific technological and socio-economic domains, providing a blueprint for resilient, equitable, and sustainable AF systems capable of securing global nutrition under escalating environmental and demographic pressures.

Keywords: Agri-Food Challenges, AI, Climate Change, Circular Economy, Sustainability, Public-Private-Partnerships, Innovation.

Introduction

The Agri-Food (AF) sector faces unprecedented future challenges demanding strategic and paradigm change in innovation and systemic transformation. At the forefront is the imperative to feed approximately 9.7 billion people, requiring a 50-60% increase in food production from current levels [1]. This substantial challenge is compounded by climate change which manifests through rising temperatures, unpredictable weather patterns, and extreme events that significantly impact crop yields and agricultural productivity [2-7]. Water scarcity, already critical in many regions, is expected to intensify. Furthermore, the sector grapples with severe resource constraints, including limited arable land and deteriorating soil quality, while evolving consumer preferences increasingly emphasize personalized nutrition for

disease prevention and health optimization [8], sustainable food choices and lower prices [9-12]. These challenges catalyze an escalation in essential input costs (e.g., energy, fertilizers, raw materials), and cause widespread supply chain disruptions [1].

The required AF paradigm shift dictates advanced scientific research, technological innovations [e.g., precise agriculture practices, artificial intelligence (AI) driven systems, vertical farming] enabling significant productivity improvements while optimizing resource usage [1, 13, 14]. The growing adoption of sustainable practices, including regenerative agriculture and circular economy approaches, offer promising pathways to meet food demand while simultaneously preserving environmental resources [15, 16]. The protein landscape is being reshaped through innovations in plant-based alternatives, cultured meat, and precision fermentation technologies [17], providing more sustainable protein sources with reduced environmental impact. Additionally, the digital transformation in the AF sectors [18], is encompassing smart farming technologies, blockchain-enabled supply chain transparency [19-21], food quality, digital marketplaces and data science techniques, are enhancing efficiency and reducing losses throughout the food system [10, 18, 22].

The convergence of AI, exponential growth in computing power, digitization, and advanced sensing technologies is catalyzing a fundamental shift toward precision agriculture [23, 24]. Contemporary agricultural innovation probably already exhibits Moore's law characteristics (e.g., computational power, sensing technologies, AI and emerging agentic AI capabilities doubling in less than two years). This trajectory catalyzes precision agriculture 4.0 amplifying autonomous decision-making systems, real-time environmental monotoring and predictive analytics optimizing resource allocation at molecular levels [13]. Quantum computing, machine learning, Internet of Things (IoT) convergence, create unprecedented agricultural optimization opportunities transcending traditional productivity boundaries [25].

Within the AF sectors, this exponential unabated advancement is most evident in the deployment of sophisticated AI systems that analyze complex agronomic data sets to optimize crop yields and resource allocation [26]. Advanced sensing technologies (e.g., hyperspectral imaging, soil microbiome analysis, satellite monitoring) is enabling predictive agricultural intelligence that anticipates environmental stressors before yield impact [13]. Blockchain supply chains and digital marketplaces create resilient distribution networks minimizing waste while maximizing value [20, 21].

Sustainable intensification mandates circular economy principles integration where waste becomes input and carbon sequestration co-benefits food production [15, 16]. Regenerative practices enhanced through precision technologies restore soil health while maintaining productivity gains [27, 28]. Another aspect of sustainability could be attributed utilization of Sterile Insect Technology (SIT) to control pests. The World Health Organization (WHO) has emphasized the urgent need for alternative strategies to chemical insecticides for controlling mosquito populations, SIT showed rapid development, with numerous pilot trials being conducted worldwide [29].

Critical AF success factors include developing adaptive human capital, establishing standardized data protocols, and creating innovation-incentivizing policy frameworks. It faces also a pressing increasing need to attract and retain young talent. This necessitates modernizing agricultural education and creating compelling career pathways that showcase the increasing sophistication and technological integration within modern agriculture integrate advanced sciences with AI, machine learning, biotechnology, data management, and environmental systems engineering through interdisciplinary curricula [30, 31].

Strategic alignment of agricultural policies with broader economic frameworks, including circular economy principles, is essential. Innovation coordination and policy alignment with large frameworks are vital. Some key incentives including R&D tax credits and venture capital are needed to stimulate private sector investment [16]. Public co-funding is warranted to mitigate the high risks in Agri-Tech (AT) investments, correcting market failures from information asymmetry and high-risk premiums.

As the AF sector faces unparalleled future challenges, this paper objective is to furnishe a holistic strategic assessment of evolving needs, opportunities and development directions. More specifically, these aims are addressed: 1. to examine future critical and cardinal trends (climate change, water and land scarcity, population growth). 2. to highlight strategic challenges and opportunities (e.g., circular economy); 3. to furnish insights on emerging innovation (e.g., AI, digital transformation, precision agriculture, sensor, robotics, real-time monitoring, twin- modeling, bioinformatics); 4. to illuminate biotech and genetics horizons [e.g., stress crops, alternative-proteins, Clustered Regularly Interspaced Short Palindromic Repeats-associated protein 9 (CRISPR-Cas9)]; 5. to portray education needs (e.g., interdisciplinary education programs, lifelong learning, industry-academic partnerships) and 6. to highlight public-private partnerships; (PPP) and consumer integration (e.g., funding, agriculture policies and alignments, socioeconomic impacts consumers).

It is anticipated that this strategic assessment will facilitate future discussion and collaboration required for jumpstarting the implementation and integration of the identified topics through, incorporating science, innovation, novel technologies, multidisciplinary collaboration, public- private alignment, new education programs, and consumers incorporation.

Methodology

Future research fields outlined below were selected based on in-depth assessment of scientific reports and publications published almost all in the last 2-years. Additionally, topics were selected and outlined based on comprehensive deliberation and assessment. Only topics of either vast foreseeable significant future impact, synergistic potential crossing to other fields and/or of high scientific relevance and importance were selected. It is clear that additional topics could be added. However, due to lack of space and the need to focus they were not included. However, it is highly recommended that the readers should carefully consider their own consideration in adding other potential emerging fields.

Future Research Fields
Crop Protection
Modern agricultural sustainability demands revolutionary ap-

proaches to crop protection that integrate cutting-edge biotechnology with ecological principles [32, 33]. Contemporary crop protection strategies encompass several critical domains such as precision biocontrol systems utilizing engineered microbial agents and RNA interference technologies within integrated pest management frameworks [34, 35]. Another topic is next-generation agricultural platforms that deploy AI-driven predictive modeling and autonomous precision systems [13, 27]. Another important topic is climate-adaptive crop development through CRISPR-Cas9 genome editing and multi-omics breeding approaches to enhance resilience against environmental stressors including drought, salinity, and extreme weather events under accelerating climate change [4, 36].

1. *Sustainable Pest Control Innovations:* Developing human- and eco-friendly microbial and pest control methods, including biological and physical techniques and integrated pest management (IPM) systems (e.g., biological control + reduced chemical dosages or treatments). Optimizing the utilization of SIT to control pests should be further explored.
2. *Next-Generation Pest Control:* Incorporating cutting-edge pest control methods into broader agricultural systems.
3. *Resilient Crop Varieties:* Creating and enhancing plant varieties capable of thriving in challenging conditions such as global warming, drought, and soil salinity.

Agricultural Systems Engineering

Modern agricultural systems require transformative technological integration of digital infrastructure, autonomous systems, and sustainable resource management [23]. Robust connectivity infrastructure enables seamless IoT integration and real-time data exchange across rural networks [18]. Blockchain-secured data systems and quantum-resistant cybersecurity protocols protect agricultural value chains from cyber threats [19]. Precision agriculture leverages hyperspectral imaging, edge computing, and federated learning for real-time crop monitoring and predictive analytics [37]. Revolutionary controlled environment agriculture advances through biomimetic greenhouse designs and vertical farming systems utilizing LED photobiology and aeroponic cultivation [38]. Swarm robotics and AI-powered autonomous systems create fully automated ecosystems for precision seeding to selective harvesting [39]. Advanced membrane technologies and atmospheric water harvesting enable sustainable agricultural production in water-scarce environments [39].

1. *Connectivity Infrastructure:* Addressing inadequate connectivity infrastructure in rural areas is crucial for enabling the seamless integration and interoperability of diverse technological solutions.
2. *Data Reliability and Cybersecurity Protection:* Data reliability and robust cybersecurity protection are paramount for ensuring the integrity and competitiveness of the AF information systems and value chains.
3. *Precision Agriculture:* Leveraging advanced and innovative technologies such as remote and close-up sensing, AI-driven tools, machine learning for improved decision-making and agricultural management.
4. *Optimization of Greenhouse Designs:* Innovating greenhouse (e.g., LED photobiology), vertical farming designs and aeroponic cultivation for minimizing land and water use while increasing productivity and sustainability.
5. *Robotics and Automation:* AI driven new technologies for all stages of agriculture and growth cycles. Advancing the development of autonomous farming systems (including drones and robotics) to improve yields, reduce reliance and optimization of manual labor, lower operational costs,

and enhance precision in planting, irrigation targeted treatments, harvesting and resource usage (water and fertilizers).
6. *Advanced Water Purification and Collecting Recycling Systems:* Advanced membrane technologies and atmospheric water are crucial for addressing water scarcity, especially in arid areas.

Soil, Water and Environmental Sciences

Contemporary environmental agricultural sciences integrate pedosphere management, hydrological optimization, and ecosystem-based adaptation strategies for sustainable food production [40, 41]. Soil conservation leverages biochar applications, mycorrhizal inoculation, and precision nutrient cycling to enhance pedological health and long-term fertility [28]. Advanced irrigation systems utilize multi-spectral sensor networks and machine learning algorithms to optimize water delivery across diverse water qualities including saline and reclaimed sources [24]. Resource optimization employs nutrient use efficiency models and real-time soil-plant-atmosphere monitoring for maximized input utilization. Environmental adaptation strategies incorporate climate envelope modeling and assisted migration techniques for agricultural expansion into marginal landscapes [5]. Soil microbiome engineering harnesses (CRISPR-Cas9) modified beneficial bacteria and synthetic biology approaches to enhance rhizosphere functionality and crop-microbe interactions [42]. Climate-smart agriculture integrates carbon sequestration technologies, drought-resilient cultivars, and regenerative farming practices to ensure ecosystem resilience under changing climatic conditions [9].

1. *Soil Conservation and Fertility*: Protecting and enhancing soil health to ensure long-term productivity (e.g., leverages biochar applications, mycorrhizal inoculation, precision nutrient cycling) to enhance pedological health and long-term fertility.
2. *Efficient Irrigation Systems*: Optimizing irrigation techniques with diverse water qualities (e.g., saline, recycling, breakwater) supported by the development of advanced sensor technologies for precision irrigation. Utilize multi-spectral sensor networks and machine learning algorithms to optimize water delivery.
3. *Resource Optimization*: Maximizing the efficient use of soil, water, fertilizers, and nutrients for sustainable agriculture.
4. *Adaptation to Environmental Changes*: Adaptation of new practices for the utilization of new agricultural areas.
5. *Exploring Soil Microbiomes*: Soil microbiome engineering harnesses CRISPR-Cas9 modified beneficial bacteria, harnessing soil microbial ecosystems to improve soil health and crop productivity.
6. *Climate-Smart Agriculture*: Promoting practices that ensure environmental sustainability and resilience to climate change. climate-smart agriculture integrates carbon sequestration technologies to ensure ecosystem resilience under changing climatic conditions.

Plant Sciences and Field Crops

Modern plant sciences integrate genomic engineering, phenotypic plasticity, and ecosystem-based breeding approaches to develop resilient crop varieties for global food security [3, 6]. Crop enhancement employs CRISPR-Cas9 systems, base editing technologies, and synthetic biology platforms to engineer traits in-

cluding biofortification, pharmaceutical metabolite production, and multi-stress tolerance mechanisms [42, 43]. Environmental stress resilience is achieved through epigenetic programming, transcriptomic profiling, and development of climate-adaptive phenotypes with enhanced thermotolerance and osmotic adjustment capabilities [44]. Genetic diversity conservation utilizes genomic selection, participatory breeding, and in-situ germplasm management to maintain adaptive allelic variation and evolutionary potential [45]. Yield stability interventions employ hormonal regulation pathways, flowering synchronization technologies, and precision phenology modeling to mitigate alternate bearing cycles in perennial systems [6]. Seed management strategies integrate cryopreservation techniques, genomic prediction models, and climate-informed breeding programs for adaptive seed system optimization [46]. Carbon sequestration enhancement leverages root architectural engineering, arbuscular mycorrhizal network augmentation, and below-ground carbon allocation optimization through selective breeding and synthetic symbiosis development [9, 47].

1. ***Enhancing Crop Quality and Biodiversity***: Creating varieties through innovative, biotechnology techniques such as gene editing (e.g., CRISPR-Cas9), advanced genetic modification, with unique and desirable traits, including higher protein content, pharmaceutical properties, antioxidants, sugar substitutes, enhanced drought tolerance, higher yields, extended storage, enhancing flavor, taste and nutritional value and resistance to pests and diseases.
2. ***Stress and Disease Resistance***: Strengthening crops' resilience to environmental stresses (e.g., heat, dryness, salinity).
3. ***Genetic Diversity for Enhanced Sustainability***: Broadening the genetic base of crops to improve resilience and adaptability, climate change and sustainability, in-situ germplasm management to maintain adaptive allelic variation and evolutionary potential.
4. ***Addressing Yield Fluctuations***: Mitigating the problem of reduced yields in perennial crops, such as fruit trees, during alternate-bearing years.
5. ***Seed Cycling Strategies***: Optimization of techniques for seed management and cycling to face changing climatic conditions and meeting high sustainability criteria.
6. ***Carbon Sequestration***: Development of root systems through selective breeding to trap more carbon. Also enhancing capabilities of mycorrhizal fungi or similar to sequestrate carbon.
7. ***Climate Engineering***: Methods for enhancing rainfall in arid zones should be developed.

Agricultural Fresh and Dry, Produce Research

Post-harvest agricultural sciences integrate advanced preservation technologies, biocontrol systems, and intelligent monitoring networks to minimize food losses and enhance supply chain sustainability [48, 49]. Quality preservation employs modified atmosphere packaging, nanocellulose-based edible coatings, and cold plasma treatment technologies combined with smart packaging systems incorporating time-temperature indicators and gas-sensitive sensors [50, 51].

Eco-friendly pest management utilizes bioactive compounds extraction, entomopathogenic microorganisms, novel techniques (e.g., enzymatic) to eliminate microbial and fungal toxins (my-

cotoxins), are nedded to replace synthetic pesticides while maintaining post-harvest product integrity [52]. Real-time monitoring solutions integrate IoT sensor networks, blockchain traceability systems, and AI machine learning algorithms for predictive quality assessment and supply chain optimization [20, 26, 51].

1. ***Preservation of Quality and Enhanced Storage Capacity***: New technique and methods are needed to preserve the quality of produce by preventing physiological damages and losses during storage and transporation, and for predictive quality assessment and supply chain optimization (e.g., modified atmosphere), nanocellulose-based edible coating, low-pressure cold plasma treatment technologies combined with smart packaging systems incorporating time-temperature indicators and gas-sensitive sensors, green pesticides, AI machine learning algorithms.
2. ***Eco-Friendly Pest Control and the Destruction of Bacterial and Fungal Toxins***: Developing quick methods based on molecular means (e.g., PCR) and immunological kits to detect harmful microorganisms in agricultural and food products. Developing environmentally safe (green) pesticides, to prevent post-harvest losses (e.g., insect, microbial and fungal damages) and preventing or eliminating harmful toxins (bacterial and mycotoxins).
3. ***Advanced Technologies and Tracking Solutions***: Sensors to monitor produce storage conditions in real time [e.g., Quick Response (QR) and time-temperature indicator], utilization of IoT, Big Data, AI, advanced analytical technologies (e.g., electronic nose) to detect agricultural and food products spoilage.

Food Science and Technology

Contemporary food science and technology is undergoing transformative innovations that address critical sustainability and health challenges through integrated systems approaches [11]. The implementation of circular economy principles in agricultural waste management is revolutionizing resource utilization by converting byproducts into valuable inputs through biorefinery technologies and waste-to-energy platforms [53]. Precision and personalized nutrition and food systems are emerging through the development of bioactive functional foods that leverage nutrigenomic insights to target specific metabolic pathways and health conditions [8]. The convergence of cellular agriculture, synthetic biology, and precision fermentation is enabling scalable production of alternative proteins through bioreactor systems and engineered microorganisms that dramatically reduce environmental impact while maintaining nutritional equivalence. Advanced manufacturing technologies, including process intensification, AI optimization, digital twins, and green chemistry applications, are simultaneously reducing prduction costs and carbon footprints while enhancing product quality through real-time monitoring and control systems [15, 54]. The impact of food processing on drug absorption, metabolism, and subsequent pharmacological activity is a pressing yet insufficiently explored area of research. Overlooking food-processing-drug interactions can significantly disrupt optimal clinical patient management [55].

A most recent review [56] delves into the extraordinary molecular complexity of food and the importance of many of the compounds consumed through various food sources remain insuffi-

ciently characterized in terms of their potential health benefits. It was estimated that more than 139,000 food-derived molecules may interact with a broad spectrum of human proteins, and only approximately 2,000 food chemicals are currently employed as pharmaceutical agents, while numerous yet unidentified food compounds are likely to hold pharmaceutical potential [56]. The potential importance of polyphenols in both nutritional science and medical research should be further studied [57]. By unveiling the molecular mechanisms through which these compounds interact with human biologic pathways, this strategy not only refines the definition of dietary quality but also opens new avenues for targeted therapies and precision nutrition. Unlocking this knowledge could revolutionize the way to explore the role of food in health [56]. Integrating omics technique, allowing the understanding of the interaction between biological molecules as refered to health and nutrition. This field should be accelerated in the food research science utilizing foodomics [58] and enginomics [59].

1. *Sustainable Waste Management:* Implementing strategies to reduce and repurpose agricultural and food waste (circular agriculture) are needed. It includes among other, converting byproducts into valuable inputs through biorefinery technologies and waste-to-energy platforms.

2. *Functional, Precision and Personalized Nutrition:* Developing specialized food products tailored for specific populations, such as those with celiac disease or diabetes. Development of bioactive functional foods that leverage nutrigenomic insights to target specific metabolic pathways and health conditions. Following processes of bioavailability and bioaccessibility.

3. *Obesity and Diabetics:* Glucagon-like peptide-1 (GLP-1) a signal peptide hormone represents a paradigm shift in the management of both type 2 diabetes and obesity. Food- derived molecules, including macronutrients, polyphenols, other chemicals, and bacterial products, involved in possible signaling pathways, aiming to contribute to developing innovative strategies for enhancing endogenous GLP-1 release should be studied.

4. *Alternative Protein and Nutraceuticals:* Production of alternative proteins and nutraceuticals through bioreactor systems and engineered microorganisms that dramatically reduce environmental impact while maintaining nutritional equivalence, advancing cellular agriculture, sustainable protein sources, precision fermentation (e.g., sweeteners, replacing milk, meat, fish), and resource-efficient methods to reduce the environmental footprint of protein production and to reduce livestock dependency.

5. *Improved Production and Distribution Processes:* New and improved processes to improve product quality [e.g., process intensification, AI, agentic AI and digital twins' optimization, nonthermal and high pressure processing (HPP), pulse electric field, 3D printing, cold plasma, ultrasound, pulsed electric fields, robotics, green chemistry applications] to lower production costs and carbon footprints. Utilization of blockchain technology to reduce waste and minimize losses throughout the distribution channels is recommended. This will also reduce environmental imapact.

6. *Omics and Bioinformatic Techniques:* Given the critical role of nutrition in disease prevention and management, foundational projects that map the chemical makeup of food is needed, overcoming the limiting ability to turn nutrition science into an accurate, data-driven, predictive discipline. Food omics, ergonomics, bioinformatic and other emerging techniques that delve into the composition, functions, and expression outcomes of genomics, transcriptomics, proteomics, and metabolomics, shedding light on how nutrients influence gene and protein expression are required.

7. *Food Processing and Drugs Interactions:* The impact of food processing on drug absorption, metabolism, and subsequent pharmacological activity should be explored.

8. *Effect of Climate Change:* Studying well-being, the effects of the climate changes on human nutrition, well-being, health, food security and food sovereignty.

Animal Science and Living Conditions

Modern animal science is experiencing a paradigm shift toward climate-resilient livestock systems that integrate genomic technologies, precision agriculture, and sustainable production methodologies to address global food security challenges. Advanced phenotyping and stress- response genomics are enabling the development of livestock breeds with enhanced thermotolerance and adaptive capacity to withstand extreme weather events and resource scarcity associated with climate change [60]. Precision nutrition platforms utilizing metabolomics and feed conversion optimization are revolutionizing livestock feeding strategies through bioactive compounds and feed additives that simultaneously improve nutrient utilization efficiency and mitigate ruminant enteric methane emissions [61]. Genomic selection programs and gene-editing technologies such as CRISPR-Cas9 systems are accelerating genetic gains in production traits while maintaining genetic diversity and animal health through marker assisted breeding approaches. Digital animal welfare monitoring systems employing computer vision, biometric sensors, and behavioral analytics are establishing evidence-based welfare standards that optimize both productivity and ethical animal management practices. Internet of-Things (IoT) architectures and artificial intelligence algorithms [62] are transforming livestock operations through real-time monitoring, automated feeding systems, and predictive analytics that optimize growth trajectories and production efficiency. Comprehensive greenhouse gas mitigation strategies incorporating precision feed additives, anaerobic digestion systems for biogas recovery, and genetically modified livestock with reduced methane production are positioning animal agriculture as a key component of carbon-neutral food systems [7, 9]. The integration of AI techniques in fish growth and health status monitoring holds great promise for the sustainability of aquaculture. By leveraging AI's capabilities in data analysis, pattern recognition, and predictive modeling, fish farmers can optimize their practices, enhance productivity, reduce environmental impact, and ensure the welfare of farmed fish [63]. Coping with unexpected phenomena such as bee's Colony Collapse Disorder (CCD) [64].

1. *Adaptation to Environmental Stress:* Climate-resilient livestock systems that integrate genomic technologies, precision agriculture, and sustainable production methodologies to address global food security challenges and environmental conditions (e.g., global heating, water scarcity).

2. *Sustainable Feeding Practices:* Precision nutrition platforms utilizing metabolomics and feed conversion optimization to improve feeding strategies through bioactive compounds and feed additives that simultaneously improve nutrient utilization efficiency and mitigate enteric methane

emissions.

3. *Genetics and Breeding:* Advanced genetic techniques (phenotyping and stress-response genomics) to develop livestock breeds with enhanced thermotolerance and adaptive capacity to withstand extreme weather events and resource scarcity associated with climate change. Breeding programs to increase productivity, including meat and milk yields.

4. *Animal Welfare:* Promoting ethical practices and improving the living conditions and well-being of animals.

5. *Computerized Control:* Transforming livestock operations through real-time monitoring, automated feeding systems, advanced sensors and computer control, automation and predictive analytics that optimize growth trajectories and production efficiency.

6. *Reducing Greenhouse Emissions:* Advanced livestock management (e.g., precision feed additives that reduce methane from cattle digestion), biodigesters capturing methane from manure for energy production, gene-edited livestock breeds with lower methane production.

7. *Fish Culture:* Integration of AI techniques in fish growth and health for enhanced sustainability of aquaculture and optimizing land base productivity, reducing environmental impact, managing water quality and waste and ensuring the welfare of farmed fish.

8. *Coping with Unexpected Phenomena:* Managing with unforeseen phenomena such as bee's Colony Collapse Disorder (CCD) and their interactions with ecological and economic systems (as expressed by the interconnectedness of honeybee health with broader ecological and economic systems), calls for urgent conservation measures, improved management practices, and sustainable agricultural strategies to mitigate the negative effects.

Strategic Economic Policy for Sustainable Agri-Food Innovation

Strategic alignment of agricultural policies with broader economic frameworks, including circular economy principles, is essential for sustainable food production, a competitive AF sector and equitable access to nutrition. Socioeconomic factors and population dynamics critically impact food security [65], with rising demand (driven by urbanization requiring the urgent development of new food sources and production systems [66]. Dietary shifts and their environmental and health implications must be further explained to mitigate negative economic externalities [12, 67]. Additionally, the importance of food sovereignty, crisis management frameworks, and job creation within the AF sector to attract younger generations should be considered. Innovation implementation is supported by dedicated its roles within firms and the establishment of incubator and accelerator centers for new ventures [14]. Innovation coordination and policy alignment with frameworks are vital, with key incentives including R&D tax credits and venture capital to stimulate private sector investments. Public co-funding is warranted to mitigate the high risks in AT investments, correcting market failures from information asymmetry and high-risk premiums [16]. The necessity of collaborative platforms and Public-Private-Partnerships (PPPs) as well as multi-stakeholder partnerships to cultivate a robust AT innovation ecosystem was emphasized [68].

1. *Agricultural Policies and Practices:* Designing agricultural policies and practices that are strategically aligned with industrial policy, trade agreements, and intellectual property frameworks, and consumers, including targeted interventions such as subsidies for sustainable farming and tariff adjustments, can significantly enhance the sector's competitiveness. Such an integrated approach, which incorporates circular economy principles is essential to ensuring a sustainable food supply and equitable access to healthy nutrition for all citizens.

2. *Socioeconomic Impacts:* Analyzing the essential interplay between economic disparities and population dynamics, and evolving consumer preferences have a direct impact on agricultural systems and food security. This investigation fundamentally entails assessing how these determinants influence resource accessibility, livelihood resilience, and the overall stability of food systems, particularly for vulnerable consumers/populations and small-scale farmers, in order to promote more equitable and sustainable outcomes.

3. *Food Price Stability:* The development of price stabilization mechanisms is imperative for managing volatility during global systemic shocks, thereby mitigating financial risk exposure for AF producers and ensuring affordable food access to consumers.

4. *Increased Food Demand Challenges:* Addressing the rising demand for food driven by population growth, migration and urbanization and examining the relationship between socioeconomic factors, consumer trends and agricultural opportunities are needed. The development of new food sources and production systems is critical for meeting this challenges.

5. *Dietary Shifts, Health and Environmental Impact:* Future research should rigorously examine the dynamics of dietary preference evolution and their systemic implications on environmental sustainability, public health, and resource constraints, with the objective of internalizing and mitigating associated adverse economic externalities.

6. *Food Sovereignty:* Strengthening local food systems and empowering sub-national institutional capacity within local food systems and empowering community-level self-determination over resource allocation and critical distribution pathways.

7. *Crisis Management and Risk Mitigation:* Developing institutional frameworks for managing agricultural crises and mitigating systemic risks, including those from climate change, pandemics, and geopolitical instability.

8. *Job Creation in Agriculture:* Promoting AF system practices that generate employment opportunities, particularly for attracting the young generation and rural and underserved areas.

9. *Dedicated Innovation Implementation Roles:* Supporing the professional development of dedicated roles within AF firms, particularly SMEs, to oversee the mainstreaming of technological innovation.

10. *Catalytic Role of Entrepreneurial Support Infrastructure:* Incubator and accelerator centers are structured environments that nurture and accelerate the growth of new AF technology enterprises and startups. They can play a crucial role in fostering innovation and entrepreneurship by providing a supportive ecosystem for nascent ventures.

11. *Policy Alignment and R&D Incentivization:* Aligning with strategic policy frameworks to foster innovation, governance, and coordinated action in AF systems. Particularly, robust incentive programs and funding mechanisms like

R&D tax credits for AF companies, access to venture capital for startups, and innovation Voucher's for SMEs, are pivotal to stimulating private sectors' R&D and technology investments.

12. ***Addressing Tech Investment Risks:*** Given the inherent high risk and uncertainty concerning the return on investment (ROI) in agricultural technologies, public co-funding is warranted to mitigate these financial barriers, acting to correct market failures driven by information asymmetry, high risk premiums and accelerate innovation adoption.

13. ***Collaboration Platform:*** Enhancing multi-stakeholder collaboration, namely, Large, Medium and Small Enterprises, food industry, academia, consumers and public-private partnerships, by cultivating a collaborative innovation ecosystem that actively promotes AT innovation.

Emerging Technologies Supporting Agricultural Implementation

Contemporary agricultural systems integrate AI, machine learning, and predictive analytics for optimized resource management across AF value chains [69]. Advanced biotechnology platforms utilizing CRISPR-Cas9 [4] and precision fermentation [17] revolutionize sustainable food production through synthetic biology and alternative protein synthesis. IoT architectures [26] with biosensors and nano-sensors enable real-time crop monitoring, soil dynamics assessment, and precision irrigation management [70]. Nanotechnology applications enhance nutrient delivery and pesticide efficiency through targeted systems while minimizing environmental impact. Precision agriculture integrates drone technology, multispectral imaging, and AI analytics for automated crop management and resource optimization. Big data platforms transform agricultural information into actionable insights for evidence-based farm management decisions. Autonomous robotics incorporating computer vision enable precision planting, harvesting, and other treatments while addressing labor shortages. Environmental systems engineering integrates productivity optimization with ecosystem sustainability through precision application technologies. Circular economy principles convert agricultural waste into valuable resources through biorefinery technologies and sustainable practices. Decision support systems utilize expert knowledge and data modeling to assist optimal farm management under uncertainty [10]. Blockchain technology enhances food traceability and supply chain transparency through immutable record-keeping and quality assurance [21]. Precision fermentation platforms using engineered microorganisms enable scalable sustainable protein and agricultural input production [17].

1. ***AI and Machine Learning:*** Applying advanced algorithms for predictive analytics, optimized resource management, and improved decision-making in all AF sectors.

2. ***Biotechnology and Genetic Engineering:*** Contemporary agricultural systems integrate AI, machine learning, and predictive analytics should be utilized for optimizing resources and efficient management across the AF value-chains. Harnessing cutting-edge methods like precision fermentation (e.g., milk, meat, fish, sweeteners, alternative proteins), to develop sustainable agricultural and food solutions.

3. ***Advanced Sensors, Bio- and Nano-sensors, and IoT Technologies:*** Resource optimization using advanced digital capabilities.

4. ***IoT Architectures with Biosensors and Nano-sensors Net-works:*** Enabling real-time crop monitoring, early disease detection, soil dynamics assessment, spraying and precision irrigation management for real-time monitoring of crops and soil.

5. ***Nanotechnology in Agriculture:*** Utilizing nanomaterials for targeted nutrient delivery in efficient fertilizer, enhanced pesticide efficiency, and innovative other agricultural solutions while minimizing environmental impact.

6. ***Precision Agriculture and Drone Technology:*** Implementing revolutionary drone technology for monitoring crops, soil conditions, imaging capabilities, and providing real-time data. Essential platform for optimizing resources (e.g., irrigation, fertilizer application, harvesting pest management, reducing waste, environmental impact, labor cost). Integration of AI with drone technology promises sophisticated future applications (e.g., automated crop spraying, early disease detection, yield prediction) to increase global food production while significantly reducing water, chemicals usage, cost and increased sustainability.

7. ***Data Interpretation and Decision-Making Tools:*** multispectral imaging, and AI analytics for automated crop management and resource optimization. Big data platforms transform agricultural information into actionable insights for evidence-based farm management decisions leveraging big data and analytics for actionable insights and informed agricultural management.

8. ***Robotics and Automation:*** Integrating autonomous systems for tasks like planting, harvesting and crop treatment to increase efficiency, reduce labor demands and improve efficiency. Other typical examples: precise irrigation, fertilization and spraying.

9. ***Environmental Systems Engineering:*** Designing systems that harmonize agricultural productivity and treatments (e.g., pesticides application) with environmental sustainability (e.g., urban population).

10. ***Sustainability and Circular Economy:*** Reducing the agricultural carbon footprint, converting waste into raw materials, energy and others. Fostering circular economic golden practices.

11. ***Decision Support Tools:*** Developing software and big data platforms to transform agricultural information into actionable insights for precise evidence-based farm management decisions assisting farmers in making precise data-driven decisions. Decision support systems utilize expert knowledge and data modeling to assist optimal farm management under uncertainty.

12. ***Blockchain and Supply Chain Management:*** Using blockchain for food traceability, enhanced supply chain efficiency, reduced food waste, and improved safety and trust in agricultural products.

13. ***Precision Fermentation:*** Expanding the application of precision fermentation for sustainable protein production and innovative agricultural inputs (alternative proteins, milk, meat and fish).

Education

Contemporary agricultural education should integrate advanced sciences with AI, machine learning, biotechnology, data management, and environmental systems engineering through interdisciplinary curricula [30, 31]. Specialized disciplines in agricultural informatics, computational agriculture, and IoT

sensor technologies address growing demand for data-driven expertise [23]. Sustainable agriculture programs focus on food systems engineering and climate-resilient practices to prepare graduates for environmental challenges [71]. Global exchange programs foster international knowledge transfer through academic partnerships and research networks. Industry-academic collaborations bridge theory with practice through internships, cooperative programs, and joint research initiatives [30, 31]. International partnerships establish global networks for innovation acceleration and knowledge sharing across diverse agricultural systems is paramount [72]. Emerging disciplines including computational agriculture and climate-smart agriculture addressing future technological challenges. Continuing professional development utilizes hybrid platforms, micro-credentials, and virtual conferences for lifelong learning are vital. Soft-skills development integrates systems thinking, cross-cultural communication, and entrepreneurial education for complex challenges should be developed [30, 73]. Special attention should be placed on attracting the young generation.

1. *Interdisciplinary Agricultural Technology Programs:* Offering degree programs that integrate advanced agricultural sciences with cutting-edge technologies such as AI, machine learning, biotechnology, genetic engineering, data science, robotics, and environmental systems engineering.

2. *Specialized Academic Disciplines:* Establishing programs and degrees in areas like agricultural informatics, computational agriculture, IoT sensor technologies, drone and satellite imaging, and AI-driven crop management. Advanced certificates in precision agriculture and professional certifications in agricultural data analytics are also key factors.

3. *Sustainable Agriculture Degrees:* Providing academic pathways focused on sustainable agriculture, food systems, and agricultural biotechnology.

4. *Collaborative Exchange Programs:* Encouraging global interaction through exchange initiatives and collaboration networks among academic institutions and research centers.

5. *Industry-Academic Collaborations:* Building partnerships with industry for internships, co-op programs, and joint research projects to bridge the gap between academic learning and practical applications.

6. *International Research Partnerships:* Fostering collaboration with global agricultural research centers by the foundation of a global network to enhance innovation and knowledge sharing.

7. *Emerging Academic Disciplines:* Promoting and integrating of fields such as agricultural informatics, computational agriculture, sustainable food systems engineering, agro-biotechnology, medicine, ecology and climate-smart agriculture to address future challenges.

8. *Continuing Professional Development:* Offering accessible hybrid and online micro-credential courses, annual technology workshops, virtual conferences, and collaborative platforms to support lifelong learning for agricultural professionals.

9. *Soft Skills Development:* Integrating complementary skills training in systems thinking, cross-cultural communication, entrepreneurial education, sustainable innovation strategies, and adaptive problem-solving to prepare students for complex, real-world challenges

Conclusions

- The AF sector must undergo a paradigm shift to address climate change, resource scarcity, population growth, and evolving consumer demands.

- Precision agriculture, AI, robotics, and digital twins are catalyzing AT, enabling data-driven, autonomous, and resource-optimized food systems.

- Biotechnological advances including CRISPR-Cas9, synthetic biology, and precision fermentation are reshaping crop resilience, protein supply, and nutritional quality.

- Regenerative practices and circular economy integration are essential to restore soil health, reduce waste and enhance carbon sequestration.

- Sustainable intensification requires advanced water, nutrient and environmental management technologies to mitigate climate and ecosystem stressors.

- Post-harvest innovations in preservation, monitoring, and traceability reduce losses, enhance food quality and strengthen supply chain resilience.

- Climate-resilient livestock systems integrating genomics, precision nutrition and digital welfare monitoring are central to sustainable animal and aquaculture agriculture.

- Interdisciplinary education and lifelong learning are critical to attract new talent, integrating AI, data science, biotechnology, and systems engineering into agricultural curricula.

- Policy alignment, R&D incentives, and robust public-private partnerships are pivotal for accelerating innovation adoption and correcting market failures in AT investments.

- Integrated comprehensive economic impact assessments into R&D can ensure that resource allocation aligns with long-term societal benefits, enhancing the cost-effectiveness of technological adoption.

- A holistic, innovation-driven approach that converges science, technology, sustainability, and policy is imperative to secure resilient, equitable, and sustainable global food systems.

Author Contributions

ISS and NP: Conceptualization of the study, data collection, reviewing and interpretation, writing the first draft. ER: Economic data review and assessment. ISS, NP and ER: interpretation and manuscript review.

Conflict of Interest Statement

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the work reported.

Artificial Intelligence

ChatGPT (https://openai.com/) and Claude (https://claude.ai/) were utilized to improve grammar, and general editing.

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